EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 83 NUMBER 29
16 JULY 2002
PAGES 309–320

Ocean Bottom Seismometers Deployed in Tyrrhenian Sea

PAGES 309, 314–315

The Institute for Geophysics (IfG) at Hamburg University and the Research Center for Marine Geoscience (GEOMAR) of Kiel University have developed new, wideband ocean bottom seismic stations (OBS) for long-term, deep-sea deployments of up to 1 year. A first long-term pilot experiment of these stations was conducted in the Tyrrhenian Sea north of Sicily, in cooperation with the first long-term, deep-sea test of the European Ocean Bottom Observatory GEOSTAR [*Beranzoli et al.*, 2000] by Istituto Nazionale di Geofisica e Vulcanologia (INGV). The seismic data retrieved prove that the new OBSs are useful for seismological studies. A large number of tele-seismic earthquakes have been recorded in good quality; waves originating from such events pass the mantle and crust below the network, and thus provide important constraints on their structure.

The data also exhibit local, tremor-like noise bursts at a station near Stromboli volcano. The origin of these bursts is unknown, but they may be related to volcanic or hydrothermal activity.

Ocean Bottom Seismology

Geophysicists recognize that long-term deployments of seismic broadband ocean bottom stations (OBS) are needed to study the deeper crust and mantle structure beneath continental margins and within the oceans. Deployment periods of more than 1 year are needed to detect a sufficient number of teleseismic earthquakes with good signal-to-noise ratio, as is needed for different seismological analysis methods, such as regional tomography, receiver function studies, and shear-wave splitting. The need for broadband stations in the oceans has also been pointed out for a long time by seismologists studying the structure of the whole Earth, to fill the large gaps of available seismic data in the oceans. In oceanic regions with moderate seismicity, long-term deployments are also needed to collect a representative pattern of the local seismicity. In spite of this need, long-term ocean bottom deployments are still the exception rather than the rule, in large part because of the extremely limited number of available OBSs with the required capabilities.

The IfG and GEOMAR both recently developed two types of wideband, free-fall instruments that can autonomously collect data on four channels with 50-Hz sampling rate for 1 year down to 6000-m water depth. The main difficulty of a free-fall station is that users do not have full control over how and where the station is landing. In particular, the coupling of the sensor remains unknown until the instrument is recovered. The big advantage is, however, that the instruments are easy to handle and do not require specialized ships or deployment tools. The use of free-fall instruments is already well-established for short-term and

