The Eastern North American Margin Community Seismic Experiment: An Amphibious Active- and Passive-Source Dataset

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Abstract

The eastern North American margin community seismic experiment (ENAM-CSE) was conceived to target the ENAM Geodynamic Processes at Rifting and Subducting Margins (GeoPRISMS) primary site with a suite of both active- and passive-source seismic data that would shed light on the processes associated with rift initiation and evolution. To fully understand the ENAM, it was necessary to acquire a seismic dataset that was both amphibious, spanning the passive margin from the continental interior onto the oceanic portion of the North American plate, and multiresolution, enabling imaging of the sediments, crust, and mantle lithosphere. The ENAM-CSE datasets were collected on- and offshore of North Carolina and Virginia over a series of cruises and land-based deployments between April 2014 and June 2015. The passive-source component of the ENAM-CSE included 30 broadband ocean-bottom seismometers (OBSs) and 3 onshore broadband instruments. The broadband stations were deployed contemporaneously with those of the easternmost EarthScope Transportable Array creating a trans-margin amphibious seismic dataset. The active-source portion of the ENAM-CSE included several components: (1) two onshore wide-angle seismic profiles where explosive shots were recorded on closely spaced geophones; (2) four major offshore wide-angle seismic profiles acquired with an airgun source and short-period OBSs (SPOBSs), two of which were extended onland by deployments of short-period seismometers; (3) marine multichannel seismic (MCS) data acquired along the four lines of SPOBSs and a series of other profiles along and across the margin. During the cruises, magnetic, gravity, and bathymetric data were also collected along all MCS profiles. All of the ENAM-CSE products were made publicly available shortly after acquisition, ensuring unfettered community access to this unique dataset.

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Supplemental Material

Introduction

The eastern North American margin (ENAM) represents a type-locale of a magma-rich passive rifted margin. Continental extension started as early as the Middle Triassic by reactivation of Paleozoic structures of the Appalachian orogen (Withjack *et al.*, 1998; Thomas, 2006). At the Triassic-Jurassic boundary (~200 Ma), a short-lived magmatic pulse, the Central Atlantic Magmatic Province, emplaced magmatism over a large region spanning parts of North America, Europe, South America, and Africa (Marzoli *et al.*, 2018), including in the oldest landward rift basins of the ENAM (Schlische, 2003). The breakup of Pangaea and subsequent onset of Atlantic Ocean seafloor

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spreading is marked by a few prominent coast-parallel magnetic anomalies, though their ages are not precisely known (e.g., Greene *et al.*, 2017). In particular, the prominent East Coast magnetic anomaly occurs at the rifted margin and is interpreted to represent synrift volcanism (e.g., Alsop and Talwani, 1984). Other evidence for magmatic rifting comes from imaging of seaward-dipping reflectors interpreted as subaerial volcanism (e.g., Oh *et al.*, 1995) and high-velocity lower crust interpreted as mafic magmatic intrusions and underplating (e.g., Tréhu *et al.*, 1989; Holbrook *et al.*, 1994). Long-term subsidence and sedimentation shaped the present-day margin (Dillon and Popenoe, 1988). High-resolution images of landslide deposits on the continental shelf and slope of the eastern United States (Twichell *et al.*, 2009) show that the margin is still a dynamic environment.

Deliberations that led to the eastern North American margin community seismic experiment (ENAM-CSE) began at a joint Geodynamic Processes at Rifting and Subducting Margins (GeoPRISMS) and EarthScope ENAM implementation workshop held at Lehigh University in October 2011. Meeting participants from the GeoPRISMS and EarthScope communities proposed a wide range of science targets. There was broad consensus that an important avenue for discovery was the exploration of linkages between mantle, crustal, and surficial processes that span spatial scales and include the onshore and offshore parts of the margin. It was concluded that the design of the CSE should include: (1) a suite of seismic datasets in a nested experimental design that incorporates different resolution length scales, (2) a broadband ocean-bottom seismometer (OBS) deployment to complement the EarthScope Transportable Array (TA) seismic stations, and (3) data acquisition in a well-chosen section of the margin, such that integration of these data sets would naturally follow.

