PROJECT DESCRIPTION
RESULTS FROM PRIOR NSF SUPPORT

B.Romanowicz (P.I.) "Instrumentation for the Deployment of a Permanent Ocean Floor Broadband Seismic System in Monterey Bay, in Cooperation with MBARI" , NSF/OCE-9911392, $159,896, 08/01/00-12/31/02.

This grant has supported the seismometer package acquisition and testing for the deployment of a long-term ocean bottom broadband seismic station, in Monterey Bay, Ca (MOBB, Monterey Ocean Bottom Broadband project). This is a collaborative project between the Monterey Bay Aquarium Research Institute (MBARI) and the Berkeley Seismological Laboratory (BSL) at U.C. Berkeley. The MOBB deployment itself, as well as auxiliary instrumentation and software development costs were supported by funds to MBARI from the Lucile and David Packard Foundation, and UC Berkeley funds to BSL. The station was installed in April 2002, 40 km offshore, on the western side of the San Gregorio fault, at a water depth of 1000 m (Figure 1). Preliminary data processing and analysis is supported in '03-'04 through an IGPP/LLNL seed grant to BSL.

The ocean-bottom MOBB station currently comprises a three-component seismometer package, a current-meter, and a recording and battery package. In addition, a differential pressure gauge (DPG) with autonomous recording (Cox et al., 1984) was installed in Fall 2002. The seismic package contains a low-power (2.2W), three-component CMG-1TD broadband seismometer system, built by Guralp, Inc., with a three-component 24-bit digitizer, a leveling system, and a precision clock. It is mounted in a cylindrical titanium pressure vessel 54 cm in height and 41 cm in diameter, custom built by the MBARI team and outfitted for underwater connection. Because of the extreme sensitivity of the seismometer, air movement within the pressure vessel must be minimized. In order to achieve this, after extensive testing at BSL, the top of the pressure vessel was thermally isolated with two inches of insulating foam and reflective Mylar. The sides were then insulated with multiple layers of reflective Mylar space blanket, and the vessel was filled with argon gas (e.g. Uhrhammer et al., 2002; Romanowicz et al., 2003b). The current-meter is a Falmouth Scientific 2D-ACM acoustic current meter. It is held by a small standalone fixture and measures the magnitude and direction of the currents about 1 meter above the seafloor. The recording system is a GEOSense LP1 data logger with custom software designed to acquire and log digital data from the Guralp system and digital data from the current meter over RS-232 serial interfaces. The seismic data are sampled at 20 Hz, current-meter and DPG data at 1 Hz, and all are stored on a 3 GB, 2.5 in disk drive. All the electronics and the sensor packages are powered by a single 10 kWh lithium battery.

The station is currently recording data autonomously. The site is revisited every three months, to replace the data recording and battery module. Between each dive, improvements to the data acquisition software can be made. During each visit, the seismometers are recentered, and the clock resynchronized to GPS time. In 2005, the system can be linked to the planned (and recently funded) MARS (Monterey Accelerated Research System; http://www.mbari.org/mars) cable and provide real-time, continuous seismic data to be merged with the rest of the northern California real-time seismic system. The data are archived at the on-line Northern California Earthquake Data Center (NCEDC, Romanowicz et al., 1994; http://www.quake.geo.berkeley.edu), along with those of the Berkeley Digital Seismic Network (BDSN).

Deployment

Prior to the instrumentation deployment, the MBARI team manufactured and deployed a 1181 kg galvanized steel trawl-resistant bottom mount to house the recording and power systems, and installed a 53 cm diameter by 61 cm deep cylindrical PVC caisson to house the seismometer pressure vessel. The bottom mount for the recording system was placed about 11m away from the

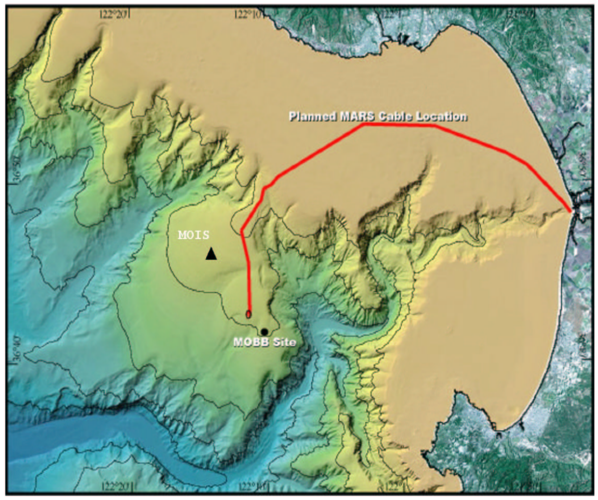

Figure 1: Location of the MOBB and MOISE stations in Monterey Bay, California, against seafloor and land topography. The 1997 MOISE experiment, in which a similar system was deployed in a similar manner for a period of 3 months, was a cooperative program sponsored by MBARI, UC Berkeley and the INSU, Paris, France (Stakes et al., 1998; Romanowicz et al., 1998; Stutzmann et al., 2001). During the MOISE experiment, valuable experience was gained on the technological aspects of such deployments, which contributed to the success of the present MOBB installation. The planned location of the MARS cable is also indicated, with its termination close to the present MOBB site.

caisson to allow the future exchange of the recording and battery package without disturbing the seismometer. Prior to deployment, the seismometer package was tested extensively at BSL, then brought to MBARI where its internal clock drift was calibrated in the cold room against GPS time.

The actual deployment (04/09-04/11/02) occurred over 3 days. On the first dive, the seismometer package was lowered into the PVC caisson (Figure 2a), and its connection cable brought to the site of the recording unit. On the second dive, the recording package was emplaced in its trawl-resistant mount (Figure 2b), and connected to the seismometer package. Tiny (0.8 mm) glass beads were poured into the caisson until the seismometer was completely covered, to further isolate it from water circulation. The seismometer package is now buried at least 10 cm under the seafloor level. On the third dive, the ROV buried the cable between the seismometer and recording packages, then connected to the seismometer through the recording system, levelled and recentered the seismometer and verified that it was operational. The current-meter was also installed and connected to the recording system.

On April 22nd, the ROV returned to the MOBB site to check the functioning of the seisometer and recording system. Some slight settling of the seismometer pressure vessel had occurred, and so the seismometer was commanded to recenter electronically. Over 3 MB of data were then downloaded from the recording system over a period of about two and a half hours, including the recordings of two regional earthquakes in California and two teleseismic events that occurred in Guerrero, Mexico and in Northern Chile.