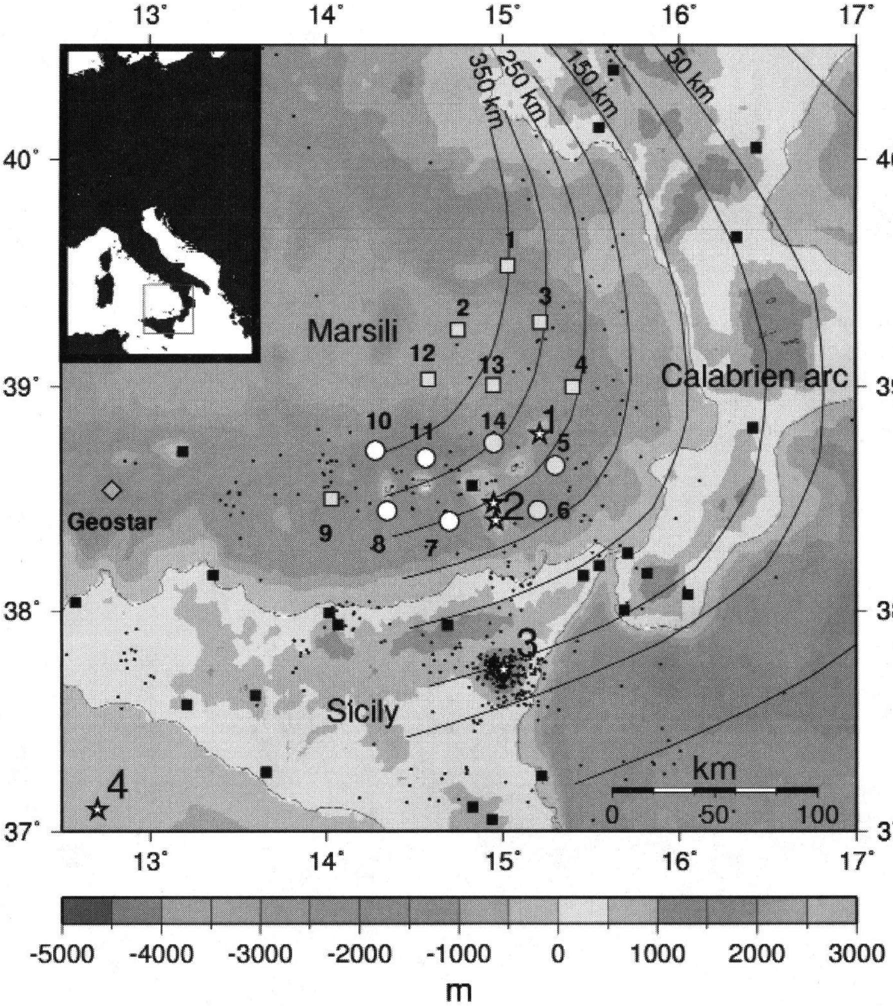

Fig. 1. Positions of OBS systems deployed during the experiment are shown. Systems 7, 8, 10, and 11 are the Hamburg type and others are GEOMAR type; white squares indicate pure hydrophones and white circles 4-channel OBS. The GEOSTAR station is indicated by a small rhombus, and land stations operated by INGV appear as black squares. Large bold numbers declare volcanic centers active during Holocene (1 = Stromboli, 2 = Vulcano and Lipari, 3 = Etna, 4 = Ferdinandea, Sicily Channel); Marsili is a submarine volcano showing no recent activity. The subducting Ionian plate is indicated by isolines, and black dots indicate earthquakes localized by the INGV network from 1996 through 2000. Original color image appears at the back of this volume.

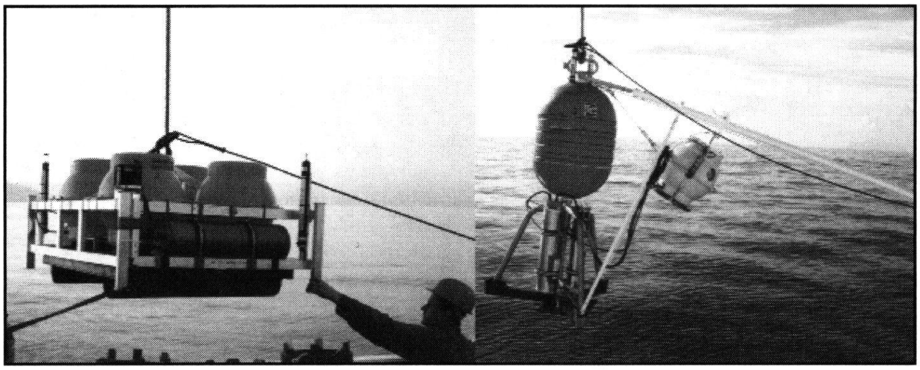

Fig. 2. OBS Hamburg-type system (left) and GEOMAR-type system (right) are shown during deployment in the Tyrrhenian Sea. The station components are described in the text. Original color image appears at the back of this volume.

"high-frequency" local earthquake studies and wide-angle active seismic experiments on the ocean floor. When wideband data are needed, however, the functionality of free-fall stations has been questioned. When landing on soft sediments, weak coupling to the ground and undesired tilt signals may occur at low frequencies. These "noise-signals" can only be reduced when the stations have a safe "standing" on the sediment, and if the differential motion-induced tilt is minimized.

The first long-term pilot experiment for the new free-fall stations was the Tyrrhenian Deep Sea Experiment, funded by the Deutsche Forschungsgemeinschaft (DFG) in cooperation with GEOSTAR, a European Union project managed by INGV. From late November 2000 until mid-May 2001, 14 ocean bottom instruments were deployed in water depths of 1500 to 3500 m north of Sicily (Figure 1). These stations continuously recorded at a 50-Hz sampling rate and collected a large number of local, deep-focus, and tele-seismic earthquake data. A continuous record of oceanic noise and oceanic microseisms has also been collected. We recovered, unexpectedly, centers of local, tremor-like noise bursts in the Tyrrhenian Sea of unknown origin.

The OBS Systems

The Hamburg and GEOMAR OBSs are modular stations that have several components in common. The data-logger (SEND MLS) supports four data channels and sampling rates of up to 200 samples per second (sps) and a dynamic range of 21-16 bit depending on sample rate. Twelve PCMCIA card slots are available with a maximum 24-Gbyte capacity at present. When using 144 alkaline cells, the possible recording duration is about 1 year. The exact power consumption depends on the sampling rate of 250 mW @ 50 sps. The time drift does not exceed 0.05 ppm. An independent acoustic releaser/transponder is used for range measurements to locate the instrument and for a controlled release of the stations from the anchor. Pressure tubes to store the electronics and batteries have identical dimensions for both station types. Recovery aids are radio beacon and flash light.

The Hamburg OBS

Since 1979, free-fall OBSs have been developed at the IfG, mainly for use in seismic refraction experiments [*Herber*, 1979]. In 2000, the IfG decided to build a new broadband, free-fall OBS for long-term deployments (Figure 2, left). The station has a flat profile for low current resistance and an optimized coupling that uses a specially-designed anchor ballast. The three-component sensor, which provides flat response in the range of 0.025-32 Hz, is passively gimbaled within one of the four flotation glass spheres that is closely fixed to the aluminum frame and anchor. The hydrophone, which has a pre-amplifier, covers a frequency range of 0.5–50 Hz. The maximal operation depth of the system is 6000 m. Two horizontal cylinders provide space for the data logger and the batteries and additional equipment when needed.

