T-PHASE OBSERVATIONS FROM THE MAY 1999 ASCENSION ISLAND EXPERIMENT

Arthur Rodgers and Philip Harben
Lawrence Livermore National Laboratory

Sponsored by U.S. Department of Energy
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation
National Nuclear Security Administration

Contract No. W-7405-ENG-48

ABSTRACT

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) specifies that an International Monitoring System (IMS) will be used to detect and locate disturbances that could be related to nuclear testing. In order to monitor disturbances in and near the world's oceans, the IMS will rely on a network of 11 hydroacoustic stations. This hydroacoustic network will be composed of 6 hydrophone stations and 5 T-phase seismic stations. The hydrophone stations will record pressure variations in the ocean. The T-phase stations will record the seismic waves in the solid earth that are excited when a hydroacoustic wave strikes an island or continental margin. The coupling of hydroacoustic-to-seismic energy is currently an active area of research for CTBT monitoring.

We report observations of hydroacoustic waves and their conversion to seismic waves (T-waves) at the volcanic edifice of Ascension Island. An earthquake to the south of Ascension Island was recorded by International Monitoring System (IMS) hydrophones and temporary seismic stations deployed on Ascension Island by Lawrence Livermore National Laboratory (LLNL). The hydrophone recordings are rich in high-frequency (10-40 Hz) energy. However, the converted seismic waves are dominated by much lower frequencies (2-8 Hz). The T-waves demonstrate amplitude and travel-time variations on the Island. In addition to the earthquake records, off-shore airgun shots were recorded as part of a crustal structure study. These shots also produced hydroacoustic-to-seismic conversions. We performed two-dimensional finite difference simulations to investigate the T-phase conversion process at ocean-island margins. The point of these calculations will be to model the transfer function of the conversion process and to determine if T-phase amplitude variability is the result of conversion along the complex bathymetry of the island, propagation on the island or a site effect.

These observations suggest that the T-phase stations of the IMS may be useful for detecting and locating events in support of the CTBT provided that T-phase travel times are appropriately calibrated. However on volcanic islands, event identification based on T-phase data, which relies on high frequencies, may be inhibited by strong attenuation and low signal-to-noise.

Key Words: hydroacoustics, T-phases

Research performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48. LLNL contribution UCRL-JC-138996.

OBJECTIVE

The objective of this study is to understand the conversion of hydroacoustic-to-seismic energy at an island using both empirical data and theoretical modeling. Seismic data from the May 1999 Ascension Island Experiment were analyzed to study the variability of on-shore T-phase amplitudes and frequency content. Theoretical investigations of the conversion of hydroacoustic-to-seismic energy were also performed.

RESEARCH ACCOMPLISHED

During the last year we have extended our analysis of on-shore T-phase recordings of a moderately large earthquake to the south of Ascension Island. We performed additional investigations of T-phase conversion with two-dimensional finite difference simulations. We are currently modeling T-phases from offshore airgun shots performed as part of a crustal structure study.

The May 1999 Ascension Island Experiment

One of the IMS hydrophone stations is located at Ascension Island in the south central Atlantic Ocean. During a five-day period in May 1999, an offshore airgun survey was conducted around Ascension Island to image the volcanic edifice. Lawrence Livermore National Laboratory (LLNL) deployed ten temporary seismic stations on Ascension Island to study the acoustic coupling and seismic propagation on the island. The goal was to simultaneously record acoustic waves in the ocean (denoted here as H-waves) on the IMS hydrophones and their conversion to seismic waves in the solid earth (T-phases) generated by the airgun shots. Additional airgun shots were used to precisely locate and calibrate the amplitude response of the hydrophones (Harben, et al., 1999; Harben et al., 2000). Figure 1 shows the locations of the hydrophone and seismic stations, the ship track and bathymetry around Ascension Island.

May 14, 1999 Earthquake Recordings

During the temporary seismic station deployment, an earthquake occurred to the south of Ascension Island and was recorded by both the hydrophones and seismic stations. Figure 2 shows the event location, the paths, and recording hydrophone and seismic stations. The hydrophone and vertical component seismic recordings of the event are shown in Figure 3. This event was reported by the United States Geologic Survey (USGS) Preliminary Determination of Epicenters (PDE) (Table 1).

Table 1. Event parameters from the USGS-PDE.