The site was revisited two months later, on June 27th, to replace the data recording and battery module, in the first of a series of such dives planned over the following 3 years. During these dives, dataloggers and battery packages are exchanged, seismometers recentered, and Guralp clock resynchronized to GPS time. Nine visits have occurred during the time period 04/10/02 to

Figure 2: left: Installation of the seismometer package inside the PVC caisson. This was later completely covered by glass beads. Right: Trawl-resistant enclosure for the recording and battery packages. This snapshot was taken as the ROV Ventana was bringing the cable from the seismometer package in order to connect it onto the recording package. The first time such a remote underwater connection was attempted during the MOISE experiment, it took 2.5 hours to succeed and led to a redesign of the geometry of the instrument packages. The ROV operators are now able to do this routinely in less than 5-10mn.

02/04/04. Because of datalogger software problems, significant data were lost between 01/16/03 and 09/16/03.

Initial results from the MOBB deployment have been described in the following presentations and publications:

McGill, P., D. Neuhauser, D. Stakes, B. Romanowicz, T. Ramirez, and R. Uhrhammer (2002). Deployment of a long-term broadband seafloor observatory in Monterey Bay, EOS Trans. Amer. Geophys. Un., 83, F1008.

Romanowicz, B., D. Stakes, R. Uhrhammer, P. McGill, D. Neuhauser, T. Ramirez. D. Dolenc (2003a) The MOBB experiment: a prototype permanent off-shore ocean bottom broadband station, EOS Trans., AGU, 84, 325-332.

Romanowicz, B., D. Stakes, D. Dolenc, D. Neuhauser, P. McGill, R. Uhrhammer and T. Ramirez (2003b) The Monterey Bay Broadband Ocean Bottom Seismic Observatory, Annales Geophysicae, submitted.

Uhrhammer, R., B. Romanowicz, D. Neuhauser, D. Stakes, P. McGill, and T. Ramirez (2002). Instrument testing and first results from the MOBB Observatory, EOS Trans. Amer. Geophys. Un., 83, F1008.

Uhrhammer, R., D. Dolenc, B. Romanowicz, D. Stakes, P. McGill, D. Neuhauser, T. Ramirez (2003), Data Analysis from an Ocean Floor Broadband Seismic Observatory, EOS Trans. Amer. Geophys. Union, Fall'03 abstract S52D-0162.

PROJECT PLAN

Scientific Motivation

MOBB is (1) the first step towards extending the on-shore broadband seismic network in northern California to the seaside of the North-America/Pacific plate boundary, providing better azimuthal coverage for regional earthquake and structure studies (e.g. Romanowicz et al., 2003a), and (2) a unique opportunity to characterize and possibly propose ways to reduce background noise for future buried seafloor deployments of broadband systems.

Two-thirds of the earth's surface is covered by oceans, which represents a significant challenge for the investigation of global scale dynamic processes in the earth's interior, as well as tectonic processes at ocean-continent boundaries. In particular, the need for long term ocean floor seismic observatories has now been widely recognized, and several national and international efforts are underway to resolve the technological and logistical issues associated with such deployments (e.g.

Purdy and Dziewonski 1988; Purdy, 1995; Forsyth et al., 1995; Montagner and Lancelot, 1995; Detrick et al., 2003).

Following pioneering efforts in the 1960's (Sutton et al., 1965), a number of pilot projects have been conducted in the last ten years, coordinated internationally by ION (International Ocean Network, Suyehiro et al., 1995), to test technological solutions and demonstrate the feasibility of seafloor seismic observatories either in boreholes or on the ocean floor (e.g. Suyehiro et al., 1992; Beranzoli et al., 1998). In particular, in 1992, a French experiment involving the manned underwater vessel *"Nautile"* installed two sets of 3-component broadband seismometers in the north-equatorial mid-Atlantic, one directly on the sea-floor, and the other, using the Ifremer re-entry vessel NADIA, at 300 m depth inside ODP hole 396B (Montagner et al., 1994a,b). The data comparison between the two systems seemed to indicate that the ocean-floor installation was quieter at long periods (Beauduin and Montagner, 1998), however, this remained controversial, as only 10 days of data were acquired in this experiment, and water circulation may have increased the noise in the borehole. Since then, several other buried seafloor installations have been deployed in the deep oceans, some of them making use of abandoned submarine telecommunications cables (e.g. Butler et al., 2000; Kasahara et al., 1998).

During the OSN1 experiment in 1998 (e.g. Collins et al., 2001) 3 broadband systems were installed 225 km southwest of Oahu (Hawaii), at a water depth of 4407 m, one on the seafloor, one buried, and the third one at 248 m below the seafloor, in a borehole drilled by the ODP in 1992 for this purpose (Dziewonski and Wilkens, 1992; Webb et al, 1994). Data were collected for 4 months and demonstrated the importance of burying the seismometer package below the seafloor to obtain good coupling with the ground and ensure good quality of data at long periods, strengthening the results obtained earlier by Sutton et al. (1981), Sutton and Barstow (1990) and Duennebier and Sutton (1995). The latter were based on the data collected during the 6 year long "OBSS" experiment in 2000 m deep water, off-shore California. The OSN1 experiment also demonstrated that a borehole installation can be quieter at teleseismic body wave periods than a buried or seafloor deployment, because it avoids signal-generated noise due to reverberations in the near surface sediment layers. This was confirmed by the long-term Japanese NEREID observatory deployment, which nevertheless documented that a properly cemented ocean-floor borehole in basement rock can be very quiet at long periods as well (Suyehiro et al., 2002; Araki et al., 2003).

Long-term ocean floor observations are also necessary to better constrain regional tectonics, such as on the western margin of North America, where tectonics and seismic activity do not stop at the continental edge. For example, in California, the zone with most abundant seismicity is associated with the Mendocino Triple Junction, and is mostly off-shore. Much effort has been expended to deploy networks of seismic stations in the western U.S., most recently broadband stations, with multiple goals of monitoring the background seismicity, understanding modes of strain release, documenting seismic hazards and providing constraints on crustal and upper-mantle structure. However, because there are very few off-shore islands in central and Northern California, practically all stations are located on the continent. As a consequence, the study of plate-boundary processes, as afforded by regional seismological investigations, is heavily squewed on the continental side of the San Andreas Fault (SAF) system. Offshore seismicity is poorly constrained, both in location and in mechanisms, as is crustal structure at the continental edge.