The GEOMAR OBS

The GEOMAR broadband OBS (Figure 2, right) was constructed using elements of an earlier OBS [*Flueh and Bialas*, 1996] intended for controlled-source seismology. A new feature is that the sensor, which is mounted within a 17-inch glass sphere, will be deployed 3m aside the instrument to reduce current-induced noise from the instrument carrier. When deployed, the sensor is mounted on a 3-m-long sledge that is used to pull it until it falls on the ground. The sensor used in the experiment was produced by Spahr Webb at Scripps Institute of Oceanography at the University of California, San Diego. It consists of a 1-Hz sensor with electronic feedback and should be operational in the range of 0.02–100 Hz. The sensor is fully gimbaled and clamped, and gimbaling can be made at pre-set intervals during recording. The added differential pressure gauge developed by Cox, Deaton, and Webb is responsive to acoustic signals in the range of 0.003–30 Hz.

Scientific Questions in the Tyrrhenian Sea

The opening of the Tyrrhenian basin and the subduction of the Ionian slab beneath the Calabrian Arc lie in the European-African collision zone. The Ionian slab has a lateral extent of about 200 km and is the narrowest active subduction worldwide. Deep seismicity in the Benioff zone is moderate. Therefore, the exact geometry of the deep slab is still controversial, as is its state of stress. For instance, a slab flattening or detachment has been postulated at about 400 km [*Cimini*, 1999] or below 600-km depth [*Lucente et al.*, 1999].

The Ionian slab is sometimes classified as a dying subduction zone with a possible beginning of slab break-off. Tomographic images of the mantle velocity structure and the current uplift of the Calabrian Arc following an uplift of the Southern Central Appennines have been interpreted to result from a southward-propagating, sub-horizontal tear-crack cutting the subducting slab [*Wortel and Spakman*, 2000]. It has also been postulated that the Adriatic slab, which is subducting beneath the Appennines, and the Ionian slab were once connected and may today be separated beneath the portion of the Southern Central Appennines where there is no deep seismicity. Further tomographic studies using data from either deep or teleseismic events are necessary to solve this controversy.

The Tyrrhenian Sea is also exceptional in terms of volcanism. This region has the highest density of active volcanoes in Europe; the most well-known ones are Stromboli and Etna. However, although they are near to each other, they seem to have different origins. While Stromboli is viewed as a typical subduction-related volcano, Etna is erupting magmatic products similar to those observed at mid-oceanic ridges. Other volcanoes are present in the Tyrrhenian Sea and near Sicily, for example, Marsili, Vulcano, Lipari, Ferdinandea in the Sicily Channel, and Pantelleria (Figure 1). The number of submarine volcanic or hydrothermal centers active in this region is still poorly known and controversial.

Our pilot experiment was planned to record the submarine seismic and volcanic activity, and to study the seismicity of the Ionian slab and the deep Earth-structure of this region.

First Results

Most of the "onshore seismologists" feel that analyzing ocean bottom seismic data is a challenge, because signals look so different, and apparently nothing from previous experience with data can be directly transferred to the sea. OBS signals have a complex coda following seismic phase-arrivals as a result of the multiple reflected waves in the oceanic layer. The soft sediments covering the oceanic basement can produce strong, shear-coupled resonating waves and are responsible for a remarkable apparent time delay of first motions on horizontal components in the range of 1 s.

A large collection of "water-noise-signals" can disturb the seismic signals of interest, ranging from oceanic gravity waves to high-frequency noise produced by ship lines, submarines, or whales [*Webb*, 1998]. We have not yet been able to identify all of the different types of signals or noise recorded during the half-year deployment.

