Project PROBES
(Puerto Rico Ocean Bottom Earthquake Survey)

By

Jennifer L. Martin[1], Uri S. ten Brink[1], Christa von Hillebrandt[2], Erich G. Roth[1,3], and Gregory Miller[1]

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[1]U.S. Geological Survey, 384 Woods Hole Road, Woods Hole, MA 02543
[2]Puerto Rico Seismic Network, University of Puerto Rico, Mayagüez, PR 00680
[3]now at Communica, Inc., 536 Macarthur Blvd., Bourne, MA 02532

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CONTENTS

FIGURES

TABLES

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EXECUTIVE SUMMARY

Puerto Rico and the Virgin Islands are located at an active tectonic plate boundary between the North American plate and the northeast corner of the Caribbean plate. 3.7 million U.S. citizens live on the islands and the population density, 392 people per square kilometer, is one of the highest in the western hemisphere. Large magnitude earthquakes and devastating tsunamis have occurred in historical times in and around the island. Lack of geological understanding of the tectonic movements in this part of the Caribbean has hampered our ability to assess the seismic and tsunami hazard. Puerto Rico and the Virgin Islands are unique among the seismically-active regions of the United States in being mostly covered by water, which presents both opportunities and challenges for geological and geophysical studies.

In 2000, the U.S. Geological Survey (USGS) Coastal and Marine Program, Woods Hole, Massachusetts, and the Puerto Rico Seismic Network (PRSN) of the Department of Geology of the University of Puerto Rico at Mayagüez (UPRM), began a program to better assess the hazards from earthquakes, submarine slides, and tsunamis to Puerto Rico and the Virgin Islands. The University of Puerto Rico, Mayagüez, maintains a permanent network of seismographs on Puerto Rico and several surrounding islands. To augment this array and fill in gaps in spatial coverage, the U.S. Geological Survey deployed three temporary land stations and 12 ocean bottom seismometers (OBS) in and around western Puerto Rico. This deployment, which is one of a series of studies planned, recorded local and regional earthquakes for 45 days during May and June 2000. It was the largest single deployment to date of the U.S. Geological Survey's OBS, the longest deployment, and the first time, where a joint onshore/offshore USGS OBS array was deployed in conjunction with land seismometers to record earthquakes.

The combined data from the USGS and PRSN arrays will be used to locate earthquakes more accurately than is presently possible, because the accuracy of an earthquake location depends on the distance from the earthquake to the seismometers and on the geographical distribution of the seismometers. A better relocation of earthquakes may reveal the locations of active faults. The data from these arrays will be used to construct seismic velocity maps of the Earth's crust under the arrays. Seismic velocity can be a good proxy for the types of rocks at depth. We also hope to learn about the attenuation of seismic energy from the earthquakes at particular seismic stations to better understand the thermal structure beneath Puerto Rico and help predict the degree of ground shaking.

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This report primarily describes the data acquisition and depicts the data from the USGS OBS array. Plots of seismographs from the experiment can be found in Appendices A and B. Information about the USGS temporary land seismometers can be found in Appendix C and information about the PRSN stations active during the OBS deployment in Appendix D.

DESCRIPTION OF THE ARRAY

The University of Puerto Rico, Mayagüez, maintains a network of permanent short-period and broadband one- and three-component land seismographs that extend along the length of the main island of Puerto Rico and several surrounding islands (Figures 1 and 5). The USGS augmented the permanent land stations with three temporary land stations and 12 ocean bottom seismometers to form two perpendicular arrays: one along a 150-km-long north-south line crossing the Puerto Rico platform along the western side of Puerto Rico, and one along a 250-km-long east-west line through the southern part of Puerto Rico to Isla Mona. Stations were roughly spaced 15 to 25 km apart.