While consensus seems to have been reached that permanent, borehole installations are best for seafloor deployments of broadband seismometers, they are very expensive: the spatial resolution required for regional studies, either off-shore or in the middle of the oceanic plates, may not be achieved for many years to come using boreholes. A more likely scenario for the broadband exploration of continental margins such as the western US as well as oceanic basins at scales of several hundred km, will involve the installation of buried seafloor broadband seismometers. While it is now established that burying the seismometers is essential to obtain useable data at long periods (periods greater than 10 sec), especially on the horizontal components, there are as of yet few data characterizing long period seafloor noise for shallow buried instruments on the continental shelf and for long enough durations. It is therefore important to conduct pilot studies to determine how to optimally deploy ocean floor broadband systems, and in particular how to minimize the strong perturbing environmental effects, both through improved installation procedures, and through a posteriori deconvolution of ocean current, tide, pressure, temperature and other such signals that can be recorded simultaneously.

In the summer of 1997, the international MOISE experiment (Monterey Ocean bottom International Seismic Experiment) allowed us to collect 3 months of broadband seismic data from a sea-floor system (Figure 1) installed 40 km off-shore in Monterey Bay, in a cooperative experiment between MBARI, IPG (Paris France) and UC Berkeley (e.g. Stakes et al., 1998; Romanowicz et al., 1998). During this experiment, the feasibility of performing under-water electrical and data cable connections between instruments, using an ROV operated from a ship, were successfully illustrated for the first time. The MOISE experiment also confirmed the sensitivity of ocean floor systems to sea currents at long periods and the importance of simultaneous recording of current velocity and direction, at a sampling rate sufficient for quantitative comparisons with seismic data: the conventional current meter sampling rate used by oceanographers (4 sample points once every 4 minutes), was too low to correct the MOISE seismic data for noise generated by currents, although this is theoretically possible (e.g. Stutzmann et al., 2001).

The Monterey Bay Ocean Broad Band Observatory (MOBB) is a direct follow-up of MOISE, and capitalizes on the lessons learned during that pilot experiment. The ultimate goal of this collaborative project between MBARI and BSL is to link the MOBB station by continuous telemetry to the shore, so that MOBB becomes part of the Berkeley Digital Seismic Network (BDSN, Romanowicz et al., 1994). The data can then be contributed to the real-time earthquake monitoring system in northern California (Gee et al., 2003). The opportunity to do so awaits the installation of the MARS cable (Monterey Accelerated Research System; http://www.mbari.org/mars), which is planned in mid-2005. The MOBB station is located in an area called "Smooth Ridge" on the western side of the San Gregorio fault, and closer to it than was MOISE (Figure 1). The planned MARS cable route is down the center of Smooth Ridge and with a termination and junction box approximately 3 km from the MOBB site. The relative proximity of MOBB to shore (and to MBARI) allows recurrent visits, during which system improvement can be performed.

Most of the differential motion between the Pacific and north American plates is concentrated along the SAF, but a significant component of the present day plate motion is taken up by dextral strike-slip displacements in a broad region both east and west of the SAF, as well as contraction in the Transverse Ranges and in the southern Coast Ranges. In particular, the slip vector derived from global plate motion models (Minster and Jordan, 1978; DeMets et al., 1987) has been found to be inconsistent with geodetic and geologic data from the San Andreas fault (e.g. Sieh and Jahns, 1984). Much of this discrepancy (5 mm/yr of lateral slip parallel to San Andreas fault and 7 mm/yr of fault-normal shortening) has been attributed to deformation west of the San Andreas fault. The present seismotectonic setting is characterized by moderate to high rates of seismicity, right-lateral shear deformation parallel to the San Andreas fault, and contractional strain both oblique and normal to the San Andreas fault(Hill et al., 1991; Hutton et al., 1991). Review by the Working Group on Northern California Earthquake Potential (1996) suggests that the slip rate on the SAF in the Santa Cruz mountains is about 14mm/yr, which is 58% of the slip rate north of San Francisco (Thatcher et al., 1997; Schwartz et al., 1998), so the rest of the slip must be accommodated by these other structures, both on-land and off-shore.

This slip gradient reflects partitioning of the plate boundary slip onto the San Gregorio (SGF), Sargent and other faults south of the Golden Gate. The SGF splays from the SAF at the Golden Gate and extends south past the San Francisco peninsula and Santa Cruz mountains, mostly off-shore. It is the principal active fault west of the SAF in central coastal California, yet it remains the largest known fault whose seismogenic potential is not well characterized in this region. Begnaud and Stakes (2000) and Begnaud et al. (2000) used a temporary offshore seismic network to demonstrate the unusually high seismicity levels of the northern SGF, dominated by compressional mechanisms as well as an east-dipping focal plane (Simila et al. 1998). The SGF is thought to be capable of $M > 6$ earthquakes, making the MOBB site particularly interesting from the tectonic and seismic hazards point of view. Using refined crustal velocities based on the results of Begnaud et al (2000), Simila et al. (1998) relocated the 1926 $M > 6$ doublet to show that the first event occurred on the northern SGF followed by the second on the adjacent Monterey Bay Fault Zone. Because of the limited onshore extent, few detailed geologic studies have been conducted to evaluate the style and rate of late Quaternary deformation along this complex fault zone.

A single off-shore station is not going to allow us to answer all the scientific questions related to the tectonics and structure of the North American continental and plate boundaries that cannot be addressed with landbased stations alone. However, in the context of the Earthscope program, there is currently interest in the idea of extending the broadband coverage off-shore, in some fashion (e.g. OMD Workshop Report). This could be done in several ways, either through a temporary (1-2 years) deployment to match the efforts of the Bigfoot component of USArray, or through a longer term deployment of fewer stations. In any case, the MOBB project provides a unique opportunity to test installation requirements in the near shore, soft sediment, intermediate water depth environment as will be encountered in the future in such a larger scale program. Because broadband seismic data are accumulated over all seasons and auxiliary environmental data are also available, we can, not only characterize the background noise and usefulness of the data for seismic event analysis, but also develop and test the performance of noise reduction by removing correlated environmental signals. Furthermore, as will become apparent in the following section, because of the availability of near by island and continental sites equipped with broadband seismometers (BDSN), we can study, under different seasonal conditions, some important aspects of the generation of long-period noise in the oceans and their transmission to land. Finally, the proximity of the MARS cable puts MOBB in the first ranks of candidate sensors to be connected to shore for a real-time, two-way communication link and continuous power. The CMG-1TD Guralp sensor is one of few available and well-characterized seafloor broadband sensors and the database, archival and public access requirements will be transparently managed by the Northern California Earthquake Data Center.

