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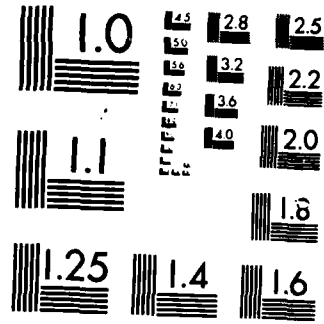
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A SYNOPSIS OF RESEARCH ON SUBBOTTOM EFFECTS  
ON UNDERWATER ACOUSTIC PROPAGATION  
FINAL REPORT UNDER CONTRACT N00014-82-K-0679

Robert A. Koch  
Jo B. Lindberg  
Paul J. Vidmar

APPLIED RESEARCH LABORATORIES  
THE UNIVERSITY OF TEXAS AT AUSTIN  
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14 November 1985

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Prepared for:

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| <p>This report summarizes research carried out at Applied Research Laboratories, The University of Texas at Austin (ARL:UT), under Contract N00014-82-K-0679, 1 June 1982 - 30 September 1984. Our purpose was to investigate some effects of the subbottom on underwater acoustic propagation. Our major accomplishment was solving the problem of ordering and counting the normal modes of propagation in the ocean waveguide when the seafloor is described by an impedance boundary condition. The boundary condition, derived from the plane wave</p> |                       |                                                                |

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reflection coefficient, introduces mathematical complexities since it is a function of the separation parameter in the acoustic wave equation. As a natural extension of our theoretical approach, the relationship between mode concepts of normalization and cycle distance, and geometrical ray concepts of beam displacement and time delay were rigorously established. Additional work was also done to examine ray and normal mode approaches for predicting propagation in a sloping geometry. *Kay and his field*

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## I. INTRODUCTION

This report summarizes research on subbottom effects on underwater acoustic propagation carried out at Applied Research Laboratories, The University of Texas at Austin (ARL:UT), under Contract N00014-82-K-0679. Our main goal was to extend the theory of normal modes to accurately treat the effects of shear wave propagation in the seafloor. This would provide the framework for determining the importance of shear wave processes in shallow water areas and areas having thin sediment cover. Methods for determining the major propagation paths in a sloping geometry were also investigated.

The major accomplishment of our research was developing a procedure for rigorously ordering and counting normal modes<sup>1</sup> (the mode identification problem) when the seafloor is represented by an impedance boundary condition. A natural extension of the theoretical methods used to solve the mode identification problem led to establishing the relationship between the mode concepts of *normalization and cycle distance* and the geometrical ray concepts of *beam displacement and time delay*.<sup>2</sup>

As part of our research, we developed a normal mode computational model that uses the mode identification procedure to assign mode numbers and verify that the mode set is complete, i.e., that no modes have been skipped. The impedance boundary condition is calculated from the plane wave reflection coefficient of the seafloor. The model is very flexible since it can be used with any subbottom description (layered viscoelastic, Biot, etc.) for which the plane wave reflection coefficient can be calculated. The computational model has already been used to examine the role of shear wave processes in propagation to hydrophones and geophones at the seafloor and in the substrate.<sup>3,4</sup>

This report is organized as follows. Section II reviews the development of the impedance boundary condition normal mode approach. Section III discusses our research on propagation over slopes. Appendix A lists documentation produced under this contract.

## II. A NORMAL MODE APPROACH USING AN IMPEDANCE BOUNDARY CONDITION

Traditional normal mode approaches are restricted in their ability to realistically treat the effects of shear waves. For example, normal mode calculations used to examine the optimum frequency of propagation in shallow water<sup>5</sup> included shear wave effects only as a correction to the mode attenuation coefficients. This approach is based on the rather oversimplified view that shear waves are generated at the water-sediment interface and are completely absorbed in the seafloor, when in fact the amount of energy coupled into shear waves at the water-sediment interface is negligible for unconsolidated marine sediments.<sup>6</sup> The unrealistically large shear wave velocities (600 m/s versus measured<sup>7</sup> values of 150 m/s) needed to successfully model acoustic data emphasizes the fact that shear wave processes are not being accurately treated. Normal mode approaches that include energy propagating as shear waves (rather than being completely absorbed) are needed to investigate low frequency propagation in areas having thin sediment cover where shear wave propagation in the basalt may be an important process.<sup>8</sup>

Including shear wave propagation in a layered, depth dependent seafloor greatly complicates the theoretical problem of defining and counting the normal modes. The mode functions themselves have both shear and compressional components in the seafloor. The usual procedure for ordering modes in a fluid, based on counting the zero crossings of the mode function, also breaks down since zero crossings can occur in both shear and compressional components.