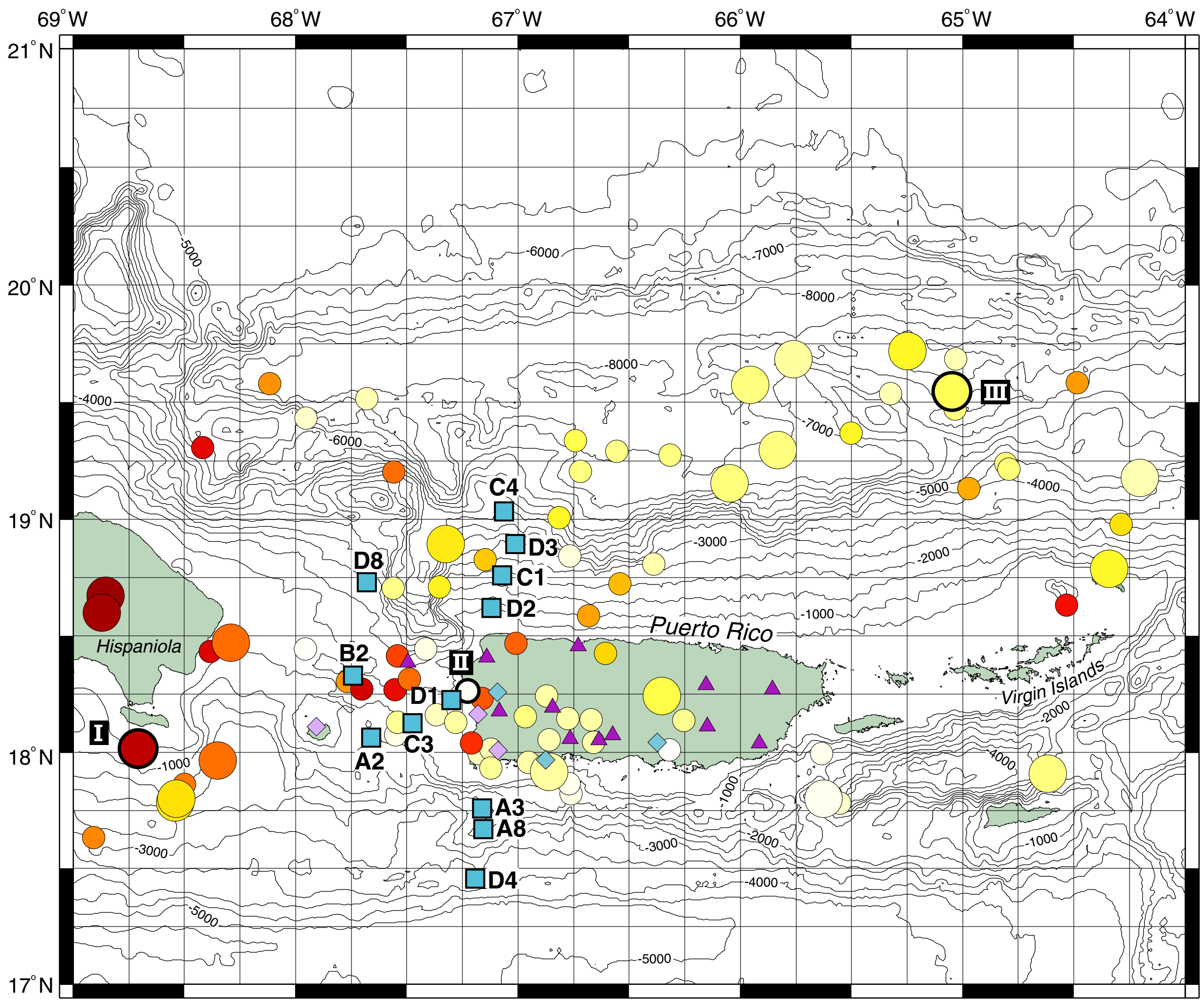
Instrumentation

Each OBS was equipped with a hydrophone and a three-component geophone package. The OBS were housed in a 27 inch aluminum sphere making them portable and easy to deploy from small vessels. Table 1 describes in more detail the technical specifications of the OBS.

In most previous refraction and reflection experiments where active sources are used, we have been primarily concerned with picking arrival times, thus waveform quality has not been of great importance. While we are continuing to use the instruments for active source seismology, we have also begun to analyze earthquakes. For this experiment, we decided it was necessary to redesign the OBS configuration to enhance waveform quality. Unlike in earlier OBS designs, the geophone package was placed external to the sphere so that it rests directly on the ocean floor (Figures 2 and 3). Prior to deployment, the geophone package is attached with a pressure release pin to a 1-meter-long arm that extends from the sphere. The arm is held by another pin in an upright position. As the OBS sinks, upon reaching the ocean floor, the pins are released by the ambient pressure, the arm is lowered and the geophone package is released from the arm. The only connection to the central unit is a flexible cable that transmits the data to the data logger, which is housed in the sphere.