Examples of Data and preliminary analysis

Figure 3 shows the location of MOBB with respect to the nearby BDSN stations. Notably, we will be discussing comparisons between recordings on the ocean floor (MOBB), in the noisy Farallon Island environment (FARB) and on the continent (SAO, YBH).

Figure 4 shows power density spectra for two different time periods, comparing background noise at MOBB and three land stations of the BDSN network. Day 143 (05/23/2002) is a "quiet" day, as assessed from the ocean wave data recorded on the NOAA buoy in Monterey Bay, whereas day 350 (12/16/2002) is a "stormy" day (spectral ocean wave density is an order of magnitude higher at around 30 sec). There are some striking differences between the noise spectra at MOBB and the land stations: one is the larger amplitude of the "microseismic peak" between 1 and 10 sec. On the quiet day (143), the microseismic band has very well defined structure, with peaks

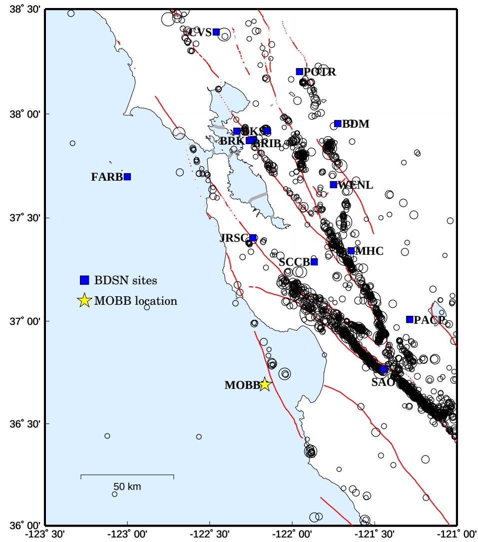

Figure 3: Location of MOBB with respect to nearby broadband stations of the Berkeley Digital Seismic Network (BDSN). FARB is located on the Farallon Islands. The main active faults are indicated in red, and the black circles indicate regional seismicity in the last 10 years. MOBB is located just west of the San Gregorio fault. Station YBH is further north, at 41.7N and is not shown.

at 2, 4 and 7 sec. The 7 sec peak is the well documented "double frequency" peak corresponding to the "single frequency" peak at $\sim$ 14 s (Longuet-Higgins, 1950), also visible at all sites, but, interestingly, not larger at MOBB. These peaks have been widely documented in the literature, as this period band is accessible on conventional short period OBS's. It is related to ocean wave interactions at the coast, near the station, or possibly in the open sea (e.g. Bernard, 1931; Haubrich and McCamy, 1969; Hedlin and Orcutt, 1989; Cessaro, 1994; Babcock et al., 1994; Friedrich et al., 1998). The shorter period peaks (2, 4 sec) could be related to a combination of local sea-state and distant storms (e.g. Bromirski and Duennebier, 2002). They are clearly distinct in frequency from those observed in the open sea (i.e. Stephen et al., 2003). The amplitude of the microseismic band is proportionally increased during the stormy day.

The most striking difference with the land stations is the noise hump between 20 and 150 sec on day 143 on the vertical component of MOBB, which widens to longer periods and increases in amplitude on day 350. On the stormy day, it is slightly perceptible at FARB, the Farallon Island site, but not on the continental sites. It is also clearly band-limited, with a well defined cut-off period beyond which the noise spectrum at MOBB resembles in amplitude and trend that of all the other stations. This "hump" in the noise is due to ocean infragravity waves, most likely generated from wave interactions in the shallow ocean (Webb et al., 1991; Webb, 1998) although some component may originate from distant locations across the ocean basin. This noise attenuates rapidly inland, because of the short wavelength of the infragravity waves, which are still faintly perceptible at island sites, as also observed in Hawaii (Stephen et al., 2003). The cut-off at short periods is generally attributed to hydrodynamic filtering, that is, because the amplitude of infragravity waves decays exponentially with depth with an e-folding depth which increases with period, only longer period waves can interact with the seafloor. The cut-off period of 20-30 sec observed here is in agreement with the location of MOBB at a water depth of 1000m. The cut-off is at longer periods

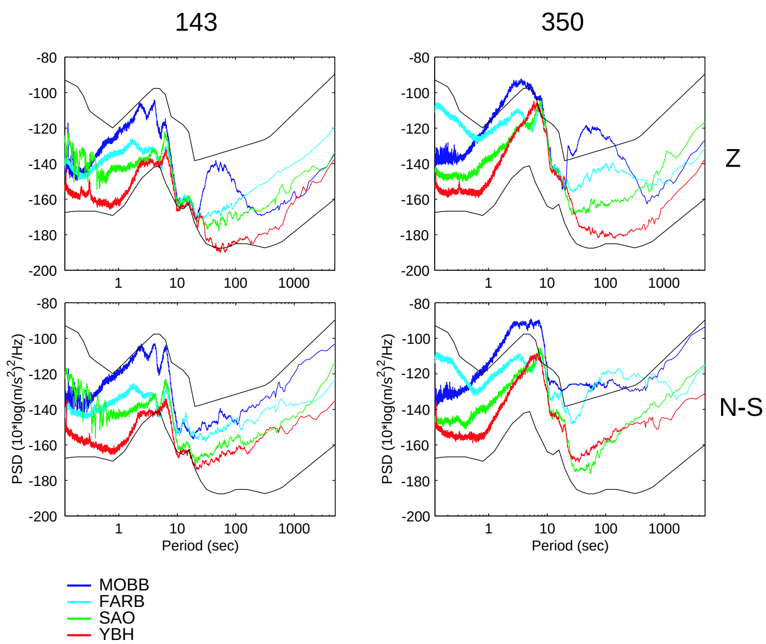

Figure 4: Comparison of noise recorded at MOBB and 2 other stations of the BDSN network, on two days in 2002 when no significant earthquake signals were recorded: a "quiet day" (143,left), and a "stormy" day (350,right), as assessed by the mean wave height recordings at a nearby NOAA buoy, located in Monterey Bay. Spectra were calculated using 4 hours of data. The USGS high- and low-noise models for land stations are shown in black (Peterson, 1993). Increased noise levels for periods between 20 and 300 sec, are observed at MOBB on both quiet and stormy days, as well as at the island station FARB on the stormy day. The noise level at MOBB between 10 and 20 sec is comparable to the land station YBH, one of the quietest stations of the BDSN. See Figure 6 for FARB and SAO locations. Station YBH is 560 km north of MOBB. (top) Vertical component; (bottom) North Component

in the deeper ocean, offering a wider "low noise notch" for high signal to noise observations of teleseismic body waves and regional surface waves. In the narrow "low noise notch" at MOBB, the level of noise is comparable to that of the best land stations. The bell shape of this noise peak is in agreement with theoretical calculations by Araki et al. (2003).

