Deep seafloor arrivals - An unexplained set of arrivals in long-range ocean acoustic propagation

Ralph A. Stephen[1], S. Thompson Bolmer[1], Matthew A. Dzieciuch[2], Peter F. Worcester[2], Rex K. Andrew[3], Linda J. Buck[3], James A. Mercer[3], John A. Colosi[4], Bruce M. Howe[5]

1 Woods Hole Oceanographic Institution, Woods Hole, MA 02543 2 Scripps Institution of Oceanography, UCSD, La Jolla, CA 92093 3 Univ. of Washington, Seattle, WA 98105 4 Naval Postgraduate School, Monterey, CA 93943 5 University of Hawaii at Manoa, Honolulu, HI 96822

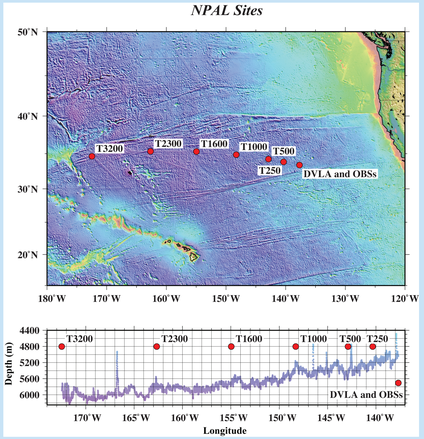

Figure 1: The locations of the sources and receivers discussed in this poster are shown on a map of the North Pacific with the satellite derived bathymetry (Smith and Sandwell, 1997). The geodetic lines from all of the transmission stations to the DVLA and South OBS coincide within 2km (Figure 2). The bathymetry along this geodetic line is shown as a function of longitude in the lower figure where the source and receiver longitudes are given as red dots. The bathymetry along this geodetic line is deeper than 4400m everywhere. Figure from Stephen et al (2009).

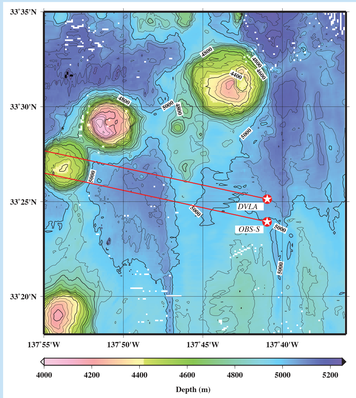

Figure 2: The swath-mapped bathymetry within about 10nm of the DVLA (Worcester, 2005) shows bottom features, as shallow as 4000m, that may contribute to the arrival structure discussed in this poster. The geodetic lines to the source locations are shown as red lines. The sources were positioned to lie on the same geodetic line to the DVLA. Propagation paths to the DVLA and OBS-S are coincident within 2km. Figure from Stephen et al (2009).

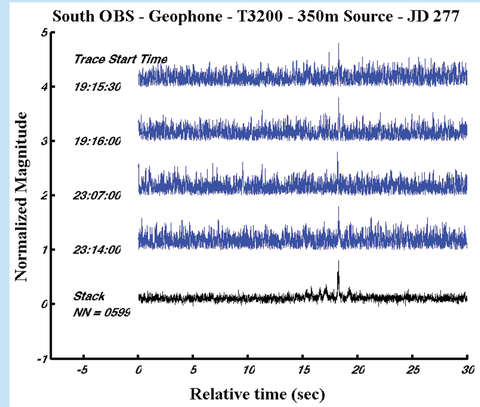

Figure 5: Four samples of unstacked traces (top) and the stack of 599 traces (bottom) are shown for propagation over 3200km range from the LOAPEX source at 350m depth as received on the vertical geophone channel of the "south" OBS at 4,973m depth. It is remarkable that transmissions are observed (at about 18sec) on single, unstacked traces in the deep shadow zone at this range. As shown in Figure 7 this arrival is an unexplained "late seafloor" arrival.

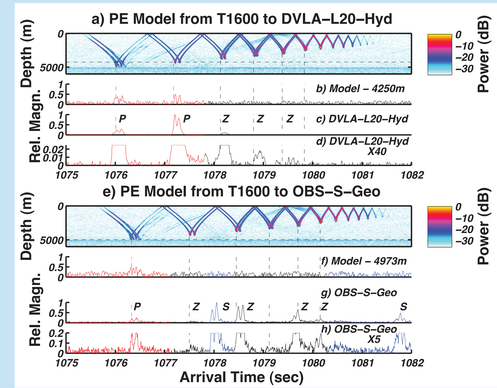

Figure 6: This figure compares the arrival structure on DVLA-L20-Hyd and OBS-S-Geo with PE (parabolic equation) model predictions for a range of 1600km. The PE models include bottom interaction. The top group of four panels (a-d) is the model-data comparison for DVLA-L20-Hyd and the bottom group (e-h) is for OBS-S-Geo. Within each group of four, the top panel is the time front diagram, the second panel is the model trace at the receiver depth (indicated by a horizontal dashed line in the time front diagram), the third panel is the data trace normalized to its maximum amplitude and the bottom trace is an expanded view of the data trace. Vertical dashed lines show the times of the turning points across all of the plots. Examples of the three arrival classes, "PE predicted" arrivals (P - red), "deep shadow zone" arrivals (Z - black) and "deep seafloor" arrivals (S - blue) are indicated. The deep seafloor arrivals are an unexplained set of arrivals.