After gathering more community input on the CSE design at the Fall 2011 AGU meeting and through an online poll hosted by GeoPRISMS, the area around Cape Hatteras was chosen for data acquisition. The experiment plan would include active- and passive-source seismic data acquisition at stations both onshore and offshore. The GeoPRISMS program would fund the gathering of these new datasets with the project lead by a large team of scientists from many institutions: (1) the University of Texas at Austin Institute for Geophysics, (2) the Center for Earthquake Research and Information at the University of Memphis, (3) The College of New Jersey, (4) Lamont–Doherty Earth Observatory of Columbia University, (5) Rice University, (6) Southern Methodist University, (7) University of Texas at El Paso, (8) Woods Hole Oceanographic Institution (WHOI), and (9) Yale University. Graduate students and early-career scientists from the broader geosciences community were invited to participate in the data acquisition through a formal application process. In total, 79 scientists and students from 49 different institutions participated in ENAM-CSE-related fieldwork. Involving so many participants and institutions served to engage a broad community, provide educational opportunities, and create an investment in the ENAM-CSE dataset.

Data Collection

The ENAM-CSE study area is located in, and offshore of, North Carolina and Virginia in the United States (Fig. 1). The ENAM-CSE collected passive- and active-source, broadband, and short-period seismic data. The broadband deployment specifically related to the ENAM-CSE comprised three stations installed at schools along the Outer Banks of North Carolina and 30 OBS instruments from the U.S. Ocean Bottom Seismic Instrument Pool (OBSIP). Because the EarthScope TA had already reached the east coast, combining the TA and ENAM-CSE provides a contemporaneous broadband dataset that spans from the Appalachian Mountains to the Atlantic sea floor.

The broadband array of the ENAM-CSE recorded data from April 2014 to June 2015 (Gaherty *et al.*, 2014). The three Outer Banks stations were direct-buried Nanometrics Trillium Compact seismometers from the Incorporated Research Institutions for Seismology–Program for the Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL) instrument pool with 120 s corner frequencies recording at both 1 and 50 samples per second. These stations are located between 1 and 3 m above sea level along the coast. The 30 OBS stations were provided by OBSIP Institutional Instrument Contributor (IIC) WHOI and use Güralp CMG3T sensors, with 120 s corner frequencies. The broadband OBS instruments recorded data at 1 and 100 samples per second and were equipped with differential pressure gauges with sample rates of 20 samples per second. They were deployed in water depths of ~1300 to ~5300 m. Example broadband data from the ENAM-CSE and regional TA stations are shown in Figure 2.

OBS instruments were deployed and recovered by the R/V Endeavor with a 100% station recovery rate. Station locations on the seafloor were determined using a roughly circular acoustic survey performed immediately following deployment. Instruments deployed in the Gulf Stream were observed to drift a substantial horizontal distance as they fell through the water column (Fig. S1, available in the supplemental material to this article). The average drift was 800 m (in average water depth of ~3400 m), but some stations drifted more than a kilometer, with the maximum drift being ~2060 m. The dominant drift direction was north-northeast, consistent with the Gulf Stream, with stations closest to the shore showing the strongest drifts.

Active-source data acquisition for the ENAM-CSE started in September 2014 with a two-ship experiment off Cape Hatteras. Four major seismic reflection/refraction lines composed of short-period OBS (SPOBS) stations and additional marine multichannel seismic (MCS) reflection lines were acquired with the R/V Marcus G. Langseth, while the ENAM-CSE broadband array was recording (Fig. 1). The experiment plan included 94