On the horizontal components (only one is shown for sake of space), the infragravity peak is absent. Rather, the high long period noise levels can be attributed to bottom currents, a significant part of which is due to complex interaction of tides with the local bathymetry, as was documented in the MOISE experiment (e.g. Romanowicz et al., 1998; Stutzmann et al., 2001). This is also illustrated in Figure 5a, which shows a spectrum of the ocean current speed at MOBB computed using a 78-day time series. The dominant effects of tides on the bottom currents are clearly visible. Figure 5b shows the corresponding distribution of current direction and velocity as a function of azimuth, showing the effect of the shape of Monterey Bay.

There are several reasons for our interest in the infragravity wave noise. First, the 10-150 sec period band is crucial for the study of long period seismic body waves and regional surface waves, therefore, it is important to find ways to reduce the effect of infragravity waves, which is also likely to be strong in this band at other relatively near shore stations. The infragravity wave signal is also present in pressure data, and in fact, the transfer function between the pressure and

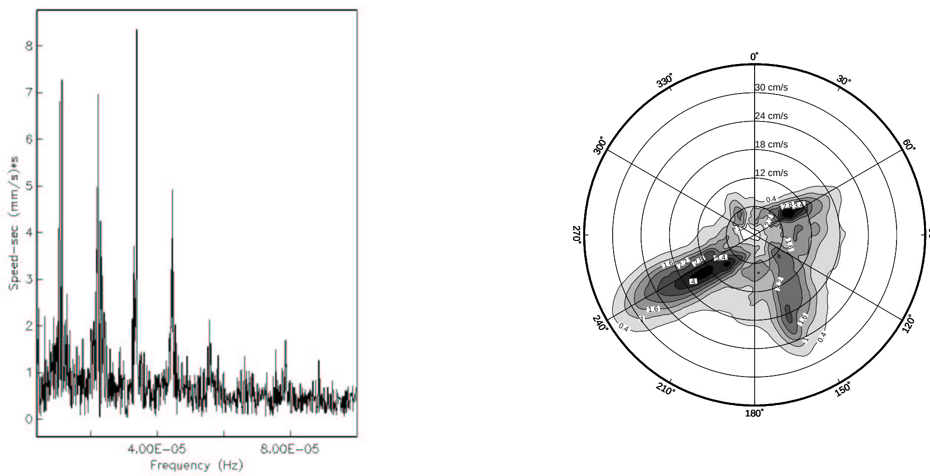

Figure 5: (a) Spectrum of current speed (units are (mm/s)/Hz) based on a 78-day period of current meter data. The four dominant group of peaks coincide precisely with the frequencies of the diurnal, semi-diurnal, 8 hour and 6 hour components of the gravitational tides. ; (b) Distribution of current velocity data as a function of azimuth for the 78-day period shown in Figure 8. The contour label units are fractions of the average density distribution of the current velocity. The two dominant maxima (centered at 60^o and 240^o, i.e. orthogonal to the continental shelf) are associated with the semi-diurnal tidal currents. The third directional peak is roughly parallel to the coastline and appears to be related to the dominant ocean circulation.

acceleration data has been used previously to infer elastic crustal structure (e.g. Yamamoto et al., 1989; Crawford et al., 1991), under the assumption of static loading. On the other hand, the correlation between pressure and vertical component seismic data can be used for deconvolution of this important component of noise, given that the sampling rate of 1 sps in our DPG is adequate for this purpose (Stutzmann et al., 2001).

In addition, the study of the time variation of the infragravity wave signal, and its correlation with weather as well as ocean surface wave height and direction data from a nearby buoy may help understand better where and how the infragravity waves are generated. The observation of the band-limited character of the infragravity related noise "hump", made possible by the very-broadband character of the CMG-1TD (low frequency corner of 360 sec), is qualitatively in agreement with theoretical predictions of loading of the seafloor by infragravity waves (e.g. Araki et al., 2003). Its change in width and height with environmental parameters is particularly interesting and warrants further investigation. It may provide more insight on the generation process of infragravity waves.

Figures 6-8 illustrate earthquake observations that have been recorded at MOBB during the two months period 04/10/2002-06/28/2002, and which were retrieved during the first datalogger exchange, on 06/29/2002. Figure 6a shows the vertical component P wave portion of the seismograms recorded at MOBB and several BDSN stations for a large deep teleseism, filtered in two different pass-bands. The comparison shows consistency between the recordings of MOBB and nearby stations. In the 0.03-03 Hz passband, signal-generated noise (ringing) is very apparent in the 3 mn long P-wave coda at MOBB. The ringing is narrow-band and disappears at frequencies lower than 0.1 Hz. Such observations should be helpful in understanding the triggering of submarine landslides in strong motion events, and may be relevant for ocean floor structures such as oil platforms and pipelines. On the other hand, this type of noise may be unavoidable in a shallow buried installation (Sutton et al., 1992). In Figure 6b, we demonstrate several ways of eliminating this signal-generated noise by post-processing. One way is by designing an ”observational” transfer-function, using data from near-by land stations that do not show the ringing (Figure 6b, panel c). Another way, is through direct modelling of the ringing effect (Figure 6b, panel d), by computing theoretical transfer functions based on simple sediment layer models (e.g. Uhrhammer et al., 2003) that can be obtained from local studies (e.g. Begnaud et al., 2000).