The purpose of the new design was to decouple the instrument package from the higher profile sphere and flotation aids, while improving seafloor coupling. Higher profile OBS are more susceptible to noise generated by ocean currents. Having the geophone package separate from the sphere and lower to the ground reduces the amount of ambient ocean noise. To improve coupling, the geophone package is enclosed in a bag of sand designed to mimic the burial of the geophones in sediment. The new OBS design has led to improved recovery of waveform shape for use in phase identification and in studies of attenuation, focal mechanisms, and crustal structure.

Extensive testing of the new design was performed in Woods Hole and Los Angeles in 1999, yielding a cutoff magnitude of 2.5 for local event detection. The PROBES experiment marks the first complete deployment of all external sensor OBS.



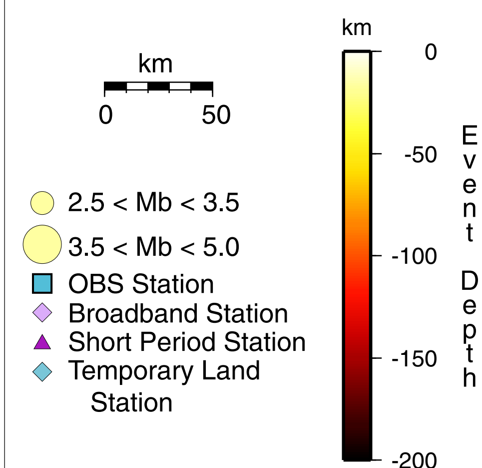


Figure 1. Map of the Puerto Rico region showing stations that were active during the Puerto Rico Ocean Bottom Earthquake Survey as well as all local events that occurred during the deployment. USGS OBS stations are the blue boxes, the USGS temporary land stations are the blue diamonds, the University of Puerto Rico's short-period and broadband seismometers are the purple triangles and diamonds, respectively. Local events are indicated as circles. The events with the heavy borders labeled I, II, and III were used to compare each event's arrival across the OBS array.

Table 1. OBS Instrument Specifications.

Sensors:	three 4.5 hertz L15B geophones OAS E-2S hydrophone Capable of recording continuously for 6 weeks
Sample Interval:	Continuous recording at 100 samples/second
Dynamic Range:	72 dB plus a 30 dB step gain range
Clock Accuracy:	~1 millisecond/day drift
Power:	Standard alkaline batteries
Maximum Depth:	5,000 meters
OBS Design:	External geophone package with sandbag
Arm Length:	1 meter
Arm Deployment:	Pressure-induced release mechanism
Anchor Type:	100 pound forged anchor
Flotation:	Aluminum sphere & attached syntactic foam
Release Mechanism:	Acoustic, with ranging capabilities
Recovery Aids:	Strobe, VHF radio beacon, acoustic transponder
Total Bottom Deployment Time:	45 days

Figure 2. Configuration of the ocean bottom seismometers (OBS). (a) OBS with arm deployed. (b) Expanded view of inset showing the external geophone package enclosed in the sandbag.