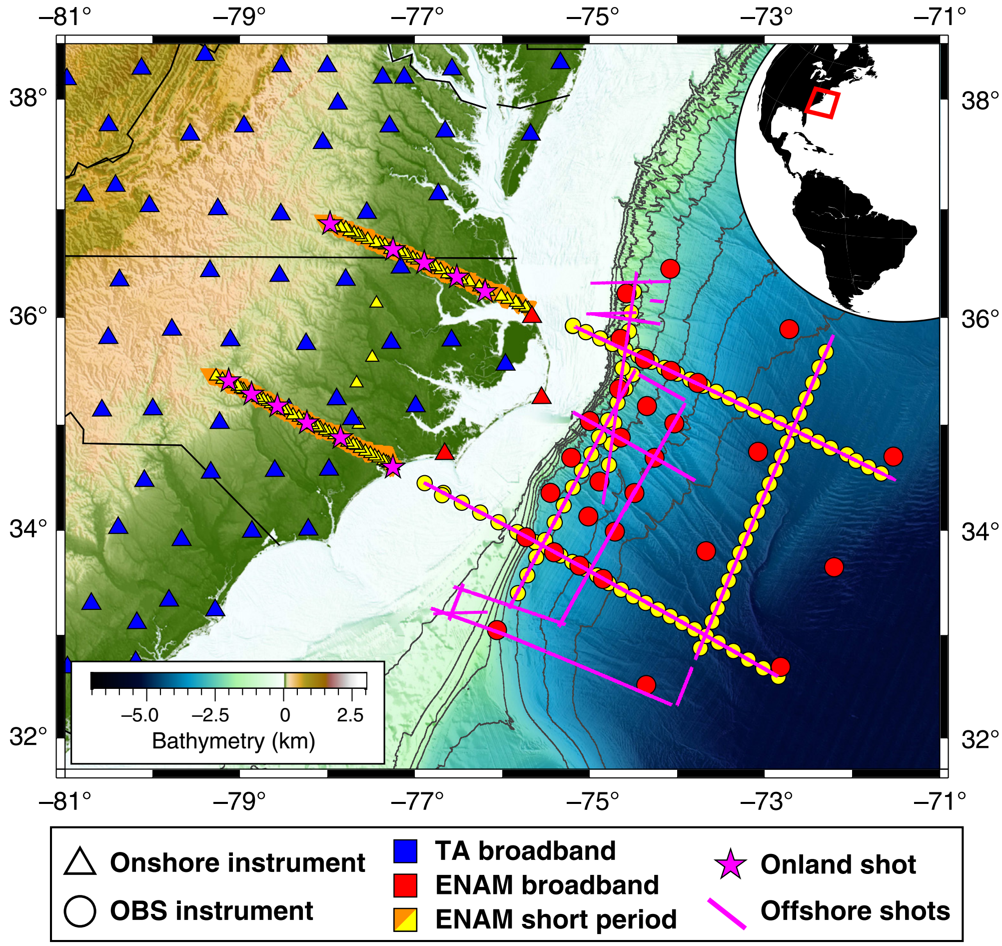

Figure 1. Station map of the eastern North American margin community seismic experiment (ENAM-CSE) plotted on top of bathymetry. Broadband ocean-bottom seismometer (OBS) seismic stations are shown as red circles, broadband Outer Banks stations as red triangles, short-period OBS (SPOBS) stations as yellow circles, three-component short-period land stations as yellow triangles, one-component short-period land stations as gold triangles, land-based shots as pink stars, and multichannel seismic (MCS) lines as pink lines. Gravity, magnetic, and bathymetry data were collected along the MCS lines. Transportable Array (TA) stations are shown as blue triangles. The color version of this figure is available only in the electronic edition.

SPOBS stations on two margin crossing and two margin parallel lines. Twenty-four of these instruments were brought on board the R/V Endeavor from the OBSIP IIC Scripps Institution of Oceanography (SIO), and 23 SPOBSs were contributed by OBSIP IIC WHOI. Each of these 47 instruments were deployed twice to cover the four marine seismic transects (Van Avendonk *et al.*, 2014, 2015). First, the southernmost and easternmost lines were deployed from the R/V Endeavor, whereas the R/V Marcus G. Langseth produced airgun shots and collected MCS data (Fig. 1). The SPOBS instruments were then recovered and redeployed along the northernmost and westernmost lines, where the R/V Marcus G. Langseth again produced shots and collected MCS data. WHOI stations used Geospace GS-11D three-component geophones that recorded at 1 and 200 samples per second. SIO stations employed Sercel L-28 LB geophones that recorded data at 200 samples per second. Both the SIO and WHOI stations used High Tech, Inc. HTI-90-U hydrophones for pressure measurements. The SPOBSs were deployed in water depths of ~30to ~5200 m. Similar to the broadband stations, the SPOBSs showed drift consistent with the Gulf Stream. All but one of the SPOBS instruments was recovered for a recovery rate of 98.9%.