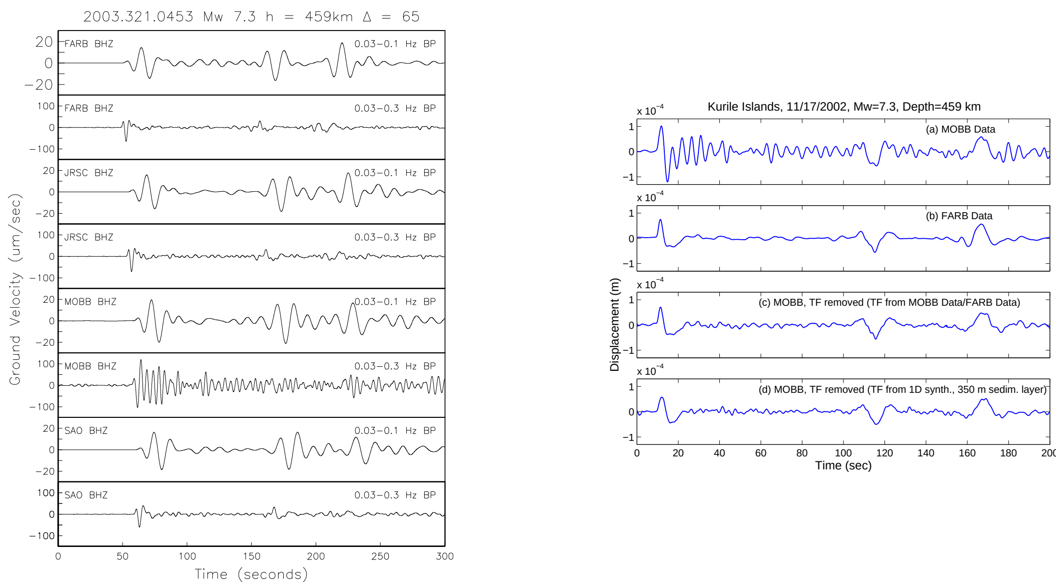

Figure 6: (a) Comparison of vertical component records at stations FARB, JRSC, MOBB and SAO for the deep Kurile Island earthquake of 11/17/2002 (Mw = 7.3; depth = 459 km; distance to MOBB = 65^o). The data are shown in two pass-bands : 0.03-0.1 Hz and 0.03-0.3 Hz to emphasize the narrow-band character of the ringing in the MOBB P wave data. Clearly visible in the lower frequency band are the P, pP and sP arrivals. (b) Raw vertical component data (P wave and depth phases) observed on the vertical component at stations MOBB (a) and FARB (b) for the 11/17/2002 deep Kurile Island earthquake. Clearly seen is the ringing due to the soft sediment layer in Monterey Bay. (c) MOBB data after removal of the transfer function constructed using FARB data. (d) MOBB data after removal of the theoretical transfer function constructed for a crustal model with a 350 m thick sedimentary layer with Vp = 0.314 km/s, Vs = 0.196 km/s, density = 1.3 g/cm^3.

Figure 7a shows the records, deconvolved to ground velocity, for a Mw 3.63 regional event which occurred on 04/23/2002 on the SAF at a distance of 53.4 km from MOBB. The very large S wave pulse on the horizontal components as well as the subsequent ringing are likely due to site response, as observed for the teleseismic event, and could be similarly removed. On the vertical component, the water reflection of the P wave is clearly seen 1.3 sec after the P wave (e.g. Ward, 1979; Blackmann et al., 1995). In spite of these strong site effects, and because of the low noise notch between 10-30 sec, these data can be used in moment tensor studies, as illustrated in Figure 7b, which shows the results of a moment tensor inversion using a time domain whole waveform methodology (Dreger and Romanowicz, 1994; Dreger, 1997). A robust solution is obtained using data from 5 stations, including MOBB. The waveform fit at MOBB is outstanding with a 92.8% variance reduction. Data from MOBB provide an additional SH lobe but, since 3 SH lobes are already sampled by other BDSN stations, this particular strike-slip mechanism is well constrained

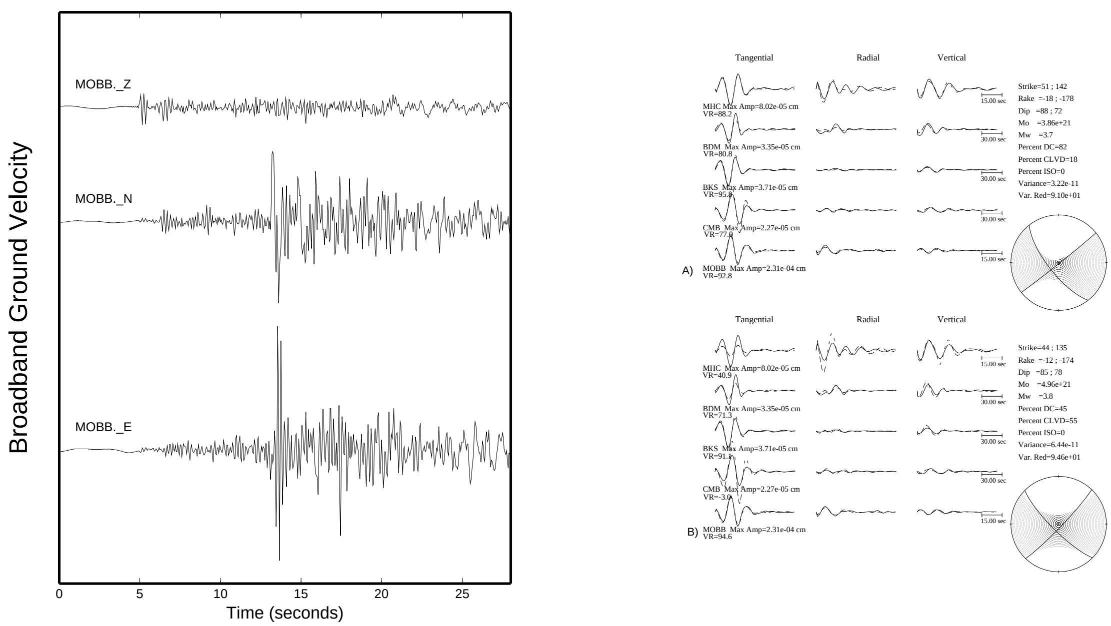

Figure 7: Left: Three component deconvolved ground velocity records at MOBB of the 04/23/2002 Mw 3.63 San Andreas fault event (lat = 36.866, lon = -121.61, depth = 9 km). Right: Results of moment tensor inversions for the M 3.63 regional event shown on left. Top: inversion using 4 stations of the BDSN and MOBB (BDM,BKS,CMB are bandpass filtered between 0.02 and 0.05 Hz; MHC and MOBB, between 0.05 and 0.10 Hz). Bottom: results of inversion using only MOBB, showing the good fits of the single station solution to the other BDSN waveform data.

in any case. However, this example serves to show that the MOBB data are well calibrated and have potential for providing valuable constraints in moment tensor studies of events of other types, such as reverse fault events in the Coast Ranges or strike slip events on faults closer to the shore or off-shore. To further demonstrate the consistency of the MOBB data, we also show the results of a single station moment tensor inversion using only MOBB, and the comparison of the corresponding synthetic predictions with the actual data at the four other BDSN stations. The single station solution results in a nearly identical focal mechanism, but a slightly larger CLVD component and scalar moment, which is not unlike other single station inversions.