DATE	TIME (GMT)	LATITUDE	LONGITUDE	DEPTH	M_B
1999, May 14 (134)	17:10:09.03	-35.71	-15.89	10 km	4.8

Note in Figure 3 that the H-wave arrival timing is consistent with the source lying to the south of Ascension Island. One of the goals of the experiment was to calibrate the responses of the hydrophones to pressure (Harben et al., 2000). It was not possible to estimate the full frequency-dependent responses because of the placement of the hydrophones on the ocean floor. Nonetheless, the gain of the hydrophones was determined at 10 Hz and the roll-off of the nominal instrument was assumed to be valid for the passband 2-50 Hz. The hydrophone data were then converted to pressure in Pascals (Pa). The seismic instruments (Sprengnerther S-6000, 2-Hz free period) were calibrated and the raw seismic data was converted to absolute ground velocity in nanometers/second. Hydrophone and seismic data were recorded at 120 and 250 samples/second, respectively.

Comparison of Hydrophone and Seismic Spectra

Using the instrument corrections described above, we computed amplitude spectra of time series of equal length for windows around the T-phase arrivals. Figure 4 shows the waveform segments and the spectra of the signals and pre-event noise. The hydrophone record is well above the noise level for the entire band shown (1-30 Hz), while the seismic T-phase signal merges with the noise at about 12 Hz. This is presumed to be due to both inefficient conversion of hydroacoustic-to-seismic energy at the island edifice as well as high seismic noise levels on the island. Additionally, the fall-off of the seismic spectrum is more rapid than that of the hydroacoustic signal in the band 4-10 Hz. This suggests that attenuation along the island portion of the path is high. All these factors result in lower signal detection thresholds at island T-phase stations. Furthermore, event identification methods that rely on analysis of the high-frequency content will be inhibited by inefficient conversion, attenuation and low signal-to-noise.

T-phase Amplitude Variability: Path or Site Effect?

Several previous studies have documented the variability in T-phase amplitudes and character and related this to source-side and/or receiver-side conversion effects (Talandier and Okal, 1998; Piserchia et al, 1999; de Groot-Hedlin and Orcutt, 1999). The T-phases for the earthquake considered were well recorded at five LLNL-deployed seismic stations. Figure 5 shows the envelopes of the T-phase records (filtered 2-6 Hz) and the peak envelope amplitudes plotted at their station locations. The envelopes show considerable differences given small inter-station spacing of a few kilometers (the island is only 10 km across). The peak envelope amplitudes vary by a factor of five between stations OBG and APS. The along-path bathymetry and topography are shown in Figure 5. Note that the path to station OBG shows that a seamount intersects the SOFAR channel at 800-m depth. This bathymetric feature could disrupt the guided hydroacoustic wave. The profile to station APS intersects an undersea canyon (not shown), which could focus incoming hydroacoustic energy and lead to amplification. Alternatively, site effects due to emplacement of the seismometers on different geologic structures could lead to the variability in the observed T-phase amplitudes. The fact that the amplitudes vary over such short spatial scales suggests that site effects play an important role in controlling T-phase amplitudes.

Modeling T-phase Conversions

We performed simulations of the propagation and subsequent conversion of hydroacoustic waves to seismic waves using an acoustic/elastic finite difference code (Larsen and Schultz, 1995). These calculations are done to investigate the T-phase conversion process. The ocean environment was simulated with the nominal sound speed profile for the Ascension Island region (Levitus et al., 1984). A soft sediment layer and solid crust with a velocity gradient were used below the ocean (Figure 6). Various scenarios were simulated. The simulation shown in Figure 6 shows the bathymetric profile from the earthquake to seismic station APS. An explosion source at the SOFAR axis depth (800 m) provided the excitation of the hydroacoustic wave. The synthetic response is also shown in Figure 6. Analysis of the particle motions provides insight into the wave-types. The large amplitude pulse has retrograde elliptical particle motion and propagates as a Rayleigh wave. The later portion of the trace shows linearly polarized waves with vertical particle motions, associated with compressional body-waves (P-waves). This behavior was first noted by Stevens et al. (2000) and suggests that the hydroacoustic energy is converted to Rayleigh waves along the sloping interface well off-shore. When the hydroacoustic energy traveling along the SOFAR axis strikes the island, it is converted mostly to P-wave energy. The Rayleigh wave energy travels faster than the acoustic wave and arrives before the converted hydroacoustic-to-P-wave energy. We saw similar, but more ambiguous, behavior in the observed T-phases.

We will perform additional calculations to model the offshore airgun shots and investigate the causes of T-phase amplitude variability on the island. Figure 6c shows three vertical component seismic records of two offshore airgun shots. The shot was just a few kilometers north of Ascension Island. We will attempt to model these data with our finite-difference simulations.