The approach we took is based on representing the seafloor as an impedance boundary condition.<sup>9</sup> This approach has the advantage of breaking the normal mode problem into two parts: (1) calculating the boundary condition as a function of the separation constant in the wave equation (the horizontal wavenumber), and (2) finding the mode functions and eigenvalues for the impedance boundary condition. The impedance boundary condition is easily calculated from the plane wave reflection coefficient of the seafloor. Note that this approach can be used with any description of the seafloor for

which the reflection coefficient can be calculated, i.e., Biot, viscoelastic, layered solid, and combinations of fluid and solid layers. Once this boundary condition is established, the calculation of the mode functions and eigenvalues is easily carried out using conventional numerical methods.

We developed a method<sup>1</sup> for rigorously ordering and counting modes when an impedance boundary condition is used to describe the seafloor. The ability to accurately count modes is important for determining whether a numerical calculation has produced a complete set of modes or has skipped one or more. The usual procedure of identifying the mode with the number of zero crossings in the mode function will not work for the impedance boundary condition because there is no information about the mode function below the water-sediment interface. The basic idea of our procedure is to decompose the mode function in the water column into a magnitude and a phase. The phase is made up of two parts; one depends only on the impedance boundary condition and the other, only on the depth dependence of the mode function in the water column. The boundary contribution to the total phase is related to the phase of the complex valued reflection coefficient of the seafloor. The pressure release boundary at the sea surface causes the total phase to increment by  $2\pi$  from mode to mode. Modes are counted and ordered by the number of phase increments.

We also developed and tested prototype software for a normal mode computational model implementing the impedance boundary condition description of the seafloor. The impedance boundary condition is evaluated from the plane wave reflection coefficient, which is supplied either as a subroutine or as a table of values. The model makes the usual assumption that the mode attenuation coefficients (the imaginary part of the complex eigenvalue) are small enough to be a small correction to the eigenvalue. The model first uses the boundary condition at the seafloor calculated without attenuation to produce an ordered set of normalized mode functions, modal phase velocities, and modal group velocities. Mode functions in the seafloor are obtained in our model as part of the calculation of the reflection coefficient at the eigenvalues. Once the mode functions are known, the

mode attenuation coefficients are evaluated as a perturbation correction based on the boundary condition calculated for a seafloor with attenuation.

Our theoretical approach also led to a clarification of the relationship between normal mode and geometrical ray descriptions of propagation.<sup>2</sup> Previous research<sup>10</sup> used the WKB approximation for the mode functions to estimate derivatives with respect to mode number by taking differences between quantities for neighboring modes. Our analysis resulted in a more accurate assessment of the analogy between rays and modes by allowing direct computation of derivatives with respect to mode number.

A second approach for including shear wave effects in a computational normal mode model was also examined. We reviewed several techniques<sup>11-13</sup> for directly integrating the equations of motion for a depth dependent, solid subbottom. These approaches were found to be equivalent to calculating the plane wave reflection coefficient of the seafloor, and therefore were not pursued.

Additional work was done to aid the design of a laboratory experiment (supported by ONR Code 425UA) to investigate propagation over a sloping bottom. The experiment, to be conducted by ARL:UT in 1985, will involve propagating a single mode up and down a slope. The acoustic field will be measured as a function of depth and range and compared to the predictions of adiabatic mode theory and coupled mode theory. We calculated normal mode functions for a sequence of water depths which will be used in designing the experiment and interpreting data.

### III. PROPAGATION IN A SLOPING GEOMETRY

There are indications that the transition from deep to shallow water is a geometry favorable to low frequency propagation within the ocean bottom. Model experiments<sup>14</sup> show that significant waterborne energy can couple into the subbottom along slopes. There is also evidence<sup>15</sup> that the ambient noise level near 15 Hz is very low both on and below the seafloor. These observations combine to suggest that sensors in shallow water can detect low frequency energy from sources in deep water.