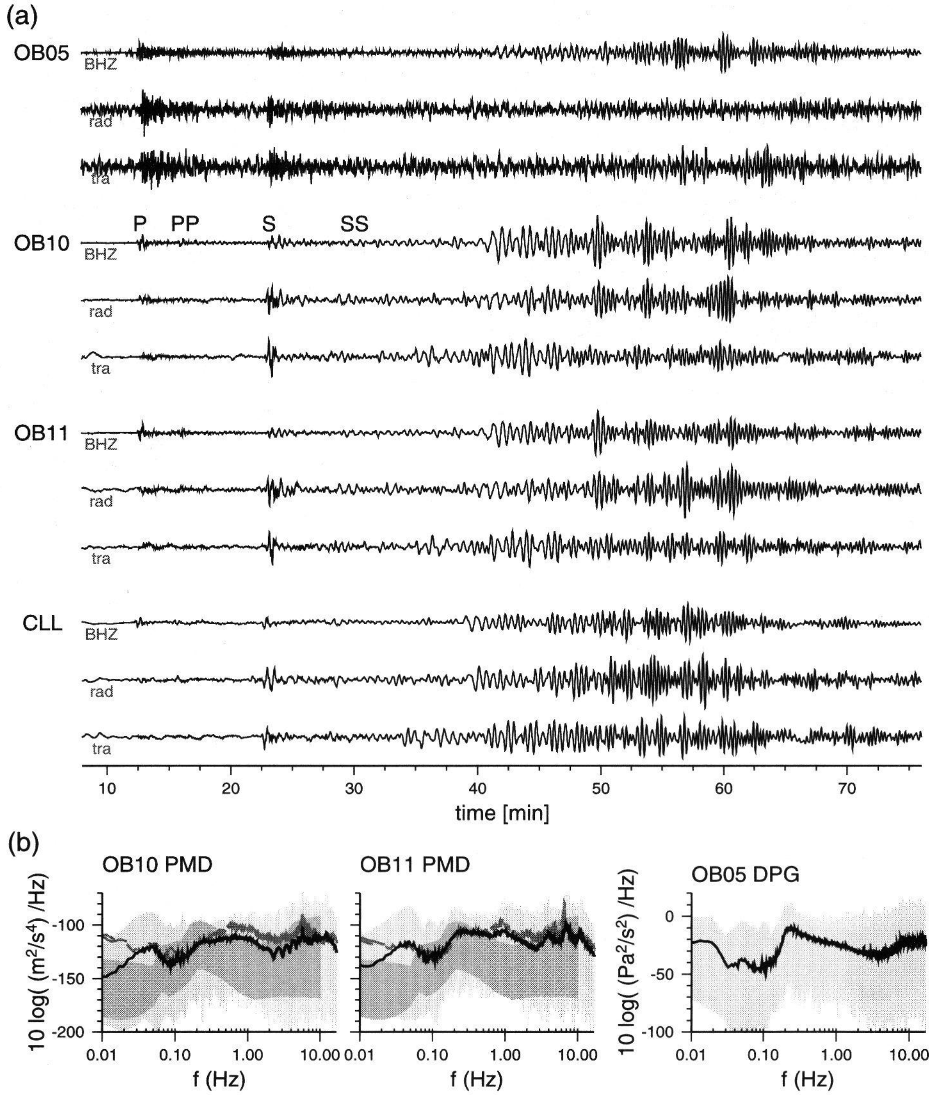

*Fig. 3. (a) This example of three-component seismograms was generated during a M=6.7 earthquake at 84° epicentral distance on Kodiak Island, 10 January 2001. Horizontal components have been rotated to great circle arcs, where the OBS orientations have been estimated from ensembles of tele-seismic Love and Rayleigh waves. Traces have been low-passed filtered. The signal-to-noise ratio is, even on the horizontal components, comparable to the seismograms from the nearby MEDNET station CII. This demonstrates that, at least at frequencies below the oceanic microseismic peak (0.2 Hz), the free-fall OBS will be useful for seismological studies; (b) Power spectral densities are given in dB for the PMD sensor on OB10 and OB11, and for the DPG sensor on OB05. The averages (continuous lines are vertical, dashed lines horizontal components) have been estimated for 1-hr records stacked over the whole measuring period from December to May. The light gray region gives bounds of maximal and minimal noise. The dark gray region indicates bounds of seismic noise observed on land stations [*Peterson, *1993].*

However, a major seismological point of interest is the study of waves from far-distant earthquakes, known as tele-seismic events, which include information on the deep structure of the Earth beneath the station. In the past, examples of free-fall OBS recordings have demonstrated a relatively poor quality of tele-seismic phases compared to those observed at nearby land or even island stations. Figure 3a shows OBS recordings of phases from an M 6.7 Aleutian earthquake at 84° epicentral distance. The body- and surface-wave amplitudes are well above the background noise.

Data from the nearby MEDNET land station CII, which lies about 270 km from the OBS net, have a similar signal-to-noise ratio. Similar observations have been made for other tele-seismic events. Hence, the first deployment of the new broadband OBS systems has demonstrated their usefulness for tele-seismic seismological studies.

