Acquiring Real Time Data from the Broadband Ocean Bottom Seismic Observatory at Monterey Bay (MOBB)

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INTRODUCTION

Two-thirds of the Earth's surface is covered by oceans, which represents a considerable challenge to investigations of global-scale dynamic processes in the Earth's interior and of tectonic processes at ocean-continent boundaries. 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. In northern California, for example, the most active seismic zone is near the Mendocino triple junction and is mostly offshore, as are a number of hazardous faults such as the San Gregorio and Hosgri faults and part of the San Andreas fault. Much effort has been expended to deploy networks of seismic stations in the western United States, most recently broadband stations, with the simultaneous 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 offshore 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 skewed 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 edge of the continent.

The need for long-term ocean-floor seismic observatories has been widely recognized, and several national and international efforts have been striving for more than two decades to resolve the technological and logistical issues associated with such deployments and establish such observatories (*e.g.*, Le Pichon *et al.* 1987; Purdy and Dziewonski 1988; Purdy 1995; Forsyth *et al.* 1995; Montagner and Lancelot 1995; Suyehiro *et al.* 2002, 2006).

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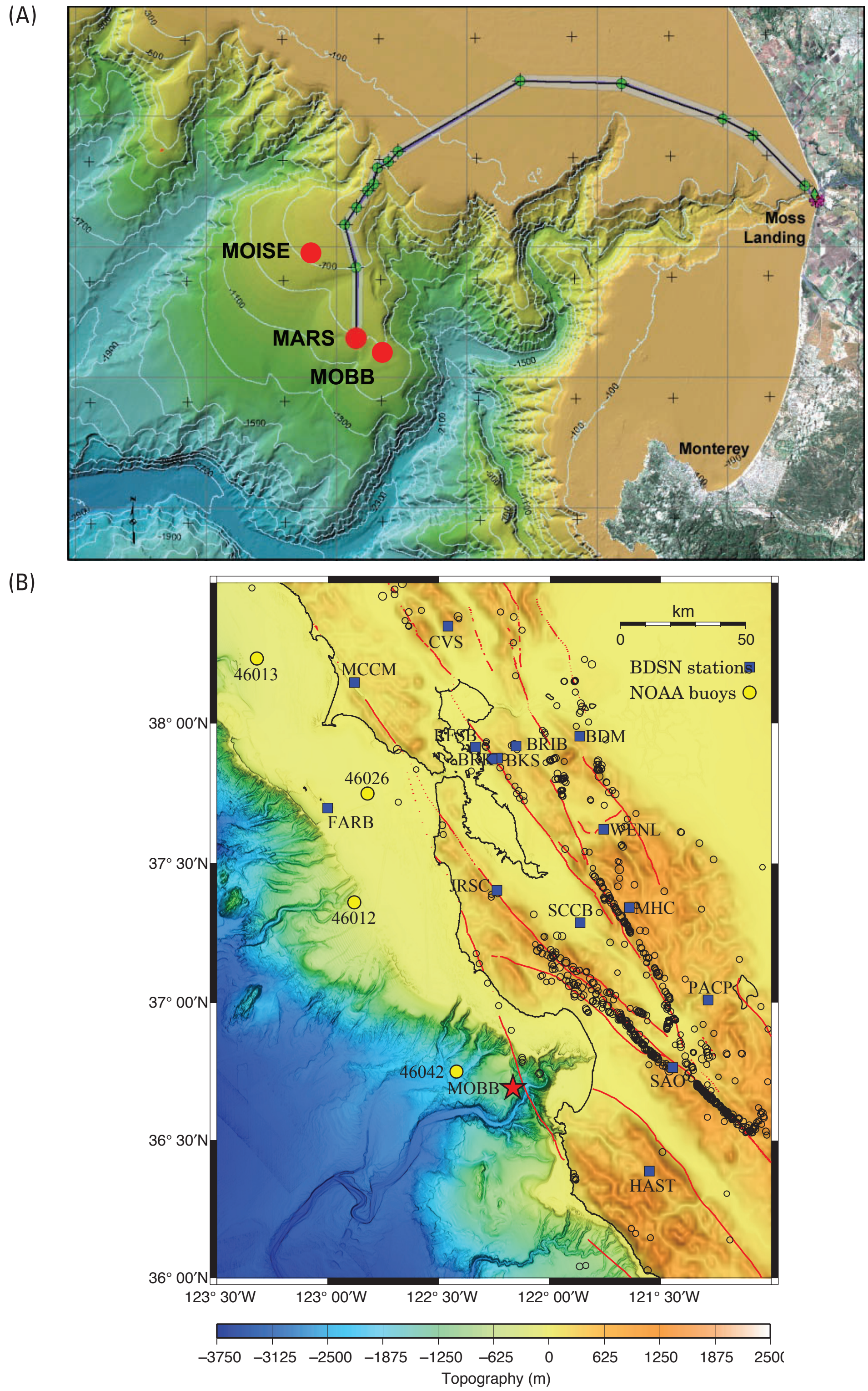
In April 2002 we deployed a broadband seismometer station 40 km off the coast of Monterey Bay, at a water depth of 1,000 m (Romanowicz *et al.* 2003, 2006) through a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and the Berkeley Seismological Laboratory (BSL). The Monterey ocean bottom broadband station (MOBB) has been operating continuously since then, with data loggers and battery packages exchanged approximately every three months using the MBARI remotely operated vehicle (ROV) *Ventana*. At the time this paper went to press, preparations were underway to connect MOBB to the Monterey Accelerated Research System (MARS) fiber-optic cable (`http://www.mbari.org/mars`), scheduled for the end of February 2009.