CONCLUSIONS AND RECOMMENDATIONS

The May 1999 Ascension Island Experiment provided valuable data for studying the conversion of hydroacoustic-to-seismic energy and seismic T-phase variability. Inefficient conversion, high attenuation and high noise levels on island T-phase stations will reduce the sensitivity of seismic T-phase sensors relative to in-ocean hydroacoustic sensors. Poor signal-to-noise for high-frequency (>10 Hz) T-phases will lower signal detection thresholds and the use of T-phases for event screening and identification. The variability of T-phase amplitudes over short distances suggests that site effects play an important role in controlling T-phase amplitudes. Amplitude variability must be accounted for if T-phase amplitudes are to be used to estimate event size.

REFERENCES

de Groot-Hedlin, C. and J. Orcutt, Synthesis of earthquake-generated T-waves, *Geophys. Res. Lett*., 26, 1227-1230, 1999.

Harben, P., J. Hollfelder and A. Rodgers, Experimentally determined coordinates for three MILS hydrophones near Ascension Island, UCRL-ID-136507, 1999.

Harben, P. E., D.K. Blackman, A. Rodgers, C. Turpin, J.R. Hollfelder, Calibration factors for three MILS Hydrophones near Ascension Island, UCRL-ID-138036, 2000.

Larsen, S., and C. Schultz, ELAS3D: 2D/3D elastic finite-difference wave propagation code, UCRL-MA-121792, 18 p., 1995.

Levitus, S., T. Boyer, J. Antonov, R. Burgett. and M. Conkright, World Ocean Atlas 1994, NOAA/NESDIS, Silver Springs, Maryland, 1994.

Piserchia, P.-F., J. Virieux, D. Rodrigues, S. Gaffet and J. Talandier, Hybrid numerical modeling of T-wave propagation: application to the Midplate experiment, *Geophys. J. Int*., 133, 789-800, 1999.

Stevens, J., G. E. Baker, R. Cook, G. D-Spain, L. Berger and S. Day, Empirical and numerical modeling of T-phase propagation from ocean to land, submitted to *Pure and Appl. Geophys.*, 2000.

Talandier, J. and E. Okal, On the mechanism of conversion of seismic waves to and from T waves in the vicinity of island shores, *Bull. Seism. Soc. Am*., 88, 621-632, 1998.