Figure 3b compares the average power spectral density with the low and high noise model of land stations. One-hour time traces from the whole measuring period from December 2000 to May 2001 have been used for averaging; earthquake signals and other events have not been removed. The dark gray shaded regions in the spectra show the bounds of seismic noise observed at land stations [*Peterson*, 1993]. The seismic noise on the ocean floor is frequency-dependent. Between 0.1 and 1 Hz, the noise is induced by regional or "tele-seismic" oceanic gravity waves (microseisms). The microseismic "peak" at about 0.22 Hz is broader on the PMD sensor than on the pressure sensor. In general, it is shifted to higher frequencies compared to typical land station recordings, which seem to indicate a closer distance of the generation areas. The level in the so-called "noise-notch" between roughly 0.01 and 0.05 is thought to be controlled largely by currents and turbulence in the seafloor boundary layer. The spectral peak, centered at about 0.048 Hz on the vertical channel, is probably coming from the sea floor deformation under pressure that is forced by linear gravity waves. The compliance signal can be used to study the shear modulus or shear velocity structure of sediments and crust [*Crawford et al.*, 1999]. The compliance peak is not seen on the horizontal components, since the effect is smaller there and the horizontal background noise is greater. Above roughly 0.4 Hz, the power spectral density is dominated by signals generated by shear-wave resonances in the uppermost sedimentary layer of the ocean floor. The shear-wave resonances are larger on the horizontal components. Resonance peaks in this frequency band can be used to estimate the thickness and shear-wave velocity of this layer [*Godin and Chapman*, 1999].

Figure 4 shows an example of tremor-like noise bursts at OB05. This station, which is the closest to the Stromboli volcano, showed pronounced and continuous seismic signals of this type during repeated noise bursts. Additionally, a large number of small and very local earthquake events at OB05 provides evidence of seismic activity near this station. It is natural to wonder whether this unusual and enhanced local activity is related to the volcano. However, the seismic recordings from a short-period land station 100 m from Stromboli crater at an altitude of about 800 m, which is run by the University of Udine, did not show unusual volcanic or seismic activity during the same period. On the other hand, the ground motion at this station is usually dominated by gas explosion signals from the continuous Strombolian crater activity. Other OBs used in the experiment are farther away from Stromboli volcano and OB05, and have not recorded comparable noise bursts, including stations of the same type.

The noise bursts at OB05 resemble signals that have been observed at volcanoes during periods of activity. At least three different types of activity are observed: continuous background noise overlaid by shock-like events; tremor noise with approximately constant intensity and sudden changes in energy and time windows of vanishing signals; and nearly continuous tremor bursts lasting for more than 24 hours (Figure 4). All these signals have pronounced spectral peaks; the tremor from 25 and 26 January had a fundamental peak between 2.0 and 2.5 Hz and five harmonic overtones (Figure 4). The whole pattern is shifted to slightly higher frequencies during strong activity phases. Peaked harmonic spectra with slow frequency shifts have been identified at other volcanoes [e.g., *Hagerty et al.*, 1998] and are viewed as typical for volcanic tremor.

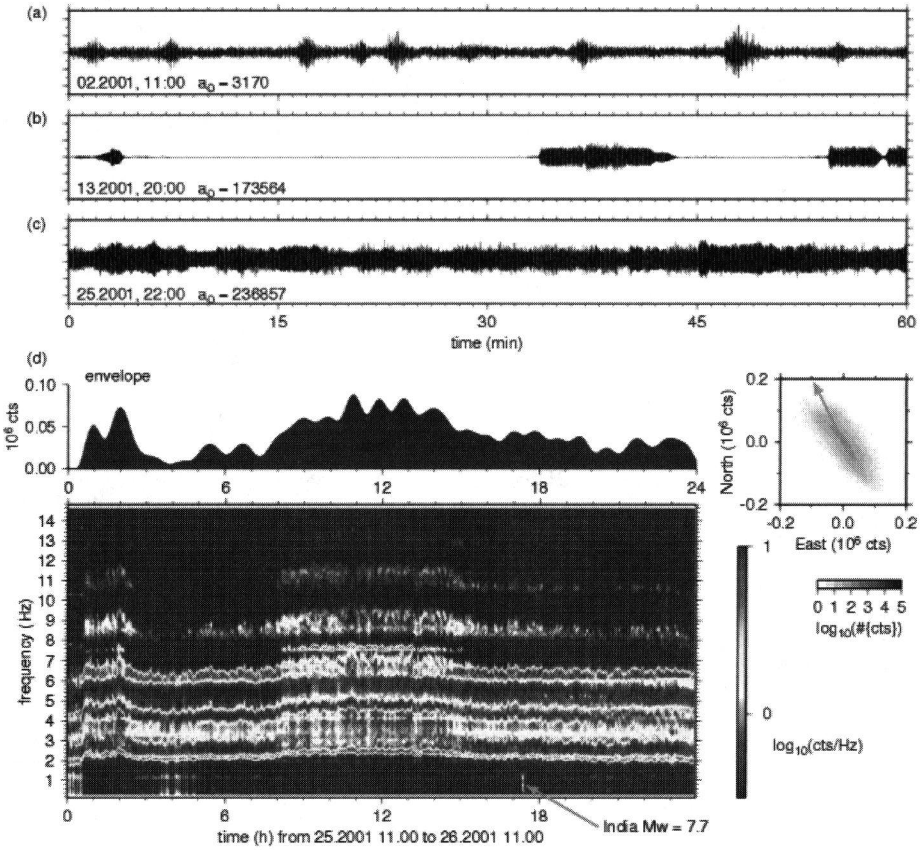

Fig. 4. Tremor-like signals were observed at OB05. The traces at the top (a,b,c) give three 1-hr examples of noise patterns (horizontal component). (d) This spectrogram shows harmonic spectral peaks that correlate in intensity and frequency with the tremor amplitude (see tremor envelope in the middle). The horizontal motions (small inset figure at right) are highly polarized in the direction of the Stromboli volcano (arrow in inset figure). Original color image appears at the back of this volume.