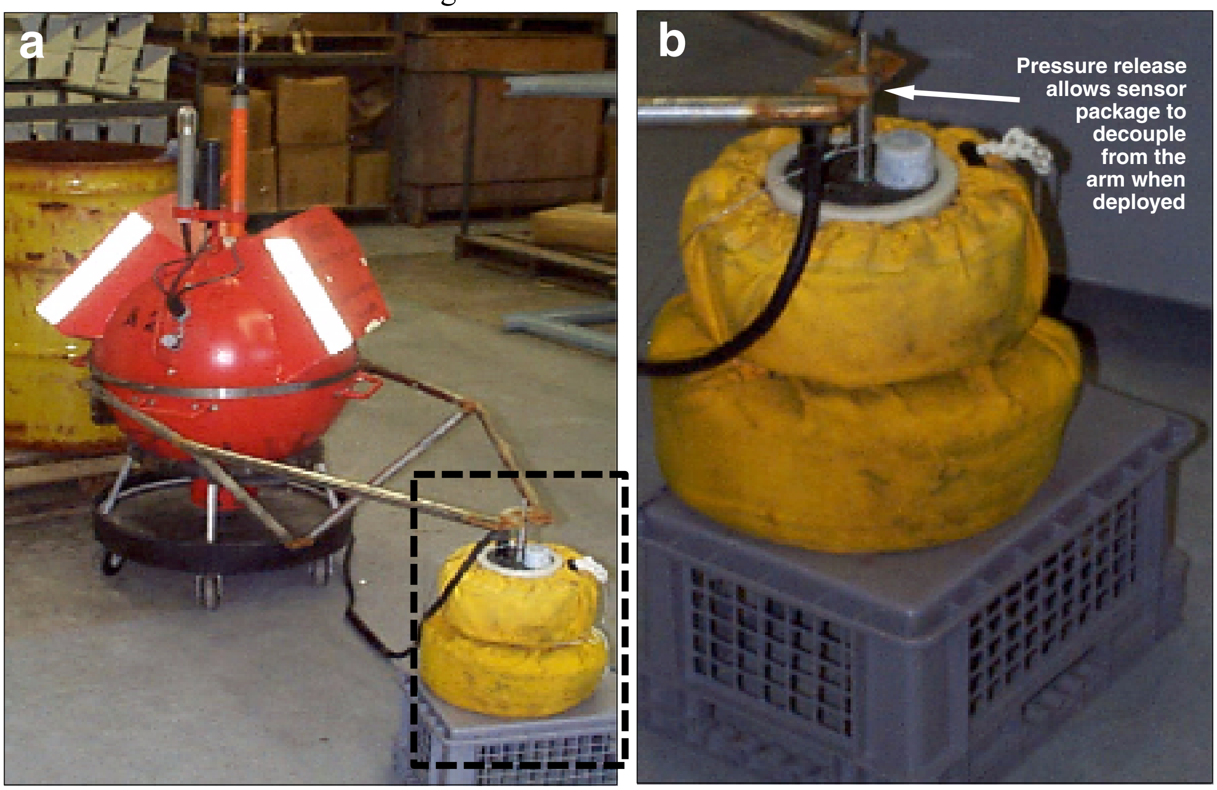
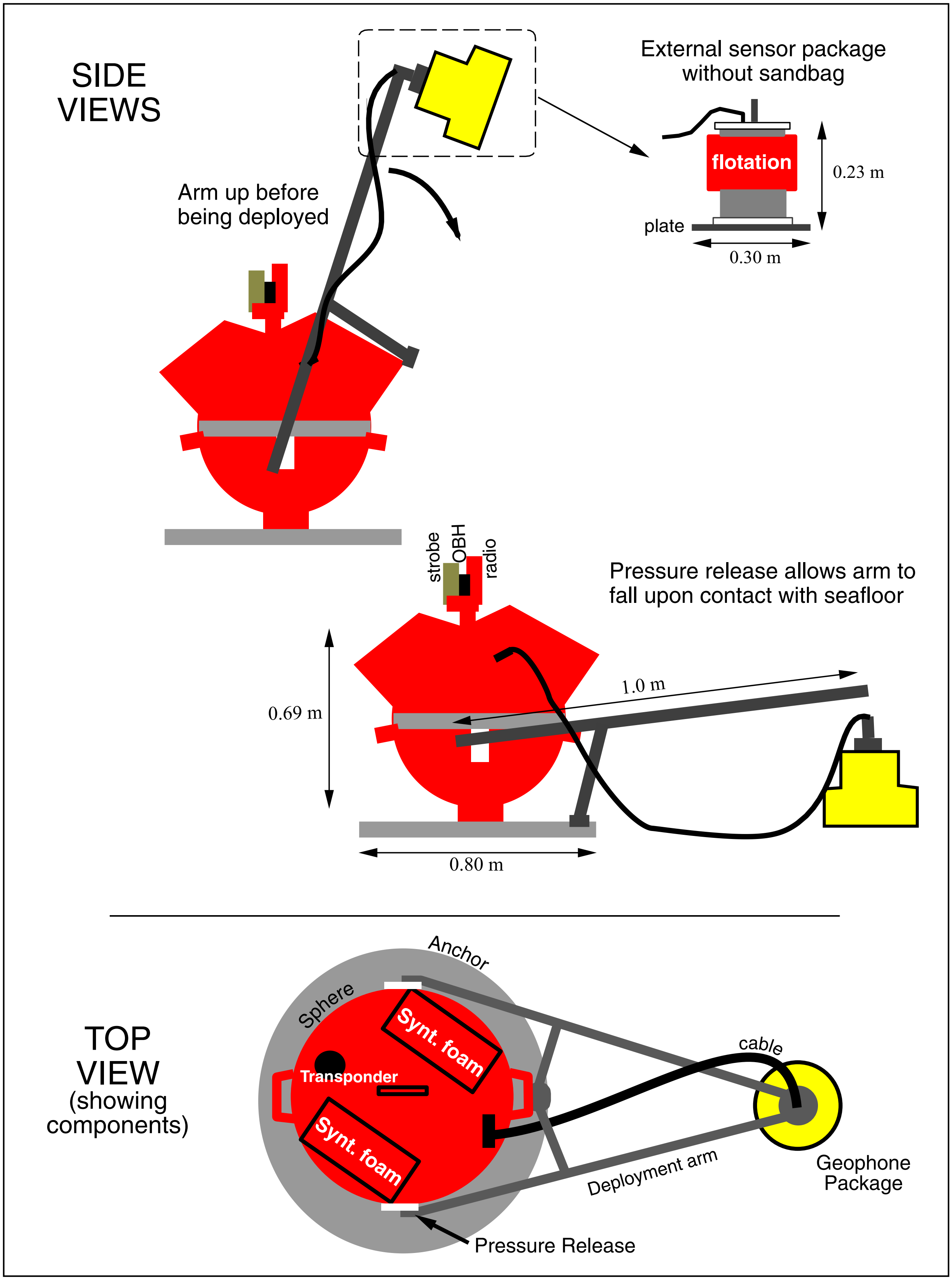