The MOBB is located west of the San Gregorio fault, one of the major faults of the SAF system, in a region characterized by diverse topography. A wide, gently sloping continental shelf is found to the north, the 1,500-m deep Monterey Canyon is just south of the MOBB, and a narrow shelf is present in the Monterey Bay and further to the south (Figure 1).

The MOBB includes a three-component broadband Guralp CMG-1T seismometer that is sensitive to ground velocity over a wide frequency range, from 50 Hz to 2.8 mHz (360 s). The seismometer is mounted in a titanium pressure vessel, which is placed inside a 53-cm-diameter by 61-cm-deep cylindrical PVC caisson, buried in the ocean floor. Data have been collected continuously onsite at a sampling rate of 20 samples/s for more than six years. Details of the deployment and the onsite data collection system are described in Romanowicz *et al.* (2003, 2006). At the same site, a differential pressure gauge (DPG) (Cox *et al.* 1984) and a current meter measure local pressure and ocean-bottom current speed and direction. These auxiliary sensors, sampled continuously at a rate of 1 sample/s, are an essential part of all long-term broadband ocean-bottom seismometer deployments, as they help reduce the considerable long-period noise due to infragravity ocean waves and ocean currents through post-processing (*e.g.*, Dolenc *et al.* 2007).

doi: 10.1785/gssrl.80.2.197



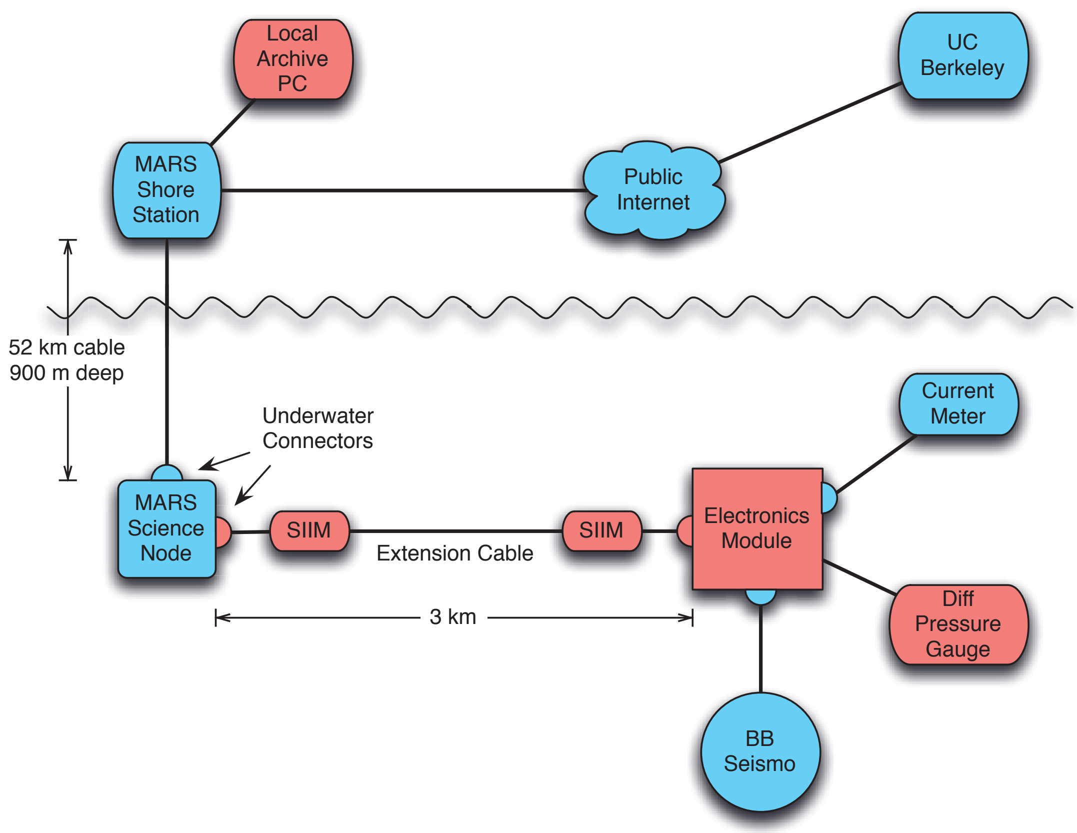
▲ **Figure 1.** (A) Location of the MOBB and MOISE stations in Monterey Bay, CA, against seafloor and land topography. The 1997 MOISE experiment, in which a similar system was deployed in a similar manner for a period of three months, was a cooperative program sponsored by MBARI, U.C. Berkeley, and the INSU, Paris (Stakes *et al.* 1998; Romanowicz *et al.* 1998). 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 location of the MARS cable is also indicated, with its termination close to the present MOBB site. (B) Location of the MOBB (red) and the BDSN seismic stations (blue) shown against the seafloor and land topography. Background seismicity (ANSS catalog, 1968–2006, **M** 3.5+) is shown in black. Locations of the NOAA buoys closest to the MOBB are shown in yellow. Fault lines from the California Geological Survey's database are shown in red.

INTERFACING MOBB TO THE NEWLY DEPLOYED MARS CABLE IN MONTEREY BAY

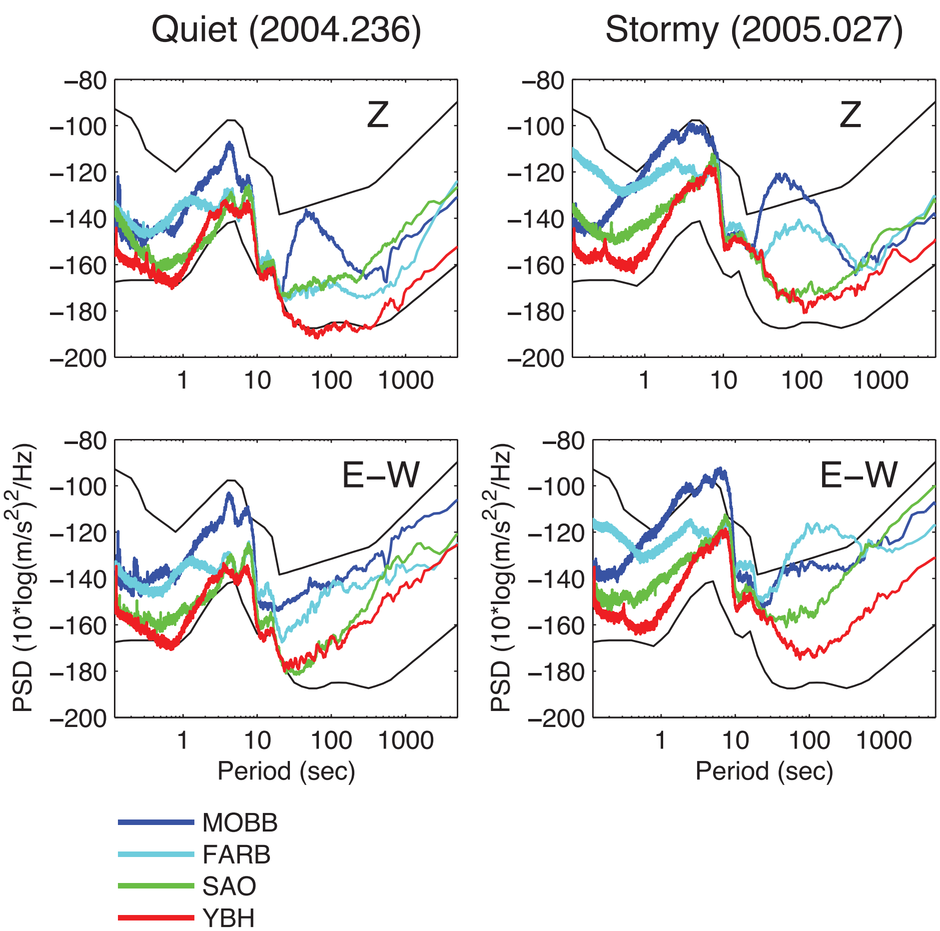
MOBB is fortunate to be located only 3 km away from the MARS science node, and is one of the first instruments scheduled to be connected to the cable, eliminating the need for periodic exchange of the battery and data package using ROV and ship, as well as allowing us to acquire seismic data from the seafloor in real time.