In 1981 ARLUT carried out a preliminary analysis<sup>16</sup> of data collected by Western Electric Company (now AT&T Technology Systems) off the coast of Nova Scotia. Figure 1 shows the exercise area and source track. Explosive source data were collected on a series of hydrophones placed along the slope, as shown in Fig. 2. The geoacoustic description of the exercise area given in Fig. 3 was developed from archived geological data. The analysis concentrated on identifying candidate bottom penetrating arrivals in the data shown in Fig. 4. These data were collected on hydrophone 4 (shown in Fig. 2) and were produced by a 1.1 oz explosive charge detonated at a depth of 18 m at a range of 243 km downslope from hydrophone 4. A candidate bottom penetrating arrival (labeled S in Fig. 4) was identified from an analysis of the time series in frequency bands from 10 to 1000 Hz. Arrival S had energy concentrated near 35 Hz and almost no energy above 100 Hz. This lack of high frequency energy is consistent with attenuation of the higher frequencies along a path through the subbottom. In contrast, arrival W had significant energy at frequencies up to 1000 Hz and was identified as an arrival that did not propagate through the subbottom.

Research carried out under the present contract focused on modeling propagation along paths through the sediment for the environment of Fig. 3, with the goal of clearly identifying subbottom penetrating arrivals in the experimental data of Fig. 4. We used two modeling approaches. The first was a ray path analysis for which the ARLUT range variable ray trace model (MEDUSA)<sup>17</sup> was modified to include ray paths traveling through the subbottom. The second was a normal mode analysis that used the ARLUT