Figure 3. Schematic views of ocean bottom seismometer (OBS) configuration.



CRUISE REPORT

OBS deployment

The offshore deployment of the OBS took place aboard the University of Puerto Rico's R/V *Isla Magueyez* during May 2-4, 2000. The *Isla Magueyez* departed Mayagüez harbor on May 2, 2000, at 18:47 local time (123:22:47 UT). The *Isla Magueyez* is a 72-ft.-long vessel with a beam of 22 ft. and a draft of 11 ft. A news conference took place in the harbor prior to the ship's departure. The OBS deployment was uneventful and proceeded quickly and efficiently around the clock. The *Isla Magueyez* arrived at the University of Puerto Rico's Marine Lab on Isla Magueyez on May 4, 2000, at 11:30 local time (125:15:30 UT).

The instruments were programmed to start recording on May 4, 2000 at 21:00 UT. Table 3 lists information about both the deployment and recovery of the OBS.

Table 2. OBS Deployment Personnel.

Crew of the R/V *Isla Magueyez*
Captain Jose Montablo 4 seamen, 1 cook
Scientific party
Dr. Uri ten Brink - Chief Scientist, USGS Rafael Abreu, Puerto Rico Seismic Network, UPRM Prof. Jorge Capella, Marine Sciences Dept., UPRM Robert Iuliucci, Contractor Greg Miller, USGS Philipp Molzer, USGS Dr. Erich Roth, USGS

OBS recovery

Recovery of the OBS took place aboard the University of Puerto Rico's R/V *Chapman* during June 13-15, 2000. The R/V *Chapman* departed Mayagüez harbor on June 13, 2000, at 16:08 local time (165:20:08 UT). The R/V *Chapman* is a 110-ft.-long fisheries research vessel, built in 1979 with 384 gross tonne. OBS recovery was uneventful and proceeded quickly and efficiently around the clock. All instruments responded immediately and arrived at the sea surface, where expected. Drift through the water column was surprisingly low, generally less than 0.1°. Drift for station B2 was 0.374 km and for station A3 was 0.238 km, but these OBS drifted on the surface for a few minutes before being found. The only significant drift was for A2, 1.187 km. The rise speed

Table 4. OBS Recovery Personnel.

Crew of the R/V *Chapman*
Captain Hector (Cabrilla) Pagan 4 seamen, 1 cook
Scientific party
Dr. Uri ten Brink - Chief Scientist, USGS Rafael Abreu, Puerto Rico Seismic Network, UPRM Sr. Ramon Alonso, Dept. de Recursos Naturales, Commonwealth of Puerto Rico Kurt Grove, Sea Grant Program, UPRM Robert Iuliucci, Contractor David Martinez, Dept. of Geology, UPRM Greg Miller, USGS Jeffrey Nealon, USGS Dr. Erich Roth, USGS Rusell Sell, USGS Samuel Vega Figueroa, Red Sismica, UPRM

Table 3. OBS Station Information.