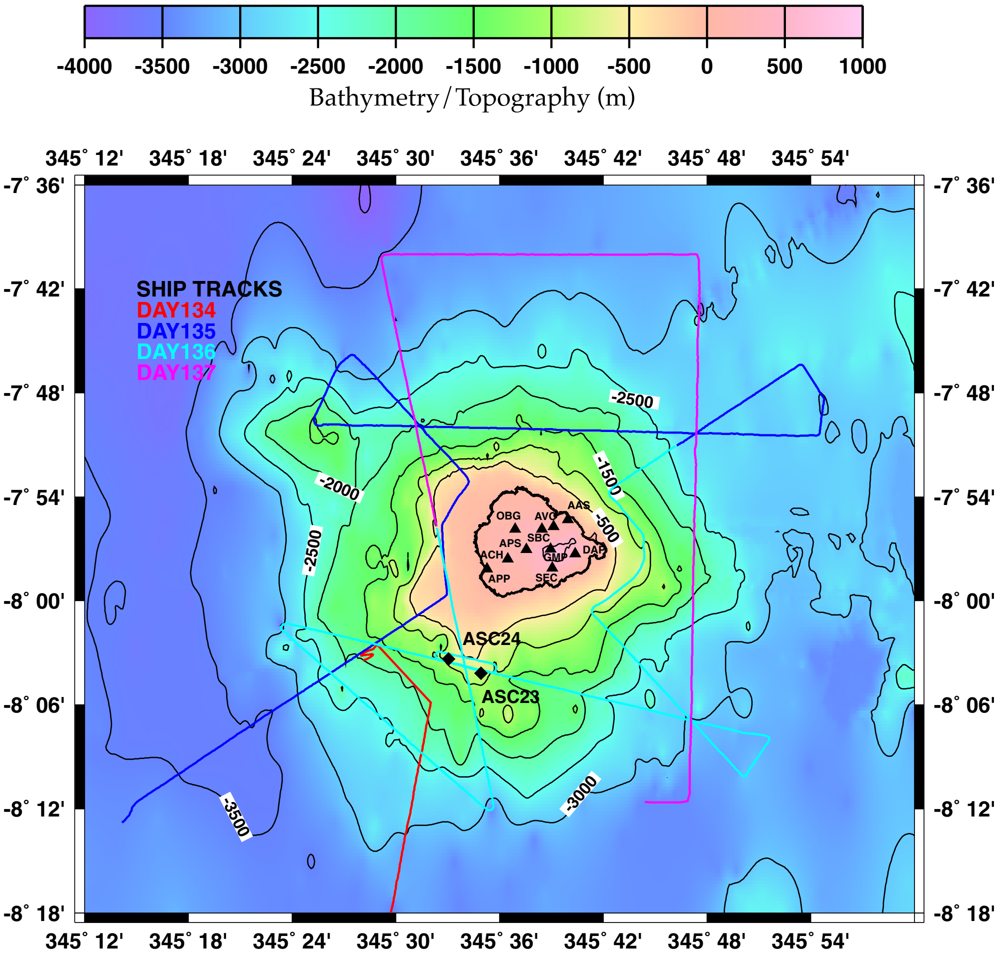


Figure 1. Map of Ascension Island with bathymetry. LLNL seismic stations (triangles) and MILS hydrophones (diamonds) are also shown. The ship tracks indicate the path of the towed airgun used for imaging crustal structure and hydrophone location and calibration.

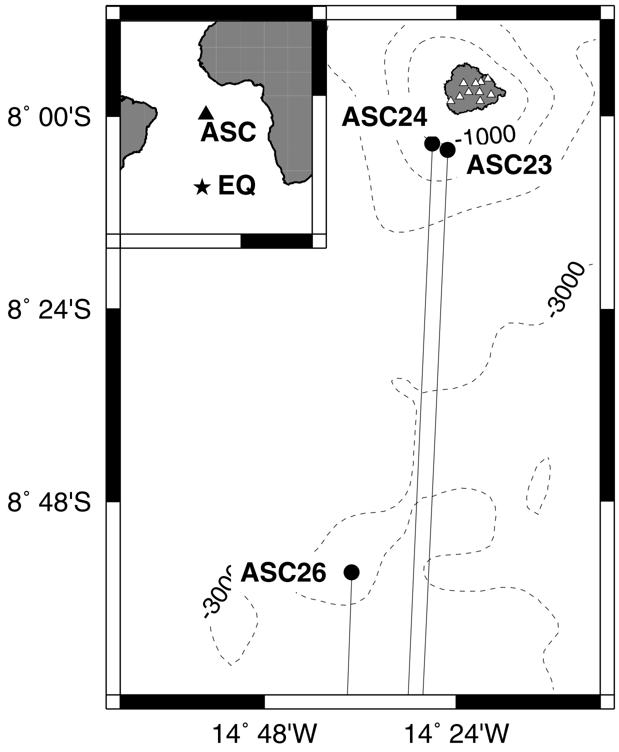


Figure 2. Map of Ascension Island, the MILS hydrophones and paths studied. The earthquake location is shown in the inset.