The MARS observatory (http://www.mbari.org/mars/) consists of a 52-km electro-optical cable that extends from a shore facility in Moss Landing out to a seafloor node in Monterey Bay (Figure 1). The node installation was completed in November 2008, and it now can provide power and data to as many as eight science experiments through underwater electrical connectors. MOBB is located ~ 3 km from the node and will be connected to it in February 2009 through an extension cable installed by the ROV *Ventana*, with the help of a cable-laying toolsled. The data interface at the MARS node is 10/100 Mbit/s ethernet, which can directly support cables of no more than 100 m in length. To send data over the required 3-km distance, the signals pass through a science instrument interface module (SIIM) at each end of the extension cable (Figure 2). The SIIMs convert the MARS ethernet signals to digital subscriber line (DSL) signals, which are converted back to ethernet signals close to the MOBB system. Power from the MARS node is sent over the extension cable at 375 VDC and then converted to 28 VDC in the distal SIIM for use by the MOBB system.

The electronics module in the MOBB system has been refurbished to support the connection to the MARS observatory. The low-power autonomous data logger has been replaced with a PC/104 computer stack running embedded Linux. This new computer runs an object ring buffer (ORB), whose function is to collect data from the various MOBB sensors and forward it to another ORB running on a computer at the MARS shore station. There, the data can be archived and then forwarded to a third ORB running at the U.C. Berkeley Seismological Laboratory. The Linux system will acquire data (via RS232) from the Guralp digitizer included in the seismometer package, data (via ethernet) from a Q330 Quanterra 24-bit A/D converter that digitizes data from the DPG, and will poll and receive data (via RS232) from the current meter. A copy of all data will be stored on a flash disk as a backup to prevent loss of data during any telemetry outage. The data will be transmitted continuously and in real time over the MARS cable to the Berkeley Seismological Laboratory, where they will be integrated in the northern California earthquake monitoring system operated jointly by the Berkeley Seismological



▲ **Figure 2.** Components of the cabled observatory: the MOBB system integrated into the MARS network. MARS-provided components and components of the current MOBB installation are shown in blue. Components shown in red are those installed or replaced as part of our current NSF-funded upgrade. When the data arrive at UC Berkeley, they will be incorporated in the joint UCB/USGS real-time earthquake notification system and made publicly accessible online at the NCEDC.