Over ~4800 km of marine MCS data were collected aboard the R/V Marcus G. Langseth between September and October 2014 (expedition MGL1408; Shillington *et al.*, 2014a). Different acquisition configurations were used depending on the depth of the science targets. MCS transects coincident with the SPOBS lines were acquired using a 36-element, four-string, 6600 cubic inch tuned airgun array towed at a depth of 9 m to maximize low-frequency energy and deep imaging. Data were recorded on a 636-channel, 8-km-long streamer towed at 9 m with a sample rate of 2 ms and a record length of 18.432 s. The shot interval was 50 m with the streamer group spacing at 12.5 m. For part of the southernmost and westernmost lines, streamer depth was deepened to reduce swell noise. In addition, for part of the westernmost line, shot spacing was increased to 62.5–75 m to maintain an 18.432 s record. An example of MCS data along the easternmost SPOBS line is shown in Figure 3.

MCS transects not coincident with the SPOBS lines used a smaller 3300 cubic inch, 18-element, two-string tuned airgun array. Deeper water lines were recorded on the 636 channel, 8 km long streamer with the same sample rate, record length, shot interval, and streamer group spacing, as described earlier. Shallow water lines, those along the shelf and upper slope, were acquired with a 480-channel, 6-km-long streamer. The sampling rate for the shallow lines was 1 ms, the record length was 9 s, the receiver group spacing was 12.5 m, and the shot interval was 25 m. The source and the streamer for all of the non-SPOBS coincident lines were towed at a depth of 6 m to

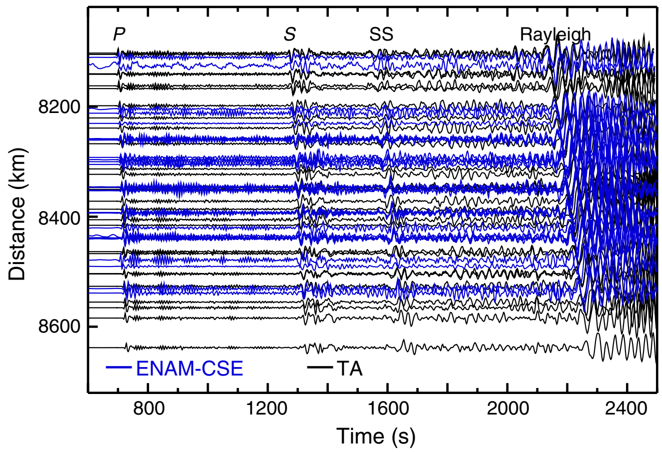

Figure 2. Vertical-component record section of the 9 October 2014 M_w 7.0 East Pacific Rise seismic event from the ENAM-CSE (blue lines) and TA (black lines) broadband seismic stations. Waveforms have been filtered between 10 and 100 s. Even without tilt or compliance corrections, the ENAM-CSE OBS stations show several clear arrivals. SS, seismic phase. The color version of this figure is available only in the electronic edition.

record high-frequency energy and provide fine-scale imaging of the sedimentary layers.

In addition to seismic data, the R/V Marcus G. Langseth collected a suite of other geophysical observables including multibeam bathymetry, sub-bottom profiler, magnetic, gravity, and expendable bathythermograph (XBT) data. Multibeam bathymetry and sub-bottom profiler data were acquired throughout the entire cruise except on transits to and from Norfolk. Multibeam data were acquired with the onboard Simrad-Kongsberg EM122/SB122 system; 3.5 kHz sub-bottom profiler data were recorded with a Knudsen 3260 Echosounder system. Total field magnetic data were recorded throughout the cruise, except on transits to and from Norfolk and for brief power downs for maintenance and streamer recovery. Magnetic data were acquired with a Geometrics G-882 Cesium marine magnetometer system that was towed 116 m behind the ship. Gravity data were collected with a Bell Aerospace BGM-3 air-sea gravimeter. XBTs were deployed on most of the MCS lines. One hundred and forty-nine XBTs and four expendable conductivity-temperature-depth probes were deployed during the cruise.

The September and October 2014 onshore active-source component of the ENAM-CSE consisted of 80 short-period three-component Sercel L28 instruments recording at 250 samples per second on RefTek RT130s to capture offshore airgun shots (Magnani and Lizarralde, 2014). These instruments were provided by the IRIS-PASSCAL instrument center. The stations were arranged along two margin perpendicular lines in a continuation of the offshore SPOBS lines (Fig. 1). The onshore recordings of airgun shots form a very large amphibious data volume spanning the entire margin, because all land stations were deployed for the duration of R/V Marcus G. Langseth cruise MGL1408. The onshore–offshore data (Magnani, Van Avendonk, *et al.*, 2015) are of variable quality, as noise levels varied significantly between day and night and between onshore sites.