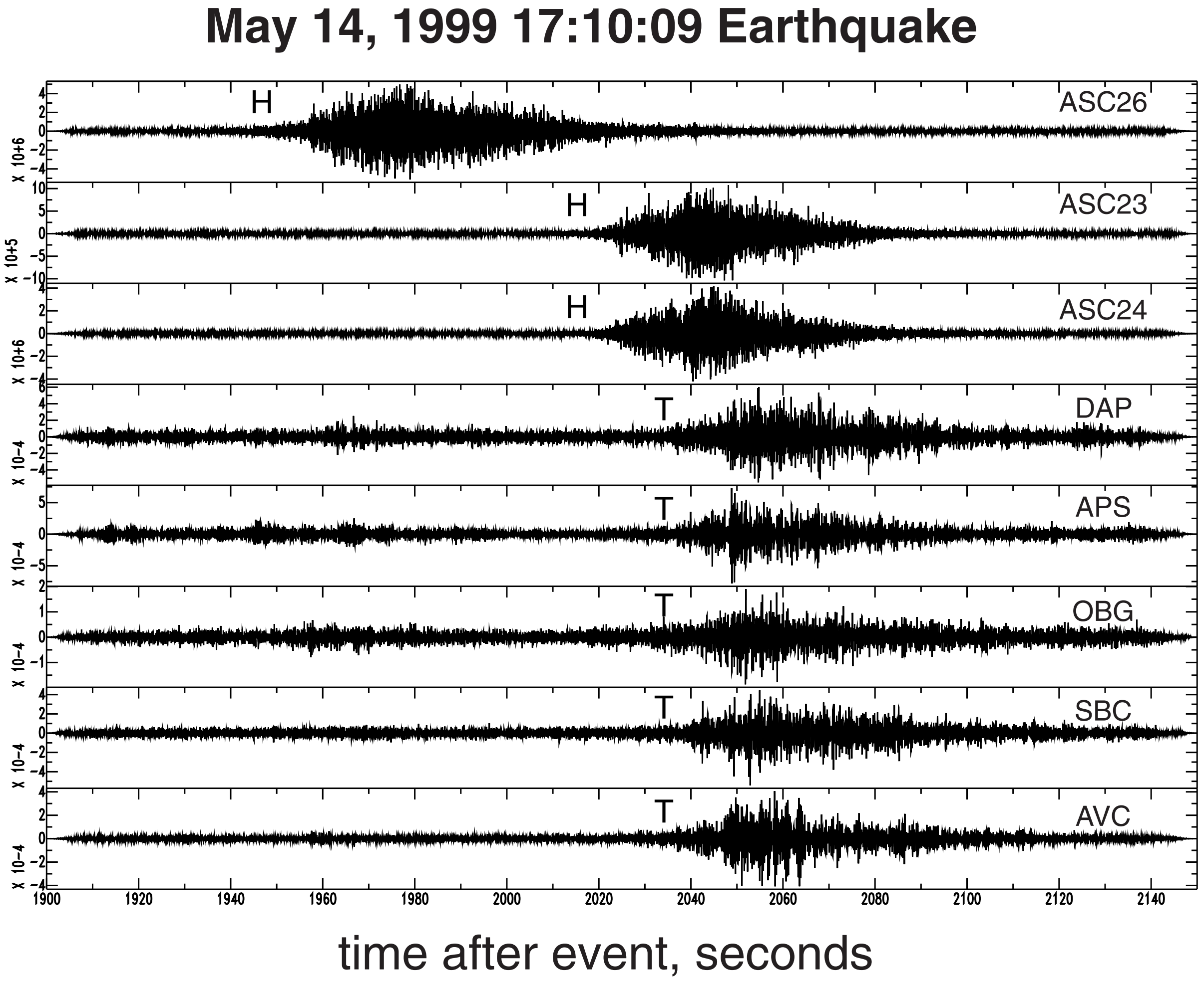


Figure 3. Waveforms for the May 14, 1999 earthquake. The hydrophones ASC26, ASC23 and ASC24 (top) and the vertical component on-shore seismic stations (bottom). Traces were high-pass filtered with a corner frequency of 2 Hz. Hydroacoustic and seismic T-phases are denoted by H and T, resprectively.