The earliest arriving doublets in red, on both the DVLA hydrophone and OBS geophone, are "PE predicted" arrivals and correspond to the deepest and earliest arriving rays. The "deep shadow zone" arrivals in black are associated with leakage below shallower turning points. The late "deep seafllor arrivals" in blue do not correlate with shallower turning points. Since we do not see evidence for these late arrivals on the deepest hydrophone in the DVLA, we postulate that they are interface waves whose amplitude decays exponentially away from the seafloor. Figure from Stephen et al (2009).

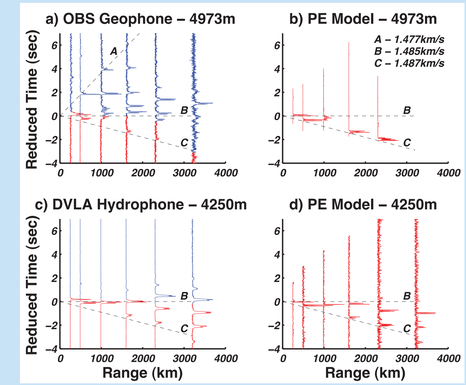

Figure 7: The stacked traces from the OBS vertical geophone on the seafloor (a) show many more arrivals than the deepest DVLA hydrophone (c) or the parabolic equation (PE) models (b and d). For the OBS geophone traces (a), events occurring with a sound speed faster than about 1.485km/s (roughly earlier than line B) are predicted by the PE but there are many "late arrivals". Dashed lines correspond to three relevant speeds: A- the apparent sound speed of the latest arrival at T500, T1000 and T1600, B - the apparent sound speed of the largest PE arrivals at the deepest hydrophone of the DVLA which seems to separate the known early arrivals from the late unknown arrivals and C - the apparent sound speed of the earliest arriving energy at the OBS and DVLA, which corresponds to the deepest turning energy (see Figure 6). The time axis has been reduced by subtracting the range divided by 1.485km/s. Figure from Stephen et al (2009).

Abstract: A thorough understanding of long-range sound propagation in the ocean is necessary both to optimally locate man-made and natural sources in the ocean as well as to infer ocean properties from acoustic measurements. In this poster we report the observation of unexplained arrivals observed on ocean bottom seismometers in a carefully executed controlled-source experiment in the North Pacific Ocean. We describe receptions, from a ship-suspended source (in the band 50-100Hz) to an ocean bottom seismometer (about 5000m depth) and the deepest element on a vertical hydrophone array (about 750m above the seafloor) that were acquired on the 2004 Long-range Ocean Acoustic Propagation Experiment in the North Pacific Ocean. The ranges varied from 50 to 3200 km. In addition to predicted ocean acoustic arrivals and deep shadow zone arrivals (leaking below turning points), "deep seafloor arrivals", that are dominant on the seafloor geophone but are absent or very weak on the hydrophone array, are observed. These "deep seafloor arrivals" are an unexplained set of arrivals in ocean acoustics possibly associated with seafloor interface waves.

Introduction: The Long-range Ocean Acoustic Propagation Experiment (LOAPEX), which was one component of the North Pacific Acoustic Laboratory 2004 (NPAL04) field program (Mercer et al., 2005; Mercer et al., 2009; Worcester, 2005), was carried out between 10 September and 10 October 2004. An acoustic source was suspended at depths of 350m, 500m or 800m and at ranges from 50km to 3200km from a receiver site consisting of shallow and deep vertical line arrays (SVLA and DVLA, respectively) and four ocean bottom seismometer/ hydrophones (OBS/H). Different types of acoustic signals, of about 30sec duration and in the band from 50 to 100Hz, were transmitted repeatedly from the source. Pulse-like arrivals with improved resolution and signal-to-noise ratio (SNR) were obtained by replica correlation. The SNR could be further improved by incoherent stacking (simply adding) the magnitude of the replica-correlated traces. Since we observed that individual arrivals on the unstacked traces could vary substantially in waveform and amplitude over periods as small as five minutes, due to ocean sound speed fluctuations such as internal waves and spice, only the most robust arrivals would survive the stacking process with good SNR. In this poster we present a preliminary comparison of the vertical geophone data from one OBS/H with single hydrophone data from the DVLA.