Station	Latitude (N) (on deploy-ment)	Longitude (W) (on deploy-ment)	Water depth[1] (m) (on deploy-ment)	Latitude (N) (on recovery)	Longitude (W) (on recovery)	Water depth[2] (m) (on recovery)	Rise speed (m/s)	Clock Drift (ms)	# tracks recorded	# channels w/data	Comments
D1	18°13.629'	67°17.849'	398	18°13.575'	67°17.898'	391	0.98	36.4	1423	4	
C4	19°01.991'	67°03.780'	~4200	19°02.037'	67°03.853'	4139	0.94	138	1422	4	
D3	18°53.660'	67°00.696'	~2900	18°53.69'	67°00.722'	2947	0.94	52.4	1421	3	No data for vertical geophone.
C1	18°45.695'	67°04.169'	~1850	18°45.708'	67°04.220'	1849	0.88	unknown	1155	4	The 24 volt battery pack was completely dead on recovery, so no checks were possible. The Seascan clock drift could not be recovered. 1155 tracks were written by the data logger before it died. The cause is unknown.
D2	18°37.134'	67°07.028'	449	18°37.190'	67°07.127'	447	0.74	92.8	1419	4	Sensor connector leaked. There was no vacuum and a lot of salt water intrusion. Arm was bent and got stuck in horizontal position, but geophone package released from arm.
D8	18°43.848'	67°40.749'	~1380	18°43.802'	67°40.852'	1373-82	0.85	62.8	1420	4	Arm released, but sensor package didn't deploy from arm. The piston was bent from the violent twisting of the sensor pack.

[1]Estimated water depths are for points beyond fathometer range and were taken from the bathymetry map.

[2]Water depth was determined by ship's echo sounder for stations D1, D2, D8, B2, A2, and C3. For stations C4, D3, C1, D4, A8, and A3, water depth was determined by direct distance between transducer and OBS transponder. This is a maximum distance because the transducer may not have been vertically above the transponder.

Table 3. OBS Station Information, cont'd.

Station	Latitude (N) (on deployment)	Longitude (W) (on deployment)	Water depth[1] (m) (on deployment)	Latitude (N) (on recovery)	Longitude (W) (on recovery)	Water depth[2] (m) (on recovery)	Rise speed (m/s)	Clock Drift (ms)	# tracks recorded	# channels w/data	Comments
B2	18°19.878'	67°44.259'	~400	18°19.825'	67°44.464'	385	unknown	unknown	0	0	Sensor connector leaked. There was no vacuum and heavy salt water intrusion. The data logger and Seascan clock boards were both destroyed by the flooding. Data logger failed before the start of data, so no data were recorded. Instrument drifted a few minutes before being found so no rise time could be calculated.
A2	18°03.171'	67°39.653'	1015	18°03.804'	67°39.531'	1009	0.99	48	1414	4	Sensor connector leaked. There was no vacuum and some salt water intrusion. Data indicate only the vertical and hydrophone worked. 4 channels were recorded, but there was no data for either of the horizontals. Sensor package and wiring check OK on the surface. Believe problem is in the mating of the sensor package cable.

[1]Estimated water depths are for points beyond fathometer range and were taken from the bathymetry map.
[2]Water depth was determined by ship's echo sounder for stations D1, D2, D8, B2, A2, and C3. For stations C4, D3, C1, D4, A8, and A3, water depth was determined by direct distance between transducer and OBS transponder. This is a maximum distance because the transducer may not have been vertically above the transponder.

Table 3. OBS Station Information, cont'd.

Station	Latitude (N) (on deployment)	Longitude (W) (on deployment)	Water depth[1] (m) (on deployment)	Latitude (N) (on recovery)	Longitude (W) (on recovery)	Water depth[2] (m) (on recovery)	Rise speed (m/s)	Clock Drift (ms)	# tracks recorded	# channels w/data	Comments
C3	18°07.487'	67°28.514'	203	18°07.528'	67°28.502'	198	1.32	unknown	100	4	The 24 volt battery pack was completely dead on recovery, so no checks were possible. The Seascan clock drift could not be recovered. Flooding of the sensor connector resulted in only ~100 tracks of data even though 1100 tracks were written by the data logger before it died.
D4	17°27.473'	67°11.419'	~3500	17°27.488'	67°11.494'	3490	1	53.6	1422	4	Arm released, but sensor package didn't deploy from arm. The piston was pulled too far out, so there was no air space behind it.
A8	17°40.237'	67°09.465'	~1900	17°40.189'	67°09.390'	1841	0.88	93.6	1421	4	
A3	17°45.588'	67°09.798'	~2150	17°45.519'	67°09.684'	2136	unknown	22.2	1423	4	The negative 12 volt connection on the 24 volt battery was dead. On recovery, instrument drifted on surface for a while before being found so no rise time could be calculated.

[1]Estimated water depths are for points beyond fathometer range and were taken from the bathymetry map.