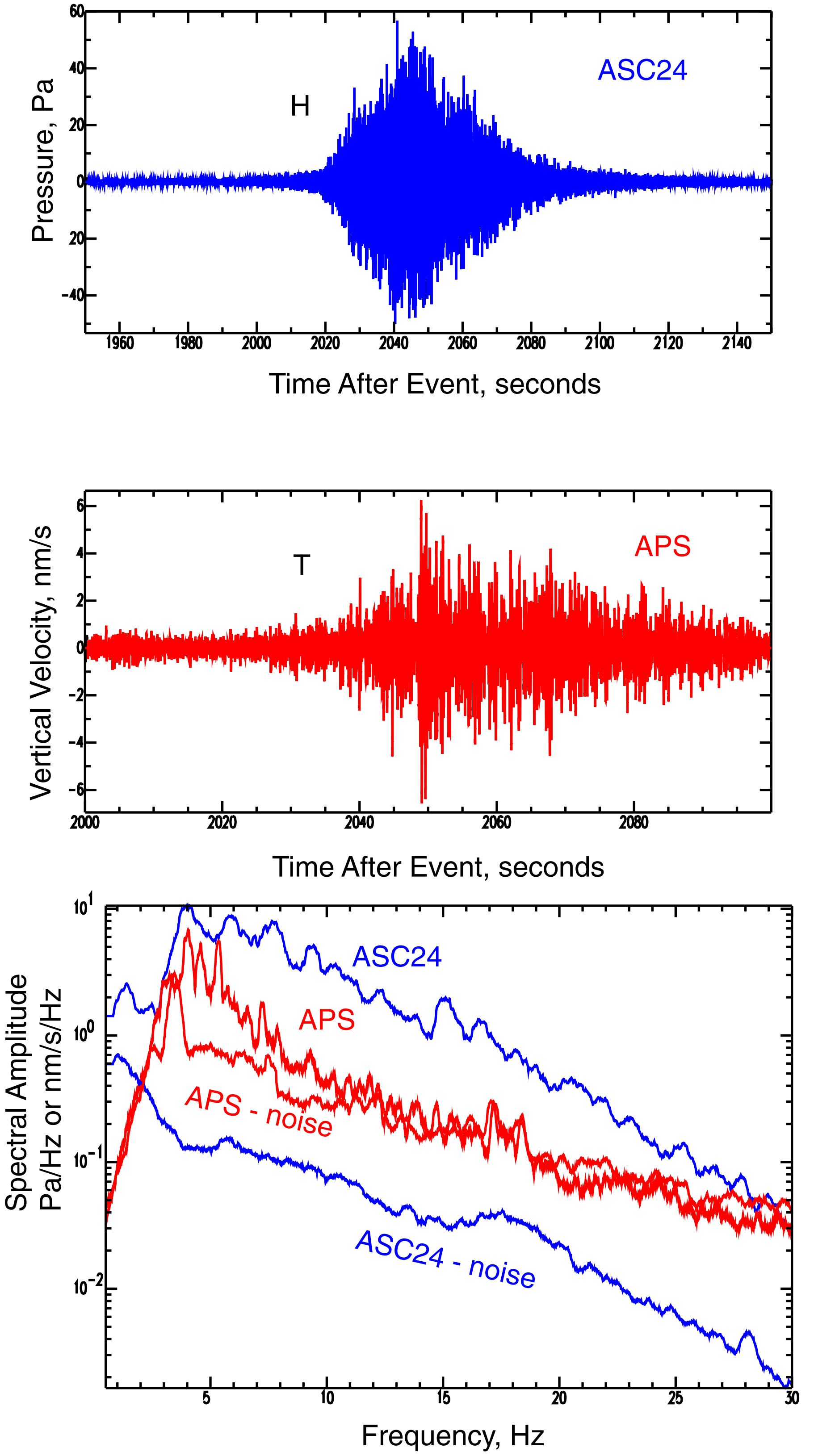


Figure 4. Waveforms of the May 14, 1999 earthquake, corrected for the respective instrument responses, for the ASC24 hydrophone (top) and the APS seismic station (middle). Signal and pre-event noise spectra for the traces are shown (bottom).