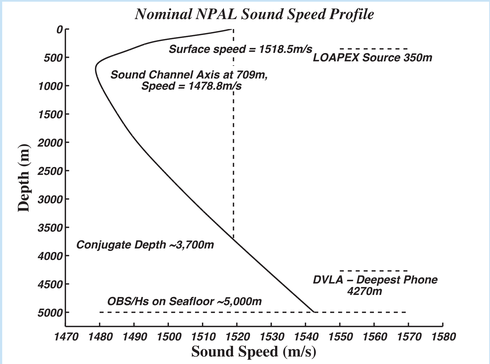

Figure 3: A typical sound speed profile for the NPAL04 experiment showing the conjugate depth and depths of the sources and receivers used in this poster. The OBS/Hs on the seafloor are in the "deep shadow zone" many acoustic wavelengths (about 20m) below the bottom of the sound channel defined by the conjugate depth. For background information on long range sound propagation in the ocean see Ewing and Worzel (1948), Clay and Medwin (1977), Jensen et al (1994), or Munk et al. (1995). Since the bathymetry everywhere along the propagation path (Figures 1 and 2) is much deeper than the conjugate depth, one would expect bottom interaction to be negligible in this experiment and one would expect that very little energy would be observed on the OBS on the seafloor.

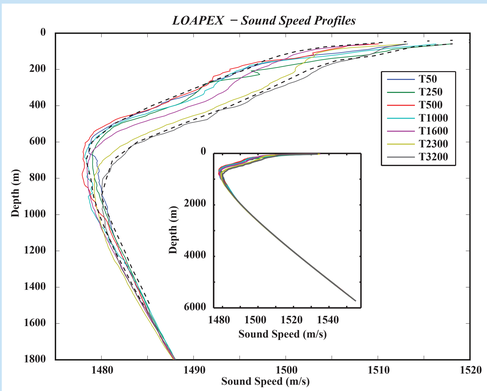

Figure 4: The sound speed profiles that were acquired at each source location during the experiment (see Figure 1) are shown as colored solid lines (Mercer et al., 2005). The maximum and minimum sound speeds as a function of depth from the World Ocean Atlas (Antonov et al., 2006; Locarnini et al., 2006), that were used for the Parabolic Equation (PE) modeling, are shown as black, dotted lines. The profiles overlap below about 1400m. Figure from Stephen et al (2009).

SUMMARY AND CONCLUSIONS

Receptions of stacked, replica-correlated traces on a single OBS geophone on the seafloor are compared with a hydrophone moored about 750m above the seafloor. The OBS geophone generally has more arrivals than the moored hydrophone. Two types of arrivals on the OBS geophone are observed that are not explained by PE modeling using simple sound speed profiles. The "deep shadow zone" arrivals occur at the time of shallower turning points (Dushaw et al., 1999; Van Uffelen et al., 2009), are consistent with decay from shallower turning points, are also observed on the DVLA hydrophones, and their arrival time is predicted by PE propagation models. The "deep seafloor" arrivals, on the other hand, occur later than the first PE arrival, are not readily observed on the DVLA hydrophones and their arrival time is not predicted by PE propagation models. There are even strong arrivals after the PE predicted finale region. Deep seafloor arrivals are among the largest events observed at the seafloor. This is an unexplained set of arrivals in long-range ocean acoustic propagation.

Deep seafloor arrivals appear to be an interface wave whose amplitude decays upward into the water column. The interface wave could be a shear-related mode coupled to the sound channel propagation (Butler, 2006; Butler and Lomnitz, 2002; Park et al., 2001) or it could be excited by secondary scattering from bottom features (Chapman and Marrett, 2006; Dougherty and Stephen, 1988; Schreiner and Dorman, 1990). These unexplained arrivals could conceivably be horizontal multi-path from some persistent ocean thermal structure (de Groot-Hedlin et al., 2009, for example), but it would be necessary to explain why they are observed on the seafloor OBS but not on the DVLA only 2km away.

ACKNOWLEDGMENTS

The idea to deploy OBSs on the 2004 NPAL experiment was conceived at a workshop held at Woods Hole in March 2004 (Odom and Stephen, 2004). The LOAPEX source deployments, the moored DVLA receiver deployments and some post-cruise data reduction and analysis were funded by the Office of Naval Research under Award Numbers N00014-1403-1-0181, N00014-03-1-0182 and N00014-06-1-0222. Additional post-cruise analysis support was provided to RAS through the Edward W. and Betty J. Scripps Chair for Excellence in Oceanography. The OBS/Hs used in the experiment were provided by Scripps Institution of Oceanography under the U.S. National Ocean Bottom Seismic Instrumentation Pool (SIO-OBSIP - http://www.obsip.org). To cover the costs of the OBS/H deployments funds were paid to SIO-OBSIP from the National Science Foundation and from the Woods Hole Oceanographic Institution Deep Ocean Exploration Institute. The OBS/H data are archived at the IRIS (Incorporated Research Institutions for Seismology) Data Management Center.

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