[2]Water depth was determined by ship's echo sounder for stations D1, D2, D8, B2, A2, and C3. For stations C4, D3, C1, D4, A8, and A3, water depth was determined by direct distance between transducer and OBS transponder. This is a maximum distance because the transducer may not have been vertically above the transponder.

for the OBS through the water column was 1±0.3 m/s. Rise speed is the average speed at which the OBS rises through the water column. The R/V *Chapman* arrived at Mayagüez harbor on June 15, 2000, at 09:00 local time (167:13:00 UT). A small news conference took place at the harbor afterwards.

DATA PROCESSING AND ANALYSIS

During the time the array was deployed, 88 local events (Figure 1) were detected by the University of Puerto Rico's permanent network of seismometers, the Puerto Rico Seismic Network (PRSN). UPRM defines these local events as events which occur within 17°N to 20°N latitude and 63.5°W to 69°W longitude. This list of local events is based on previous detection thresholds. If it is found that additional lower magnitude regional and global events can be seen in the data, the working event catalog will be augmented.

Data from the OBS were written both in raw format and as 120-second-long SEGY traces. The traces were then written into day-long SEGY files for each component of each station. For some analyses, the list of local events was used to extract a subset of data into 120-second-long SEGY traces whose start corresponds with the start of the known event.

Each SEGY file contains 17.5 megabytes of data. There are four components for each station and 12 stations, resulting in 840 Mb per day and 37.8 gigabytes for the entire deployment. The raw OBS data traces for each station are 1.403 Gb, resulting in 16.836 Gb total.

Two methods were used to check the quality of the data. In the first method, the arrivals for four known regional and teleseismic events were compared across stations. Plots derived from this analysis are in Appendix A. The second method compared the expected arrival time with the actual arrival time for 20 known events located within the permanent network. The locations of the 20 events, which are within or near the Puerto Rico Seismic Network, are considered reliable. Plots for this method are in Appendix B.

For the first method, three local events plus one teleseismic event were used (Table A1). The events are labeled I through IV on Figures 1 and 4. All three of the local events were recorded by PRSN. The teleseismic event was located under the Andes at the northwestern tip of Argentina some 4,853 km (41.5°) away from our array.

Figures A1-A4 depict each of the four events at the OBS stations. All data are unfiltered. The times for station D1 have been shifted to match the times of the other instruments because of a delay in station D1's clock. Events I through IV were shifted by -60.5 sec., -73.7 sec., -61.3 sec., and -60.4 sec., respectively.

The second method, which compared predicted and actual arrival times, used a

Figure 4. Location of Event IV, the teleseismic event used to compare arrivals across the OBS array.