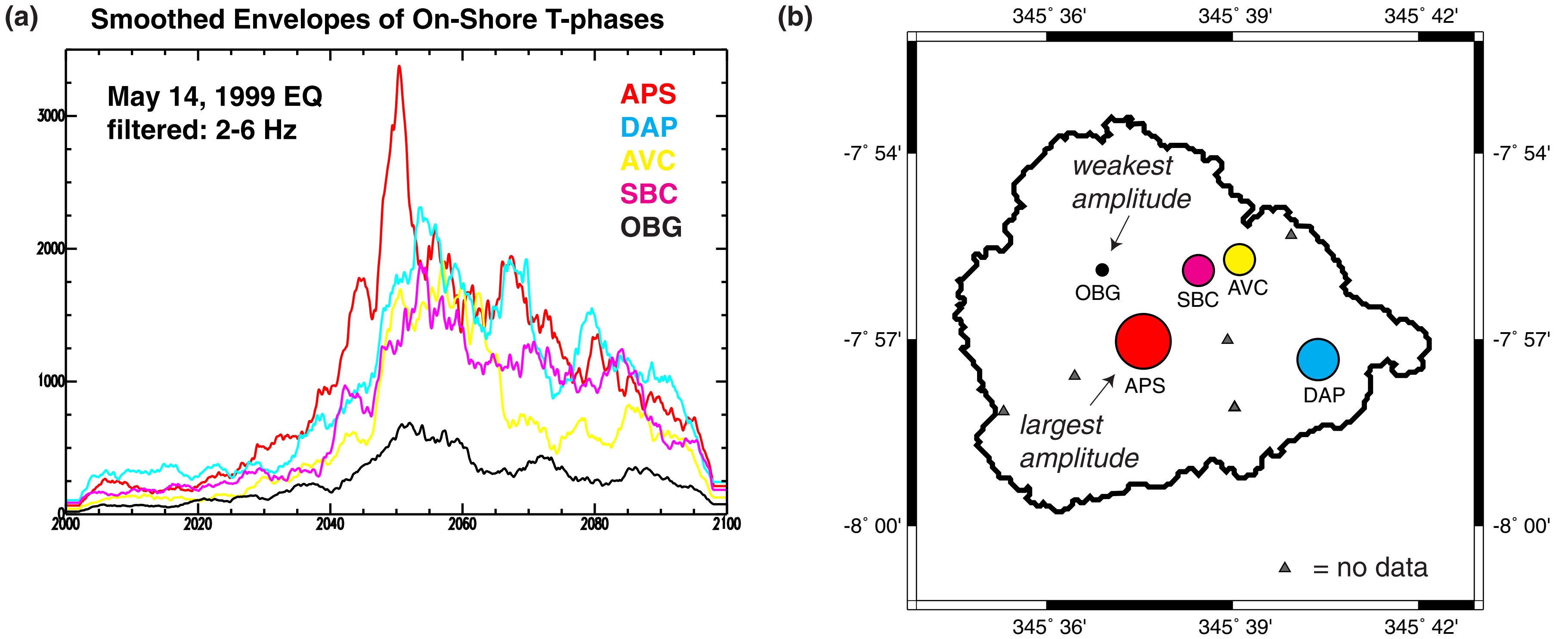
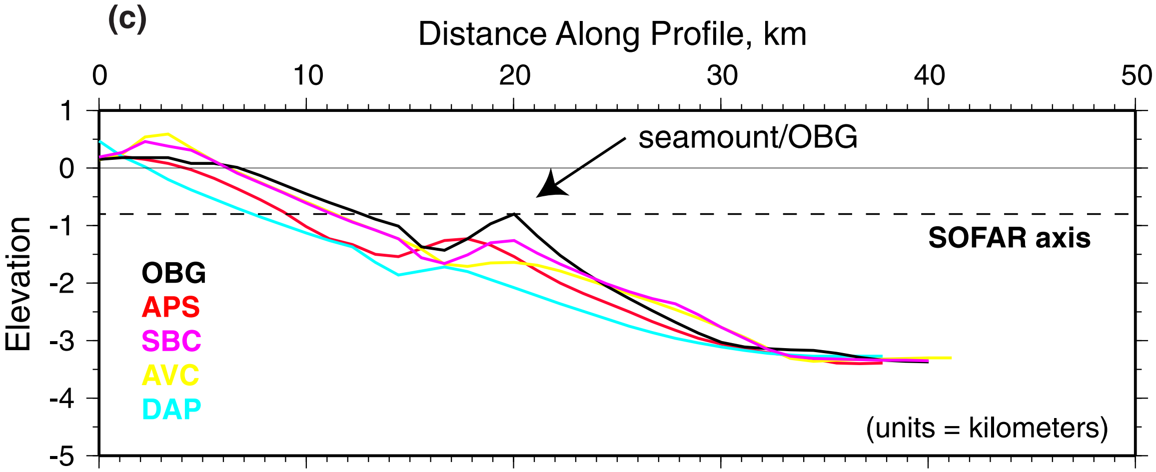
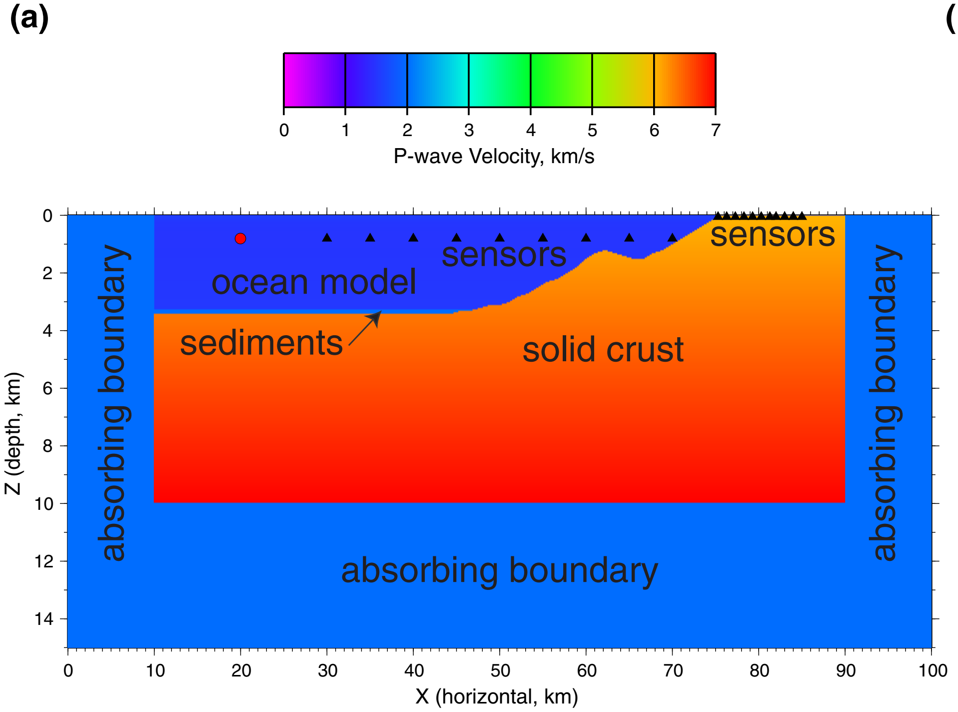
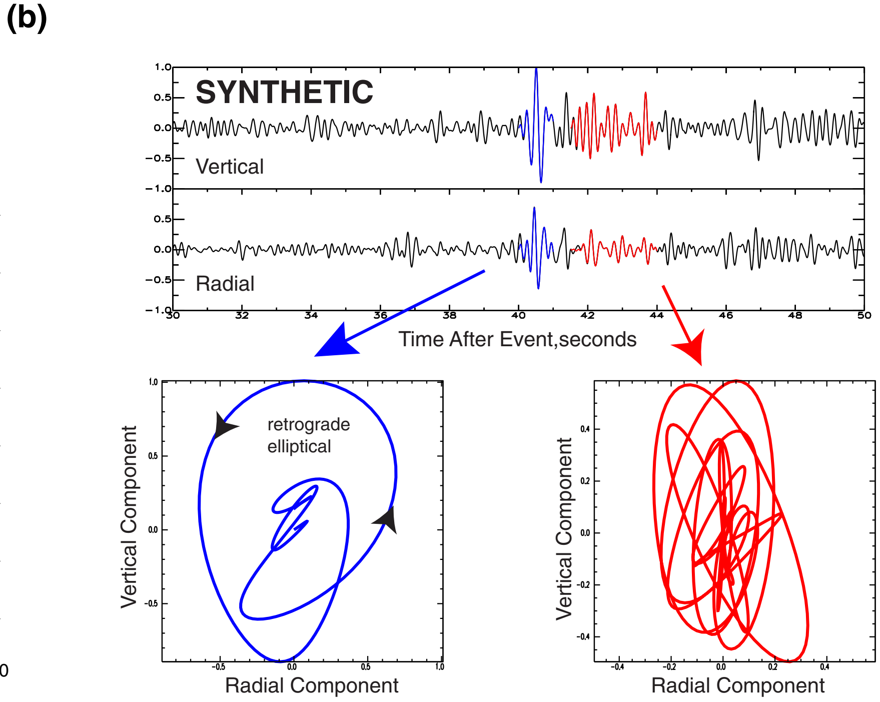