A second onshore seismic experiment took place in June 2015 (Magnani, Lizarralde, and Harder, 2015; Magnani *et al.*, 2018). Roughly 800 vertical-component Geospace GS11D instruments with RefTek RT125A recorders (commonly known as Texans) recorded at 250 samples per second. These instruments were provided by the IRIS-PASSCAL instrument center and installed in two phases along the same transects that were

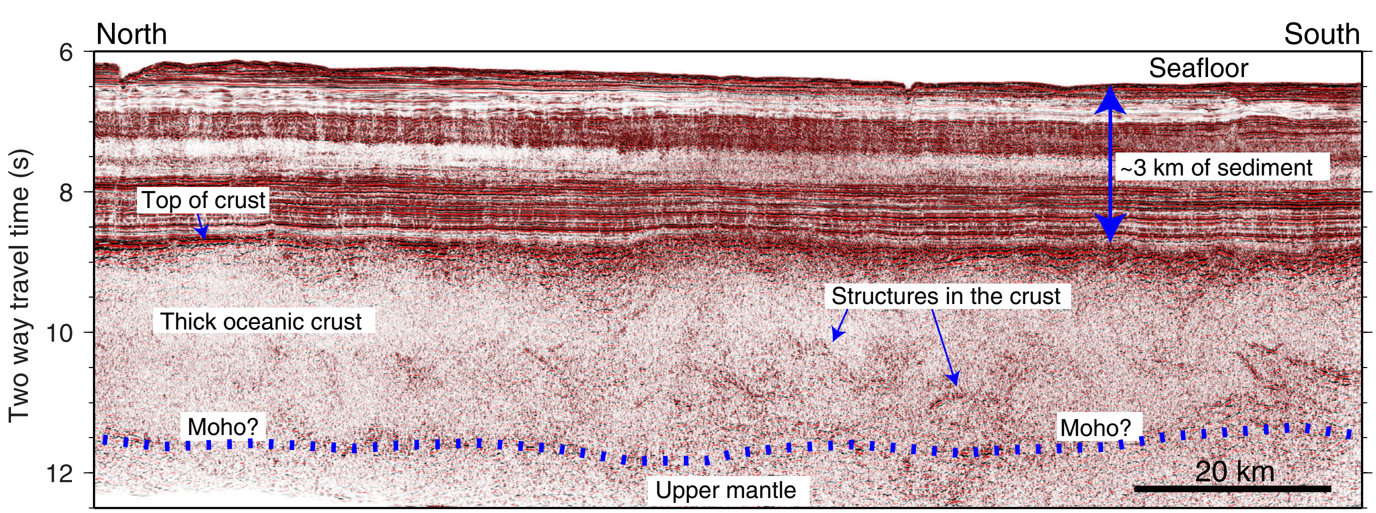

Figure 3. Example of shipboard time migration of MCS data acquired along the easternmost SPOBS line on the R/V Marcus G. Langseth. Prominent reflections highlight a ~3 km thick sedimentary layer, thick oceanic crust, and several internal crustal reflectors. The color version of this figure is available only in the electronic edition.