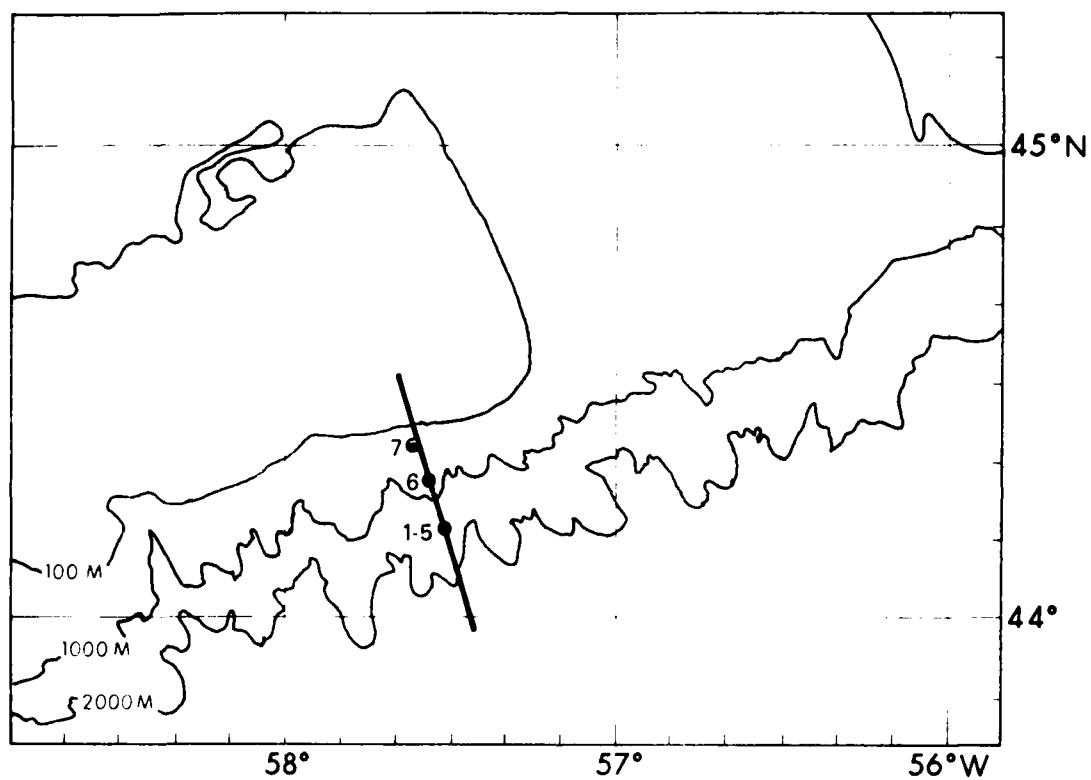


FIGURE 1  
EXERCISE AREA

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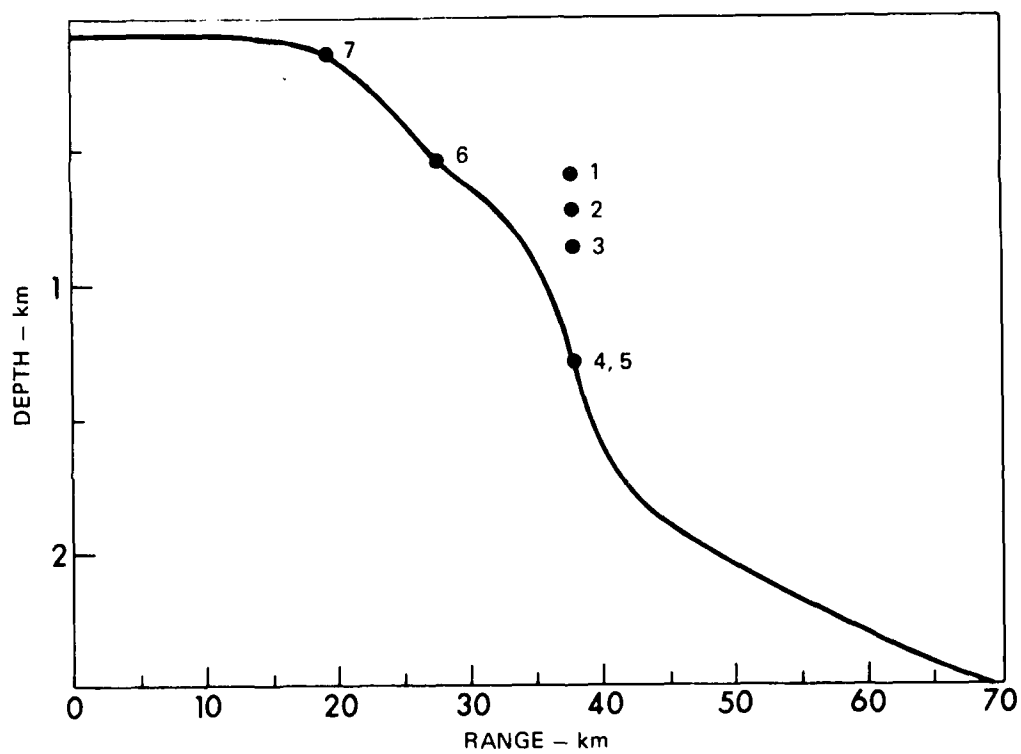
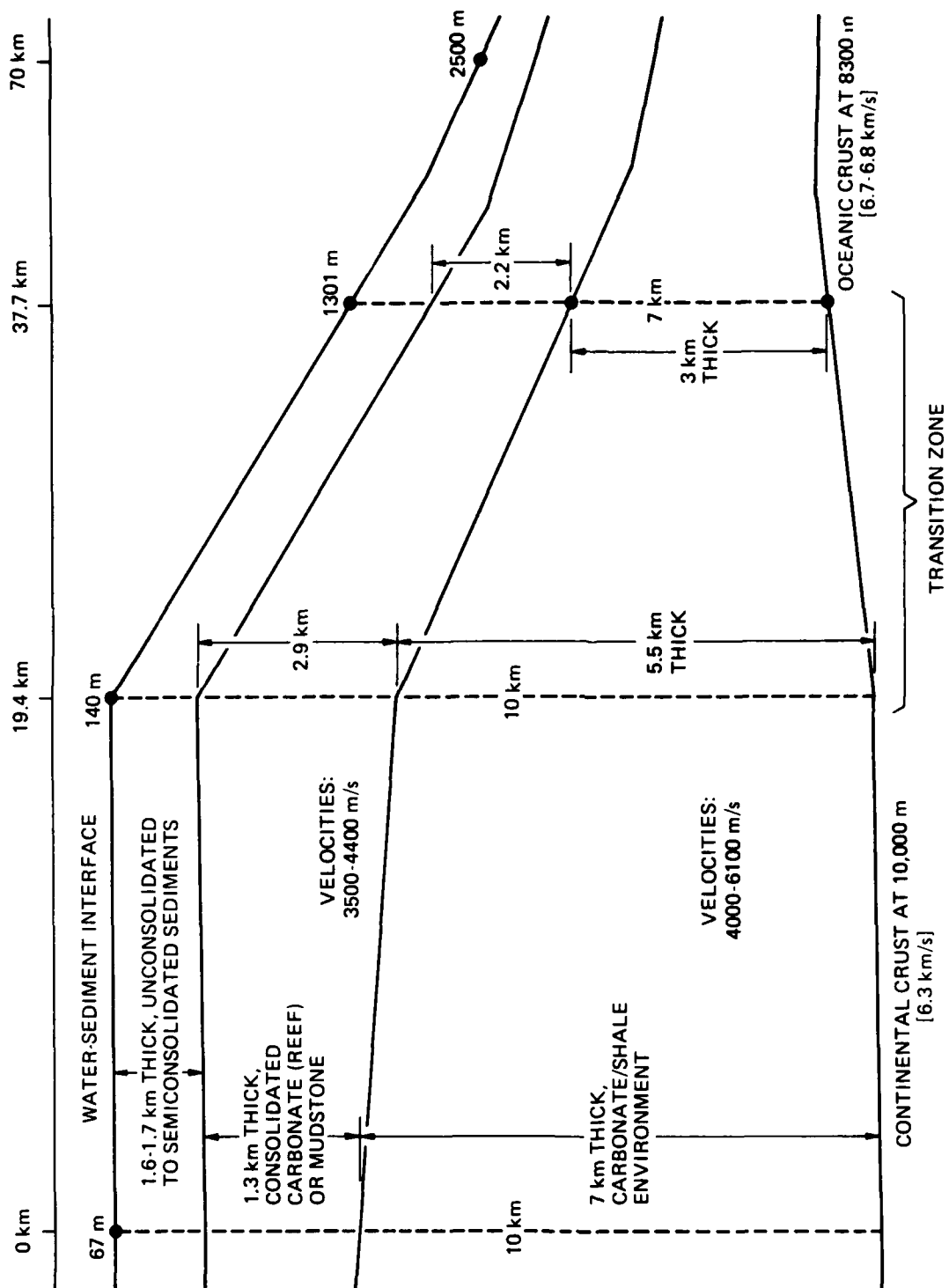