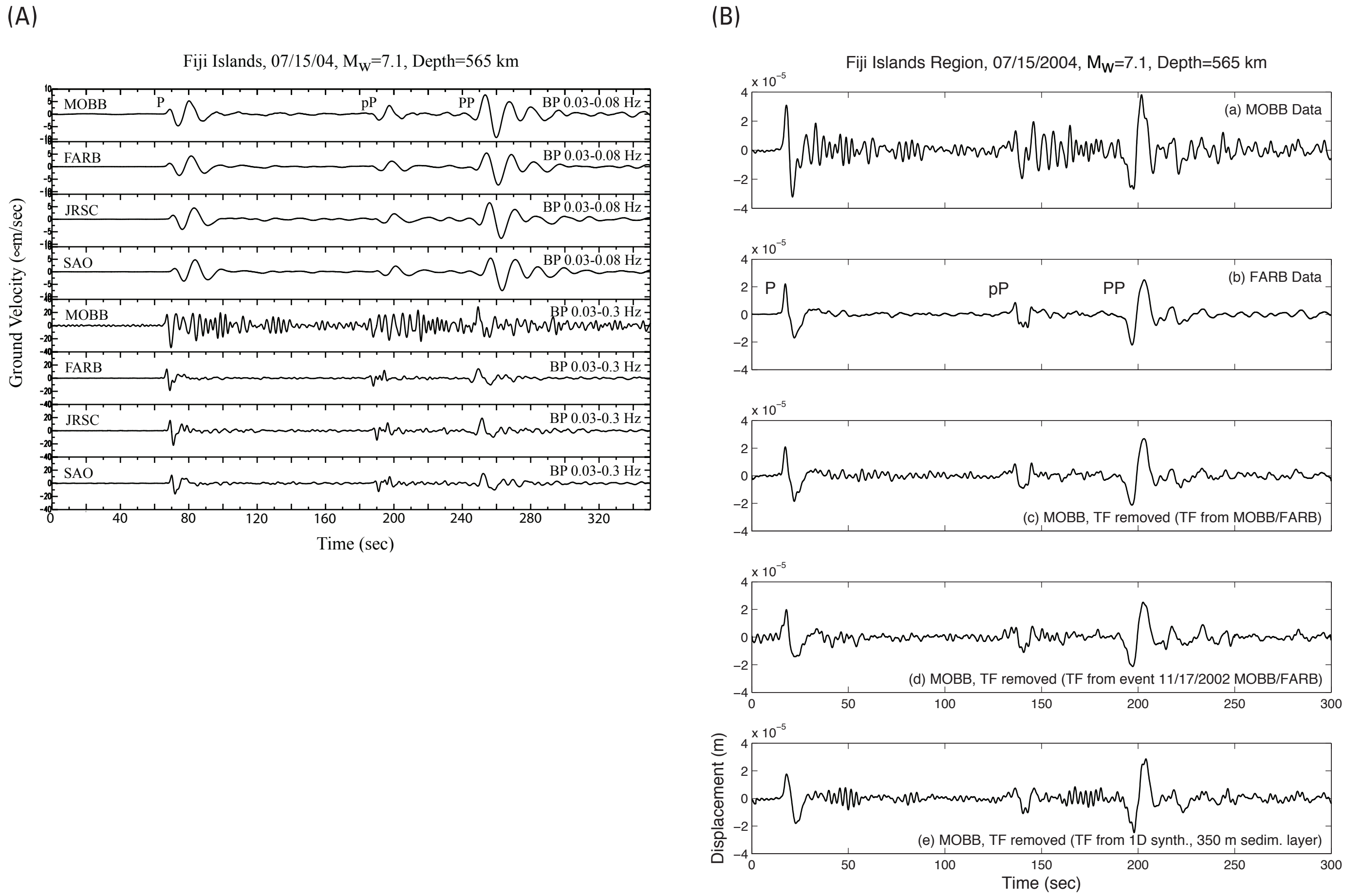
▲ **Figure 3.** Comparison of vertical component (top) and E/W component (bottom) noise recorded at MOBB and three other stations of the BDSN network on two days in 2004 and 2005 when no significant earthquake signals were recorded: a "quiet day" (left), and a "stormy" day (right), as assessed by the mean wave-height recordings at a nearby NOAA buoy in Monterey Bay (Figure 1B). Spectra were calculated using four hours of data. The USGS high- and low-noise models for land stations are shown in black (Peterson 1993). Increased noise levels for periods 20 to 300 sec are observed at MOBB on both quiet and stormy days, as well as at the island station FARB (Farallon Islands) 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. Note how the height and also the width of the infragravity noise band increases on the vertical component on stormy days.