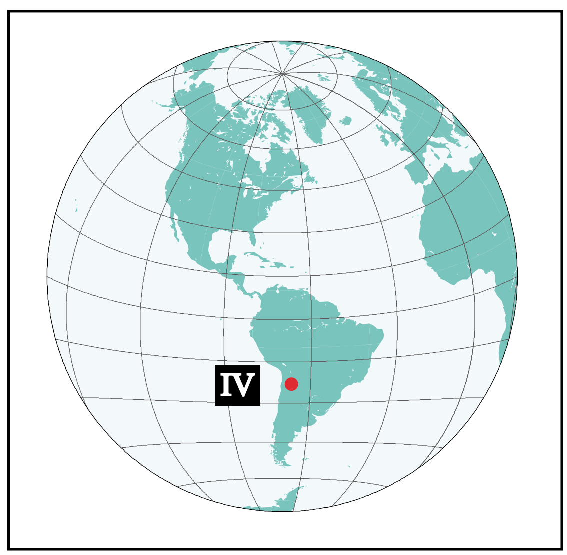
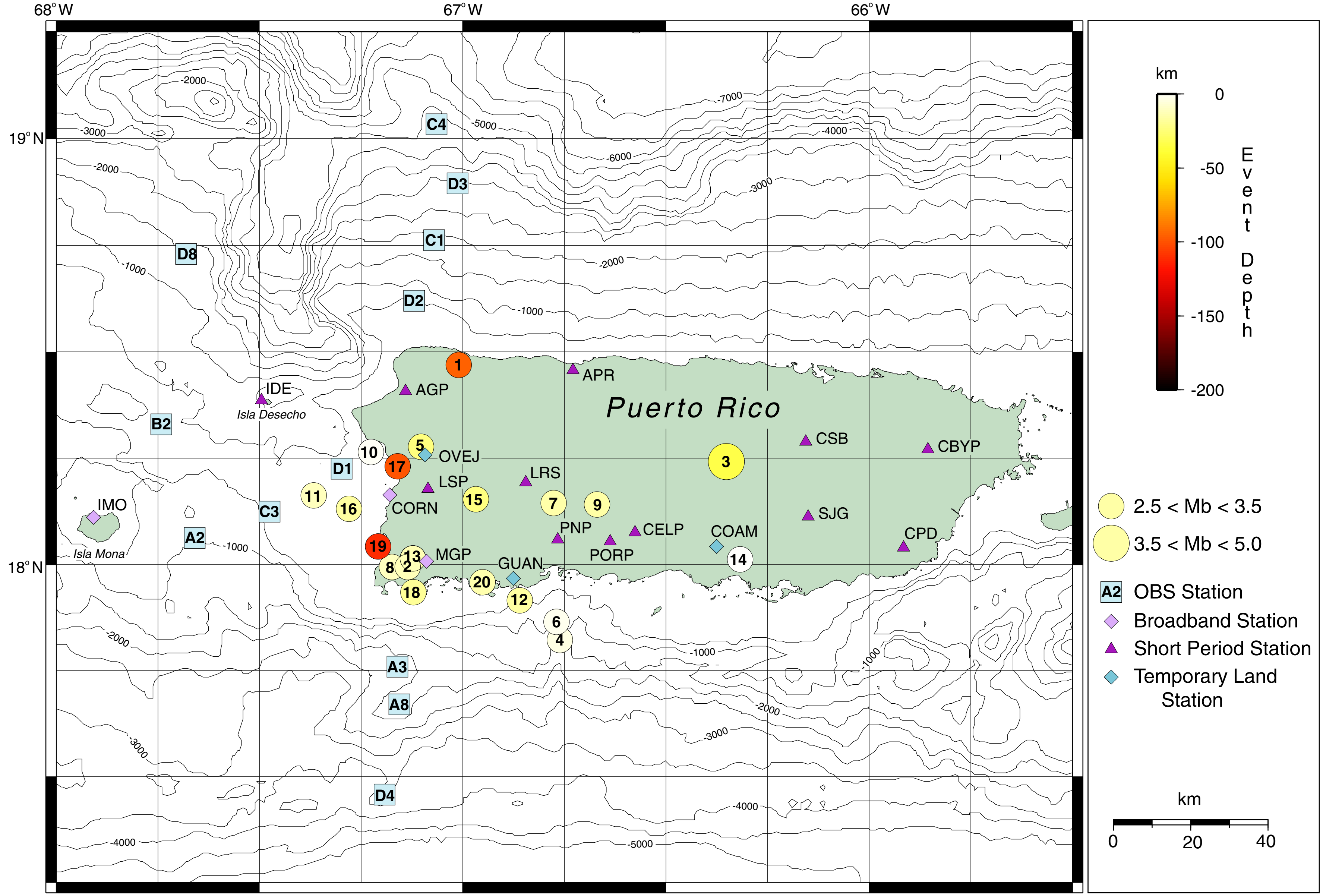


Figure 5. Map of the Puerto Rico region showing the 20 local events used to compare predicted and actual arrival times. Numbers correspond to the event numbers in Table B1.



regional velocity model prepared by Robert Sohn at the Woods Hole Oceanographic Institute to calculate the predicted P-wave arrival times for 20 events at all stations. Figure 5 shows the locations of these events and Table B1 lists the important information for each event. Note that Event II used in the previous method was used in this analysis as well, now labeled Event 10. Tables B2-B10 and Figures B1-B9 compare the difference between the predicted and actual arrival times of the 20 events at each station. Rough estimates of observed arrival time errors were calculated by subtracting the next best pick times before and after the chosen arrival time. Not all events were seen clearly enough at each station to choose an arrival, so only those events which were resolvable at a particular station were included in the analysis. None of the 20 events had clear arrivals at station D2, so D2 was not included in this analysis.

Plots of each event at each station can be found in Appendix B (Figs. B10-B102). The predicted arrival times are marked on each plot with a red vertical line. The plots marked “filtered” have been filtered using an Ormsby bandpass filter. Filter frequency values used were generally 1.0-2.0-12.0-13.0 Hz. Time is in milliseconds after the start of the event. All traces shown are of the vertical component unless otherwise noted.

ACKNOWLEDGMENTS

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