FIGURE 2  
BATHYMETRY AND HYDROPHONE LOCATIONS ALONG THE SOURCE TRACK

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**FIGURE 3**  
**GEOLOGICAL STRUCTURE OF THE EXERCISE AREA**

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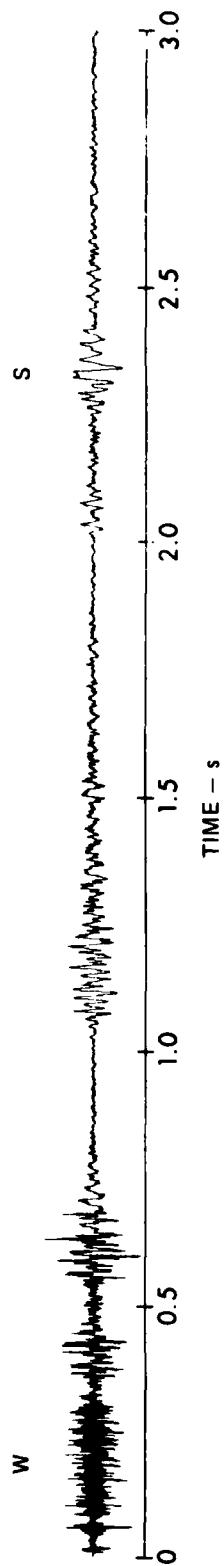


FIGURE 4  
RECEIVED TIME SERIES

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adiabatic normal mode model (ADIAB) to calculate the travel time of modes from their group velocities.

For the range variable ray trace analysis, the water column was constructed from the measured bathymetry and sound speed profiles. Published relationships between sediment type and geoacoustic parameters<sup>7</sup> were used to develop a geoacoustic profile for the geological structure of Fig. 2. The profile had three sloping layers, each having a different dependence of compressional velocity on depth. Velocity ratios across the water-sediment interface and across interfaces between sediment layers were assumed to be constant in range.