We have analyzed the polarization of horizontal motions during the tremor bursts. Horizontal motions toward Stromboli are highly polarized (Figure 4). Rayleigh waves, originating from a source near Stromboli, would be able to produce such a pattern of horizontal motions on OB05. Tremor signals observed at other volcanoes have also often revealed horizontal motions polarized toward the volcanic source and have been interpreted as being due mainly to Rayleigh waves.
It is interesting, however, that the signal amplitudes have been extremely small on the hydrophone channel compared to those of the seismometer recordings. The reason is not fully understood; it may be due to enhanced noise levels in the water or due to an inefficiency of Rayleigh waves to generate pressure signals.

Are the recordings observed at OB05 caused by volcanic or hydrothermal activity at a submarine center or vent? Submarine volcanic activity near the station was not documented prior to the deployment. Detailed bathymetric and magnetic maps of the Strombolian region [*Gabbianelli et al.*, 1993] show that former submarine vents and magmatic extrusions exist southwest of Stromboli crater in water that is about 800 m deep. However, a submarine eruption has, to our knowledge, never been observed at Stromboli volcano.

Another possible explanation of the signals is ocean bottom currents. In the presence of currents, certain types of sediments, and certain anchors, a harmonic oscillation may result and behave similarly to a volcanic harmonic tremor. However, the current-induced "peaks" observed by Trehu [1985] are much broader than here and do not have harmonic overtones. During GEOSTAR's first mission in the Adriatic Sea [*Beranzoli et al.*, 2000], the measured high current velocities of up to 0.4 m/s resulted in a broad increase of the seismic noise level between 1 and 10 Hz, but not in spectral peaks or overtones. It is also difficult to explain abrupt changes in the seismic noise level or shock-like events by bottom currents, which are expected to be continuous or to correlate with the ocean tides.

The Tyrrhenian Sea experiment has already achieved two important goals: it has yielded promising records indicating that the new free-fall stations can be used for broadband seismological studies, and it has recovered tremor-like noise bursts at a station close to Stromboli volcano. The origin of these signals is not yet understood, but they may be correlated with submarine volcanic or hydrothermal activity. Future studies and data analysis will help resolve this question.

For the duration of this project, the data will be analyzed by the project partners and then be made available to the scientific community.

Acknowledgments

We thank Roberto Carniel (University of Udine, Italy) for providing data from their station at Stromboli crater. Data for CII in Figure 3 were provided by the MEDNET Data Center. We also thank the crews of the *Urania* and *Thetis*. J. Reinhard, A. Polster, A. Wittwer, R. Sitko, R. Knut, S. Mazza, C. Montouri, S. Monna, R. D'Anna, L. Passalacqua, and M. Grimaldi helped with data processing during the cruise and OBS construction. We are indebted to the critical comments of Jay Pulliam, which helped to improve the article. The Tyrrhenian Sea project was funded by DFG, the University of Hamburg, GEOMAR, and INGV, with additional support through the European Union Programme HPRI CT00037.

Authors

T. Dahm, M. Thorwart, E. R. Flueh, Th. Braun, R. Herber, P. Favali, L. Beranzoli, G. D'Anna, F. Frugoni, and *G. Smriglio*
For additional information, contact Torsten Dahm, Institut für Geophysik, Universität Hamburg, Bundesstr. 55, 20146, Hamburg, Germany; E-mail: dahm@dkrz.de.

References

Beranzoli, L., et al., European seafloor observatory offers new possibilities for deep-sea studies, *Eos, Trans. AGU, 81*, 47–49, 2000.

Crawford, W. C., S. C. Webb, and J. A. Hildebrand, Constraints on melt in the lower crust and Moho at the East Pacific Rise, 9°48'N, using the seafloor compliance measurements, *J. Geophys. Res., 104*, 2923–2939, 1999.

Cimini, G., P-wave deep velocity structure of the Southern Tyrrhenian subduction zone from nonlinear tele-seismic travel time tomography, *Geophys. Res. Lett., 26*, 3709–3712, 1999.

Flueh, E., and J. Bialas, A digital, high data capacity ocean bottom recorder for seismic investigations, *Int. Underwater Sys. Des., 18*, 18–20, 1996.