Laboratory and the U.S. Geological Survey at Menlo Park. The data from all northern California broadband and short-period seismic stations are available from the Northern California Earthquake Data Center (NCEDC; http://www.ncedc.org/ncedc).

The new system uses off-the-shelf hardware and open-source software and will serve as a versatile prototype for data acquisition in real time from future instruments, both analog and digital, connected to seafloor cabled observatories.

NOISE AND DATA FROM THE MOBB OBSERVATORY

As is also the case on land, but exacerbated by the dynamic ocean environment, two main sources of noise affect data from broadband seismometers installed on the ocean floor: environmental noise and signal-generated noise due to local site effects. Figure 3 shows a comparison of noise spectra on the vertical and east-west components at MOBB and several land stations of the Berkeley Digital Seismic Network (BDSN; Romanowicz *et al.* 1994), on a quiet summer day and on a stormy winter day. Noise levels in the microseismic band (1–15 s) and infragravity band (25–200 s at MOBB) change considerably with the weather. In particular, the infragravity peak, visible primarily on the vertical component, becomes stronger and wider in frequency during stormy days (*e.g.*, Dolenc *et al.* 2005). MOBB provides valuable data to help understand the generation of infragravity waves and their relation to the Earth's low-frequency "hum" (*e.g.*. Rhie and Romanowicz 2006; Webb 2008). Burial of the seismometers under the ocean floor is essential to minimize this noise source. On the other hand, signal-generated noise can be particularly severe for shallow buried broadband seismometers, as illustrated in Figure 4, which shows noise due to reverberations in the sediments under the station, following the *P* and



▲ **Figure 4.** (A) Comparison of the vertical component records at stations MOBB, FARB, JRSC, and SAO (Figure 1B) for the 565-km-deep *Mw* 7.1 Fiji Islands earthquake of 07/15/2004. The data are shown in two passbands, 0.03–0.08 Hz and 0.3–0.3 Hz, to emphasize the narrow-band character of the signal-generated noise in the MOBB *P*-wave data. Clearly identifiable in the lower frequency band are the *P*, *pP*, and *PP* arrivals. (B) Two examples of deconvolution of the signal-generated noise at MOBB for the Fiji Islands event. (a) Original MOBB data; (b) Original FARB data; (c) MOBB data after removing empirical transfer function constructed using MOBB and FARB data; (d) Same as (c) except that the empirical transfer function obtained from the *Mw* 7.3 Kurile Islands event of 11/17/2002 was used; (e) MOBB data after removing a synthetic transfer function obtained by 1-D modeling of the shallow structure with a 350-m sedimentary layer with vp = 0.324 km/s, vs = 0.196 km/s and ρ = 1.3 g/cm^3. The synthetic transfer function was computed using a propagator matrix approach (Kennett and Kerry 1979) applied to a 1-D crustal model for the region (Begnaud *et al.* 2000) augmented by a stack of slow sedimentary layers of 1-km thickness and elastic parameters as estimated from a USGS velocity model (Jachens *et al.* 1997) constructed to represent the San Francisco Bay shallow sediments. The sedimentary structure was then perturbed to obtain an optimal result.

pP waves. This noise is unavoidable short of installing the seismometer in a deep borehole (*e.g.*. Collins *et al.* 2001; Suyehiro *et al.* 2002), but much of it can be removed by post-processing, using several possible approaches (Figure 4).

The data acquired in real time will help constrain moment tensors of earthquakes occurring on near-shore and offshore faults and for which onshore stations provide poor azimuthal coverage. Single-station reliable moment tensors can be obtained using MOBB data for nearby **M** > 3.5 events (*e.g.*, Romanowicz *et al.* 2006). Importantly, the real-time data acquisition demonstrated here can be ported to other settings, such as the cabled observatory in the Pacific Northwest (*e.g.*, http://www.ooi.washington.edu) or other cabled observatories that may be deployed offshore California or in other parts of the world.

ACKNOWLEDGMENTS

We acknowledge support for this project from the Packard Foundation (to MBARI) and the National Science Foundation, under grants OCE-9911392 and 0648302. B. Romanowicz thanks Peggy Hellweg for making this report happen. This is BSL contribution 09-02.

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