The ray analysis showed that sediment penetrating compressional waves alone could not predict the observed arrival structure. There were no strong eigenrays corresponding to the second and third arrivals in the first 0.7 s of Fig. 4. Some deep penetrating paths with arrivals in this interval were found, but they were too heavily attenuated to carry significant energy. Eigenrays with one, two, and three shallow penetrations into the subbottom (300 m or less) had differences in travel time of about 1 s and could not explain the arrivals with time separations of 0.3 and 0.5 s seen in the data. Of particular concern were the lack of an eigenray corresponding to arrival S in Fig. 4 (the suspected sediment penetrating arrival) and the existence of an energetic eigenray at about 0.75 s, a time at which there is no signal in the data.

Sensitivity studies were carried out to determine whether errors in the geoacoustic description of the area could explain the lack of agreement between eigenray arrival times and the data. The thickness and compressional velocity gradient of each layer and the velocity ratio across each interface were varied. Reasonable variations of these parameters did not have a major effect on the eigenray structure. Thus, our conclusion is that propagation mechanisms (e.g., shear waves, interface waves, head waves, etc.) that were not included in our ray analysis are important for this environment.

To determine whether propagation at low frequencies in this environment had a modal character, we used the ARL-UT adiabatic normal mode model to calculate travel times of the modes for comparison with the data. For our adiabatic normal mode analysis, we approximated the range dependent environment of Fig. 3 with a sequence of horizontally stratified range intervals. The discrete normal mode spectrum at 35 Hz was calculated for each of these intervals. The travel time of each mode was then evaluated from the range dependence of the group velocity.

About half of the 60 modes existing at the receiver had arrival times within the 2.5 s extent of the data--far too many modes for the arrivals in the data to be individual modes. Because calculation of the constructive interference of several modes over the frequency band of the data was beyond the scope of the cw adiabatic model, it was not possible to make a definitive comparison with Fig. 4. However, the analysis did show that there are modes at 35 Hz with travel times consistent with arrival S in Fig. 4. The identification of these modes with arrival S is strengthened by the observation that their propagation loss is close to that obtained in Ref. 17 for arrival S in the 35 Hz band. These modes penetrate 200-400 m into the sediment. There are also nine modes with arrival times between 0.3 and 0.7 s that could make up the second and third arrivals in the first 0.7 s of data. These modes are mostly waterborne, but do penetrate shallowly (50-100 m) into the sediment near the receiver.

While the normal mode analysis was successful in predicting mode travel times that are consistent with the overall duration of the data, further research is needed to understand the time series of Fig. 4. The adiabatic approach treats the range variability of the environment, but does not include effects due to the broadband nature of the signal. The interference between modes at different frequencies could be a major factor in producing the time dependence and magnitude seen in the data. If this is true, further progress in the adiabatic analysis would require a more sophisticated computational model capable of simulating broadband time series.

APPENDIX A  
DOCUMENTATION

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| 36 | J. Lynch                                  |
|    | Hawaii Institute of Geophysics            |
|    | The University of Hawaii                  |
|    | 2525 Correa Road                          |
|    | Honolulu, HI 96822                        |
| 37 | Attn: L. N. Frazer                        |
|    | The Scripps Institution of Oceanography   |
|    | The University of California/San Diego    |
|    | San Diego, CA 92151                       |
| 38 | Attn: F. Fisher                           |
|    | Department of Geological Oceanography     |
|    | Texas A&M University                      |
|    | College Station, TX 77840                 |
| 39 | Attn: W. R. Bryant                        |
|    | The Catholic University of America        |
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|    | Washington, D.C. 20017                    |
| 40 | Attn: H. M. Uberall                       |
|    | Lamont-Doherty Geological Observatory     |
|    | Palisades, NY 10964                       |
| 41 | Attn: G. Bryan                            |
| 42 | R. D. Stoll                               |
|    | Department of Civil and Ocean Engineering |
|    | The University of Rhode Island            |
|    | Kingston, RI 02881                        |
| 43 | Attn: A. J. Silva                         |
|    | University College of North Wales         |
|    | Marine Science Laboratories               |
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|    | Anglesey, LL59 5EY, U.K.                  |
| 44 | Attn: D. Taylor Smith                     |
|    | Western Electric Company                  |
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|    | P.O. Box 30                             |
|    | State College, PA 16801                 |
|    | Attn: S. McDaniel                       |
|    | D. McCammon                             |
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| 50 | Department of Geology                   |
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