Gabbianelli, G., C. Romagnoli, P. L. Rossi, and N. Calanchi, Marine geology of the Panarea-Stromboli area (Aeolian Archipelago, southeastern Tyrrhenian Sea), *Acta Vulcanologia, 3*, 11–20, 1993.

Godin, O. A., and D. M. F. Chapman, Shear-speed gradients and ocean seismo-acoustic noise resonances, *J. Acoust. Soc. Am., 106*, 2367-2382, 1999.

Hagerty, M., S. Y. Schwartz, M. Protti, M. Garces, and T. Dixon, Observations at Costa Rican volcano offer clues to causes of eruption, *Eos, Trans. AGU, 79*, 569, 570–571, 1998.

Herber, R., Ocean-bottom-seismograph of the Institut für Geophysik Hamburg, *Mar. Geophys. Res., 4*, 247–253, 1979.

Lucente, F., C. Chiarabba, and G. Cimini, Tomographic constraints on the geodynamic evolution of the Italian region, *J. Geophys. Res., 104*, 20,307–20,327, 1999.

Peterson, J., Observations and modeling of seismic background noise, *U.S. Geol. Surv. Open- File Rep. 93-322*, USGS, Albuquerque, N. Mex., 1993.

Trehu, A. M., A note on the effect of bottom currents on an ocean bottom seismometer, *Bull. Seismol. Soc. Am., 75*, 1195–1204, 1985.

Webb, S., Broadband seismology and noise under the ocean, *Rev. Geophys., 36*, 105–142, 1998.

Wortel, M., and W. Spakman, Subduction and slab detachment in the Mediterranean-Carpathian region, *Science, 290*, 1910–1917, 2000.

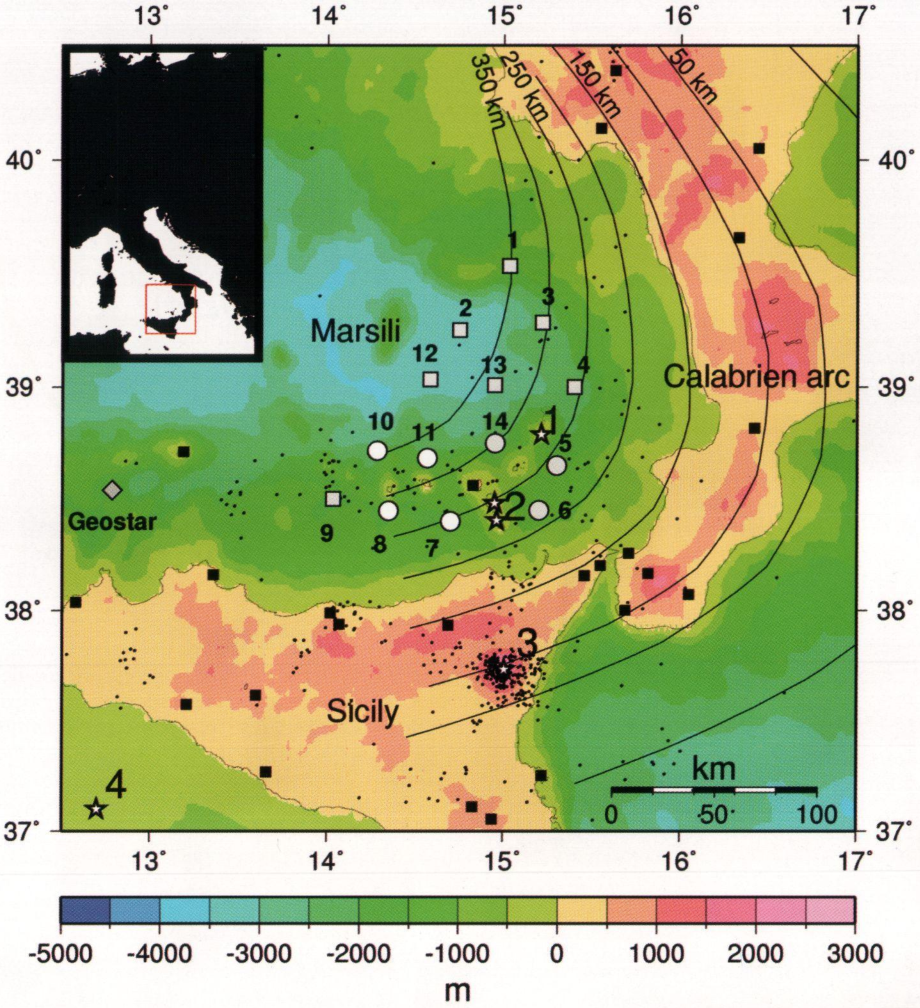

Fig. 1. Positions of OBS systems deployed during the experiment are shown. Systems 7, 8, 10, and 11 are the Hamburg type and others are GEOMAR type; white squares indicate pure hydrophones and white circles 4-channel OBS. The GEOSTAR station is indicated by a small rhombus, and land stations operated by INGV appear as black squares. Large bold numbers declare volcanic centers active during Holocene (1 = Stromboli, 2 = Vulcano and Lipari, 3 = Etna, 4 = Ferdinandea, Sicily Channel); Marsili is a submarine volcano showing no recent activity. The subducting Ionian plate is indicated by isolines, and black dots indicate earthquakes localized by the INGV network from 1996 through 2000.