Work Plan

We request funds towards the following collaborative tasks: 1) characterizing the three component background noise at MOBB at periods longer than 10 sec and developing post-processing methodologies to improve seismic data quality, 2) evaluating the improvement thus obtained for the study of regional and teleseismic events, 3) continue to operate MOBB and periodically retrieve data, as well as prepare the system for the connection to the MARS cable.

Task 1:

We plan to evaluate the long term time evolution of background noise, as the system continues to settle and stabilize. Figure 8 shows the three component "mass position" channel of the seismometer, as a function of time from April'02 to beginning of January'03. One advantage of the frequent visits to the site is that, each time, the seismometers can be recentered. The subsequent gradual settling observed on the horizontal component has an increasingly longer time constant and smaller amplitude.

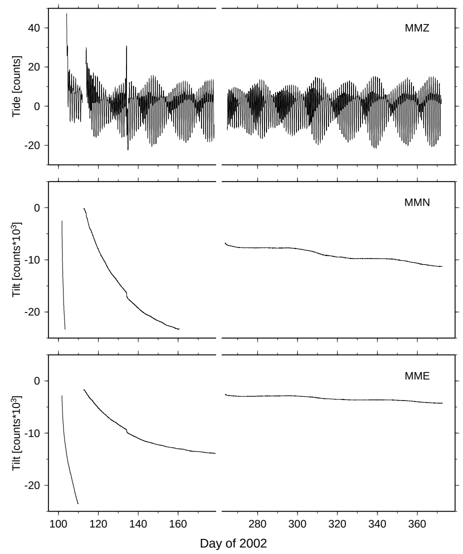

Figure 8: Mass position data for portions of the time period 04/11/2002-01/07/2003, showing the progressive settling of the seismometers. The large steps on the horizontal components (MMN, MME) are associated with: 1) installation (day 100); 2) re-centering (day 112, day 263). There is a smaller step on day 134, associated with a local Mw4.95 earthquake. The vertical component data (MMZ) have been detrended by subtracting a running 36 hour average (+/-18 hours) from each 1/2 hour duration smoothed data sample, to bring out the tide signal. Note the different scale on MMZ. Gap in data was due to datalogger problem.

At the shorter time scale, relation to tides, currents, pressure data will be analyzed systematically. In Figure 9, we compare a spectrogram of vertical component MOBB data in the period range 10 to 200 sec, over a 7 day period with the corresponding time derivative of the theoretical tide, and current speed and direction data. Current speed extrema are generally associated with extrema in the tide time derivative. Consequently, there is also periodicity in the noise level in the infragravity wave band (30-200 sec) related to tides and currents as already noted in the MOISE experiment (e.g. Romanowicz et al., 1998). Interestingly, in the period band 10-30 sec, where the noise is minimum, we detect several dispersed trains, which correspond to ocean waves travelling from large distances (e.g. Bromirski and Duennebier, 2002). These trains can be traced back to northern Pacific storms: for example, the dispersed train spanning days 340-344 corresponds to a source at a distance of $\sim$ 4500 km on day 338 (near Aleutians).

The relation of background noise to bottom pressure fluctuations is illustrated in Figure 10, where we show a preliminary comparison of DPG and vertical component seismic spectra. The two spectra track each other, especially at periods greater than 10 sec, down to fine details, in a manner that is relatively stable with time, except on the microseismic peak side of the low noise notch.

We will design time dependent deconvolution filters based on available current meter and DPG data. Finally, we will also incorporate weather data from NOAA coastal buoys off-shore central California (in particular buoy 46042 located only 50 km west of MOBB) to model the variations in the spectral characteristics in the infragravity wave band, in an attempt to verify existing theories on the generation of infragravity waves (e.g. Herbers et al., 1994, 1995).

We will also refine our preliminary models of the near-surface ground structure and ocean layer

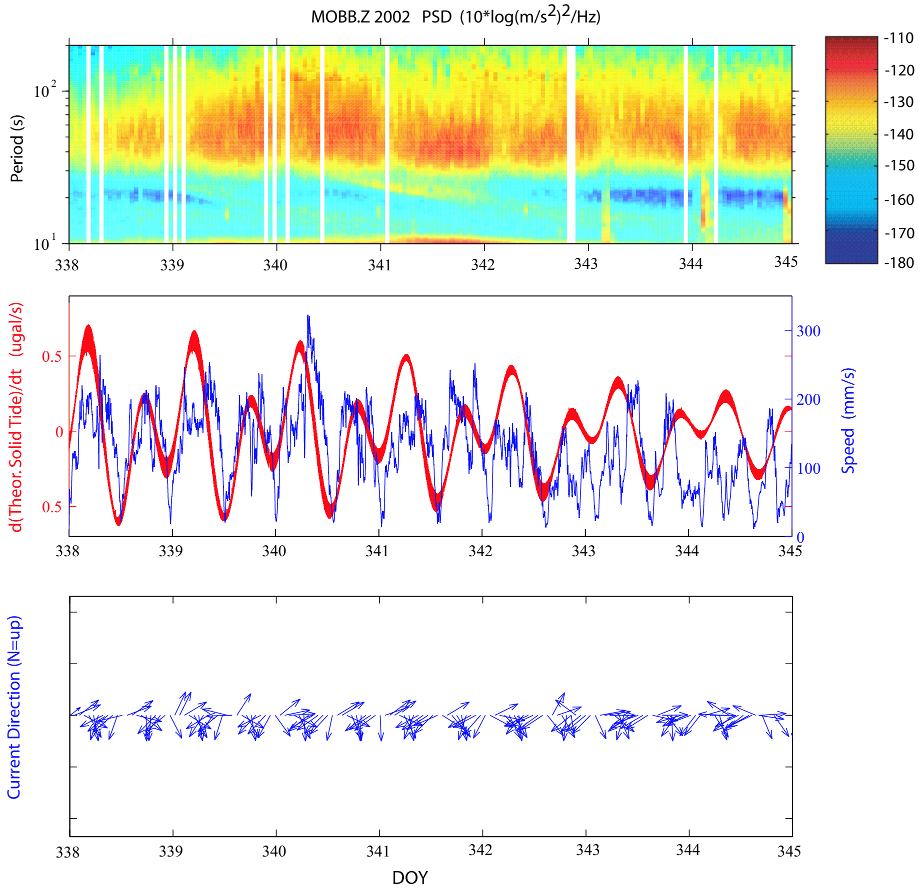

Figure 9: Top: Spectrogram showing power spectral density as a function of time for a 7 day interval at the end of 2002, on the vertical component of MOBB. White lines correspond to data loss due to a software problem in the datalogger, which has since been fixed. Middle: corresponding time derivative of the theoretical tide (red) and current speed (blue). Bottom: corresponding directions of current.

response to obtain robust procedures to correct recorded seismograms for signal generated noise due to reverbation in the soft sedimentary layers.