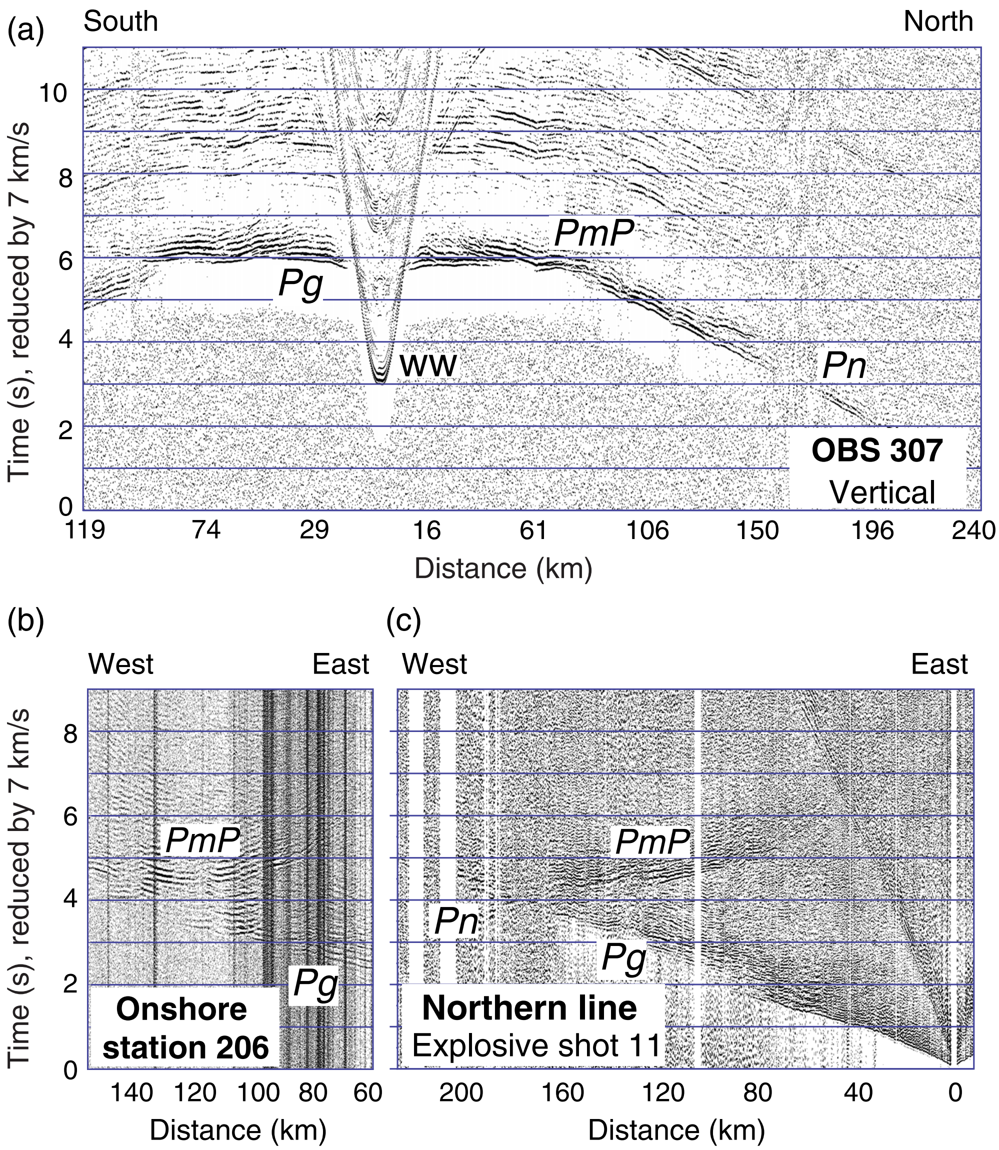

Figure 4. Example refraction data from the short-period stations. (a) Vertical channel of OBS 307 recording airgun shots from the R/V Marcus G. Langseth along the easternmost SPOBS line. (b) Example of the ENAM onshore–offshore seismic refraction data. Airgun shots of the R/V Marcus G. Langseth along the southernmost line recorded on land station 206. (c) Example of the 2015 ENAM land explosion refraction experiment. Texans recorded data from explosion 11 along the southern line. The time axis is reduced at 7 km/s for all three plots. *Pg* is *P*-wave turning in crust, *PmP* is wide-angle Moho reflection, *Pn* is mantle refraction, ww is the water wave. The color version of this figure is available only in the electronic edition.

used in the 2014 onshore–offshore field campaign (Fig. 1). They were first deployed along the southern ENAM-CSE line then along the northern line. A total of 11 land-based 182 kg shots, provided by the U.S. National Science Foundation (NSF)-funded seismic source facility at University of Texas El Paso, were recorded by the Texan array, five shots along the northern line and six shots along the southern line. An example of the explosion seismic data (Fig. 4) shows very clear deep-crustal and mantle seismic refractions.