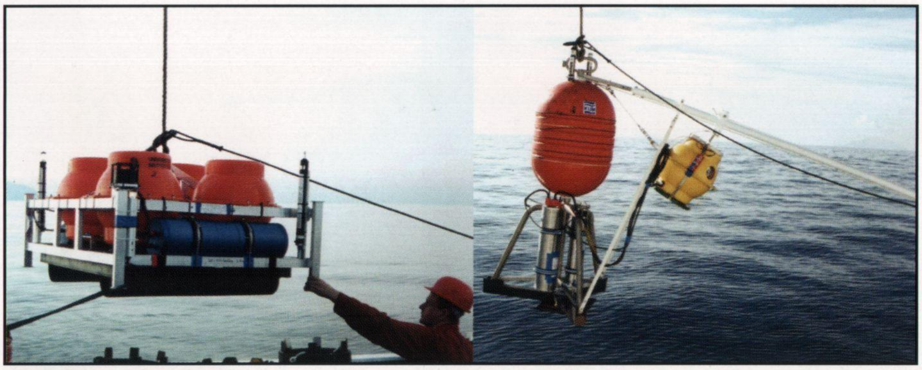

Fig. 2. OBS Hamburg-type system (left) and GEOMAR-type system (right) are shown during deployment in the Tyrrhenian Sea. The station components are described in the text.

Page 314

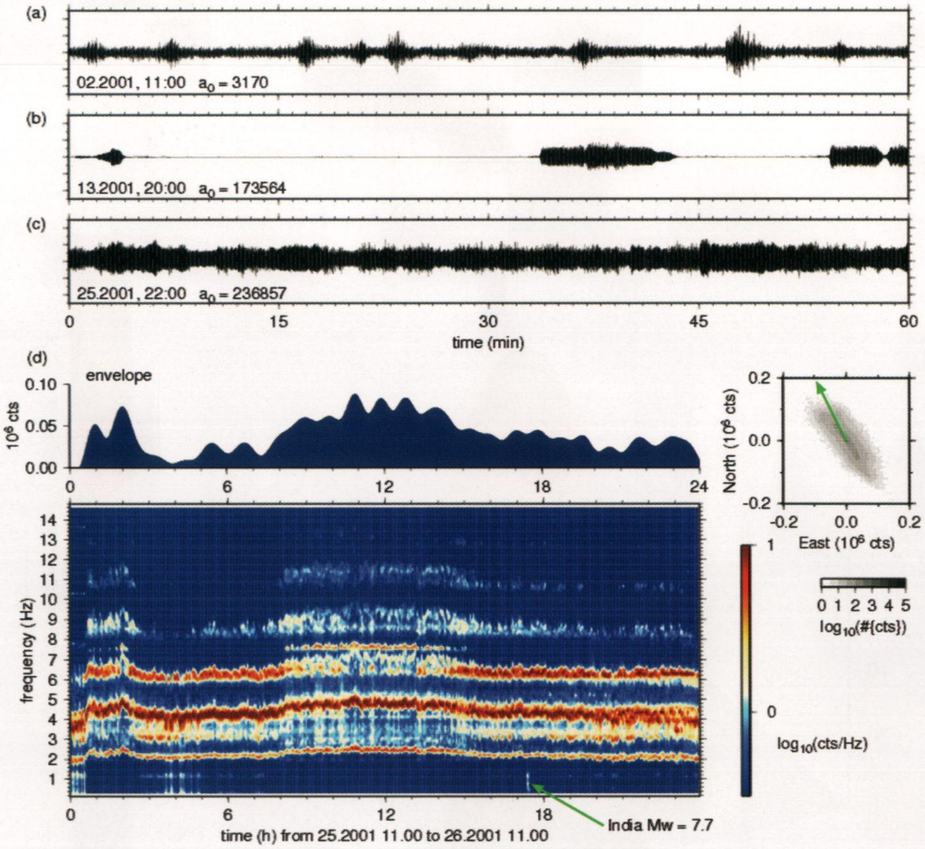

Fig. 4. Tremor-like signals were observed at OB05. The traces at the top (a,b,c) give three 1-hr examples of noise patterns (horizontal component). (d) This spectrogram shows harmonic spectral peaks that correlate in intensity and frequency with the tremor amplitude (see tremor envelope in the middle). The horizontal motions (small inset figure at right) are highly polarized in the direction of the Stromboli volcano (arrow in inset figure).

Page 314