Task 2:

We will assess the improvement of data quality by comparing post processing earthquake detection levels to those achieved on the raw data, as compiled using catalogs of regional and teleseismic networks, and as compared to landbased stations. We will also systematically analyze constraints brough by MOBB data for the estimation of moment tensors of regional earthquakes. The data for the 12/23/03 San Simeon, CA event will be particularly interesting, as they will allow us to determine how the station behaved in relatively strong shaking (distance about 120 km).

After applying noise reduction procedures developed in Task 1, the resulting filtered records at MOBB, combined with those of other stations of the BDSN from regional earthquakes will also be used to obtain constraints on the three dimensional crustal structure, in the transition region from off-shore to continent, much as is currently being done with only on-shore data (e.g. Antolik, 1996), to help address the issue of the nature of the plate boundary at depth, i.e. the depth extent

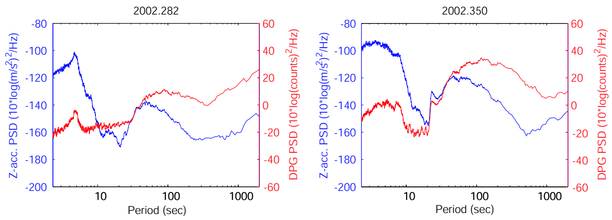

Figure 10: Top: DPG (red) and Acceleration (blue) Spectra for a quiet (left) and a stormy (right) day without earthquakes. Spectra have been computed for a 4 hour period. There are still uncertainties about the instrument response of the DPG, so that the DPG spectrum is expressed in counts rather than physical units of pressure.

of the major fault zones in the San Francisco Bay Area, the reality and significance of the mid-crustal detachement (e.g. Eaton, 1985; Brocher et al., 1995; Bürgmann, 1997), crustal thickness variations, and, more generally, delineation of major structural blocks that govern the details of regional tectonics, and the continent/ocean transition.

Task 3:

Recurring on-site visits to exchange data logger and battery packages will continue with a frequency of about 3 months until the station can be connected to the MARS cable. These have proven valuable since the beginning of the project, as problems developed and could be addressed within a relatively short time. Thus, several problems with the data logger software have been uncovered and subsequently fixed. These problems resulted in loss of all data for a period of ~ 6 months but have now led to an improved and more robust system. More recently (Sept'03), the N/S component seismometer refused to respond to recentering commands. Plans are underway to retrieve the seismometer package and repair it. During the repair period, a seismometer package "borrowed" from the University of Washington KECK project will be temporarily installed (three of these packages are being tested at UC Berkeley and MBARI in a collaboration with U of W.). This offers an opportunity to bring improvements to the installation procedures in preparation for the connection to the MARS cable (such as better control of tilt of the package with respect to the vertical, and depth of burial).

In addition to recurrent visits to the site, the MBARI effort will focus on several technical issues that are critical to the connection of the MOBB sensor and extremely important for the seafloor cabled observatory community at-large. These issues include the implementation of the fiberoptic extension cables (required for any experiment over a few hundred meters distant from the node), the physical interface to the node and packaging the timing information from the MARS network so that it appears to the Guralp sensor as a GPS time-mark. We also plan to address more fundamental issues such as software to report "health of the experiment" and utilization of the back-up battery power. Because the MOBB system is based on the low-power LP1 datalogger, the modifications made as part of this experiment could be easily adapted to a telemetered mooring for which there is no external power and only limited communication.

During the term of this project, MBARI will provide the technical requirements for the connection of the MOBB Guralp broadband sensor to the MARS cabled observatory in Monterey Bay. The results of this project will provide a sensor package that can be connected to a fiberoptic extension cable from a seafloor node providing power, two-way communications and GPS timing. The system will be capable of a future deployment on a mooring with a telemetry connection to shore. The connection of the sensor to the MARS node will require a 3 km extension cable and four ship/ROV days for installation. We intend to request the extension cable, its connector to the MARS node, and the four days of required ship time from the MARS Facility, once the specifications are defined (which they are not at the present time)

The technical requirements for a MOBB Connection to MARS are:

- Power Converter

  MOBB must convert 48V MARS voltage to 12V MOBB voltage at a power level of 5W.

  Any changes to the MOBB power system must fit within the existing MOBB pressure housings.

- Data Interface

  MOBB must provide an underwater connector conforming to the MARS standard.

  MOBB must provide any required isolation or over-voltage protection as required by MARS.

  MOBB must accommodate a copper (not fiber) Ethernet connection from MARS. However, because the distance from the MARS node exceeds 100m, a pair of copper-to-fiber media converters must be built into the MARS science extension cable.

- Software

  MOBB must send all data back to shore, assuming the existing of a network data management system such as SIAM.

  MOBB must locally generate synthesized GPS timing signals (NMEA message and 1PPS) from the MARS provided timing signals. These GPS signals are currently provided while the ROV is connected to the system and are used by the Guralp Broadband Sensor to determine its clock drift.

  MOBB must be able to report state-of-health information, such as the remaining capacity of the backup battery system and data storage.

After MOBB hook-up to the MARS cable, it is expected that visits will only be required at most once a year. Raw data as well as de-nuisanced data will be available publically and in close to real-time from the NCEDC. If the plans for a borehole broadband system nearby come to fruition (C. Paull, personal communication), the two systems will be run side by side for 6 months, after which, if the noise levels in the borehole are documented to be significantly lower, MOBB will be retired and the package available for another location.

Broader Impacts

MOBB data analysis will directly contribute to the training of a graduate student, as well as indirectly to the training of 8-12 graduate and undergraduate students in geophysics/seismology at UC Berkeley, through the sharing of results during weekly discussion meetings.

The experience gained through MOBB may help design better future near-off-shore ocean floor broadband seismic station deployments to complement the land based networks in the western US, either permanently, or in the intermediate time scale (1-2 years), for example in complement to such programs as the USArray of Earthscope. Already, the MOBB instrument preparation and deployment experience acquired over the last 2 years has benefitted similar experiments planned in the context of preparation for the Neptune program (collaboration on testing and conditioning of broadband systems for the Univ. of Washington KECK project).