Data Quality and Availability

All of the ENAM-CSE data were intended to become immediately publicly available. The broadband OBS data had a brief distribution delay, needing to be first reviewed, filtered, and redacted by the U.S. Navy. The onshore-offshore broadband data and the SPOBS data are available through the IRIS Data Management Center (DMC) under the network code YO (Gaherty *et al.*, 2014) in miniSEED format. The redacted OBS data are archived under HH? channels, and the continuous data filtered above 3 Hz are archived under HX? channels. Continuous redacted 1 sample per second data are archived under LH? channels. Data return for the broadband OBSs was 98.6% with an additional 6.6% redacted by the U.S. Navy on the unfiltered channels (Figs. S2 and S3). The onshore active-source data can be accessed via the IRIS-DMC under network code ZI (Magnani and Lizarralde, 2014; Magnani, Lizarralde, and Harder, 2015) and are stored in PH5 format. It is also available through the Interdisciplinary Earth Data Alliance (IEDA) (Magnani, Van Avendonk, *et al.*, 2015; Magnani *et al.*, 2018). The MCS data collected by the R/V Marcus G. Langseth can be accessed via the Marine Geoscience Data System (MGDS) in several forms (Shillington *et al.*, 2014a, 2018; Van Avendonk *et al.*, 2014, 2015). All of the underway geophysical data collected aboard the R/V Marcus G. Langseth are also accessible through the MGDS under cruise MGL1408 (Shillington *et al.*, 2014b). Amphibious short-period data can also be accessed through the MGDS (Magnani, Lizarralde, and Harder, 2015).

The overall data quality of the ENAM-CSE is good. The percent data availability, as calculated by Modular Utility for STAtistical kNowledge Gathering (MUSTANG) (Casey *et al.*,

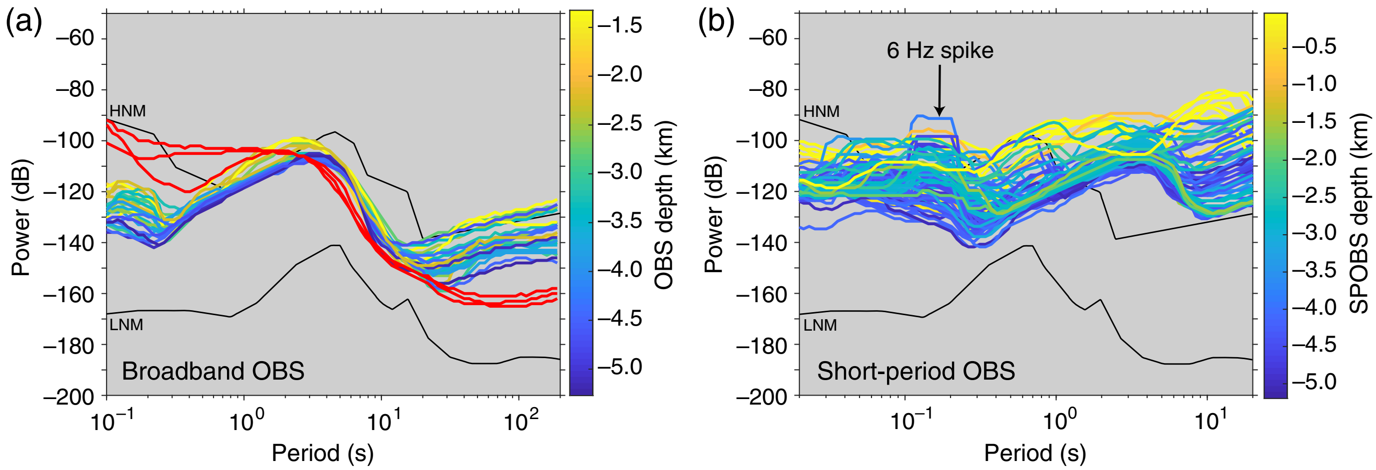

Figure 5. Mean noise spectra for the vertical components colored by deployment depth for (a) broadband OBS and (b) SPOBS instruments. Spectra for the three onshore broadband stations are shown in red and high-noise (HNMs) and low-noise models (LNMs) models in black. For both the broadband and SPOBS stations, shallower-water stations generally exhibit higher noise levels than deeper-water stations. An anomalous peak at ~6 Hz can be seen in some of the SPOBS instruments. Problematic stations are not plotted due to noisy or compromised data. The color version of this figure is available only in the electronic edition.