Figure 5. (a) Smoothed envelopes of the on-shore T-phases for the May 14, 1999 earthquake. The data were bandpass filtered 2-6 Hz, then the envelopes were computed and smoothed. (b) Map of the peak envelopes projected to the seismic station locations. (c) Profile of the bathymetry and topography for each path. The SOFAR axis channel depth (800 m) is indicated.







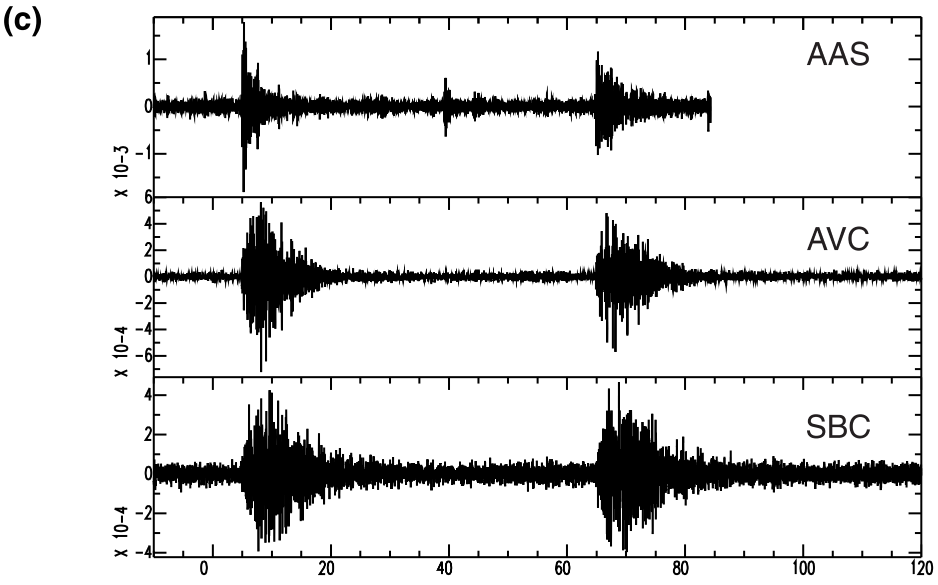


Figure 6. (a) Schematic of one of the two-dimensional finite difference simulations. An ocean sound speed profile was used for the acoustic environment and the solid crust was simulated with a velocity gradient. The source (red circle) was placed in the SOFAR channel to simulate a guided wave. The wavefield was sampled by sensors (triangles) both off- and on-shore. (b) Synthetic response of the model at an on-shore sensor, bandpass filtered 2-4 Hz. Two portions of the response were isolated for particle motion analysis. The blue segment shows large amplitude retrograde elliptical polarization, suggesting Rayleigh wave propagation. The later red segment is linearly polarized with vertical motions, suggesting P-wave propagation. We saw similar, but more ambiguous, behavior in the observed T-phases. (c) Vertical component seismic records for two offshore airgun shots.