2018), was ~98% for the YO network (Fig. S2). A significant portion of the ENAM-CSE study region encompasses an area impacted by the Gulf Stream. As such, the OBS data have high levels of noise (Fig. 5, Figs. S4 and S5). The OBS instruments also exhibit depth-dependent noise characteristics, such that shallower stations have slightly higher noise levels than deeper water stations. A few of the SPOBS instruments exhibit an anomalous peak in noise at ~6 Hz that warrants further study. The Gulf Stream also impacted the MCS data acquisition by creating significant streamer feathering.

A few stations had issues with significant noise or problematic seismic components. Broadband OBS station C01 had excessive amounts of noise on the vertical component, possibly brought on by leveling issues. Station B01 returned bad seismic channels. A few SPOBS stations also experienced excessive noise levels and/or issues with seismic components. All ENAM-CSE stations with known issues can be found in Table T1. We caution future users of the ENAM-CSE dataset when using data from any of the potentially problematic stations. Inherent to the deployment of OBS instruments is the lack of initial station orientation information. The broadband OBS stations have had their orientations calculated by Lynner and Bodmer (2017). Orientations for the SPOBS stations have not yet been calculated.

Initial Observations

A major part of the ENAM-CSE was outreach and inclusion of participants from the broader community. In addition to the extensive field participation described earlier, in May and June 2015, as part of the ENAM-CSE, week-long OBS and MCS processing workshops were held at University of Texas Institute for Geophysics and at the Lamont–Doherty Earth Observatory of Columbia University, respectively. The goal of these workshops was to introduce students and early career scientists to analysis of active-source seismic data. In the refraction workshop, participants learned to plot data, pick arrivals, build a starting model, carry out tomographic inversions, and analyze results. In the reflection workshop, each participant processed one of the reflection profiles from raw shot gathers to a time-migrated image.

Summary

The ENAM-CSE was derived from a community desire for a margin crossing amphibious dataset that could address science questions from the GeoPRISMS rift initiation and evolution initiative at a variety of scales. Timed to leverage the presence of TA stations along the east coast, 30 OBS and three coastal broadband stations were deployed for ~1 year, creating a continuous amphibious broadband seismic dataset that spans from the Appalachian Mountains to Atlantic seafloor. The short-period data acquisition was also amphibious with two lines of instruments deployed onshore simultaneously with offshore lines. Onshore short-period data collection was further bolstered by subsequent deployment of ~800 instruments and 11 onshore shots. Four lines of SPOBSs and ~4800 km of MCS data were collected offshore. This unprecedented geophysical dataset has already produced several studies than span scales and geophysical data types (e.g., Greene *et al.*, 2017; Lynner and Bodmer, 2017; Lynner and Porritt, 2017; Hill *et al.*, 2018) and will continue to support a wide scope of scientific analyses, ranging from the critical zone to Earth's deep interior.

Data and Resources

The data discussed in this article were collected as part of the eastern North American margin community seismic experiment (ENAM-CSE) and are publically available. The short-period and broadband ocean-bottom seismometer (OBS) data, along with data from the three coastal Outer Banks stations, are archived at the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC) under network code YO (Gaherty *et al.*, 2014). The IRIS-DMC also hosts the onshore short-period datasets under network ZI (Magnani and Lizarralde, 2014; Magnani, Van Avendonk, *et al.*, 2015) and the EarthScope Transportable Array (TA) data under network TA (IRIS Transportable Array, 2003). Metrics requested from Modular Utility for STAtistical kNowledge Gathering (MUSTANG), the IRIS data quality metrics service, were used and can be accessed at service.iris.edu/mustang. The multichannel seismic (MCS), bathymetry, gravity, and magnetic data are available through the Marine Geoscience Data System (MGDS) (Shillington *et al.*, 2014a,b). The OBS seismic refraction data are also available in SEGY format through the Interdisciplinary Earth Data Alliance (IEDA) in the form of field data with a cruise report (Van Avendonk *et al.*, 2014), and processed, relocated data (Van Avendonk *et al.*, 2015). Cruise reports for the R/V Endeavour and R/V Marcus G. Langseth can be found at http://ds.iris.edu/data/reports/YO_2014_2015/. Report for the onshore active-source deployment and shots can be found at http://ds.iris.edu/data/reports/ZI_2014_2014/. The supplemental material for this article includes a table of ENAM-CSE stations with known issues and figures showing station drifts, percent data return, and station noise characteristics.

Acknowledgments

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