A Towed Seafloor Source for Seismic Exploration

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***Abstract*- We have a new design for a pneumatically-activated, deep-towed seismic source that can be operated at or near the seafloor. This design overcomes some of the limitations of the seafloor imploder we developed three years ago. Our present working version - a 20-liter, 220dB (re 1uPa @ 1m) imploder - is robust and creates repeatable signals that excite shear waves. However, it is necessary to bring it up on deck and reseal it between shots. Our new design solves the long repeat interval problem while allowing for much more control on the signal bandwidth and amplitude.**

New petroleum and methane-hydrate deposits are being found in deep water at previously unexplored sites. To fully exploit these deep-sea resources, new tools and methods for imaging will be required. One such improvement needed is an active, seismic seafloor source. For deep-water seismic exploration, seafloor signal generation has several advantages over surface generation. The principal advantage is that seafloor sources directly excite shear waves. This allows differentiation of structures by shear velocity, adding another dimension to subsurface visualization, and is particularly useful in regions of unconsolidated sediments and gas. In addition, energy is focused a kilometer or more (depending on the water depth) closer to the zone of exploration with bottom sources, allowing better feature resolution. A secondary advantage is that an equivalent sea-floor source will have less effect on marine mammals, who, depending on their species spend all or a majority of their time near the sea surface - far removed from a working bottom source.

A useful seismic sea-floor source will require the following characteristics: it produces signals of the desired bandwidth and amplitude for seismic prospecting, it is robust, the source signature is repeatable, firing time is controllable, and it can be fired repeatedly on the order of one or two minutes. We have made substantial progress in developing a seismic bottom source that meets these requirements.

I. INTRODUCTION

Active seismic work at sea has been scientifically and economically fruitful in advancing our understanding of sub-sea structure and locating new oil and gas reserves. Source type has evolved from the use of explosives during WWII [1] to the use of high-voltage sparkers and gas-ignited sleeve-guns through to the present use of compressed air to power air- and water-guns [2]. The vast majority of these sources have been fired near the sea surface, mainly because of the added effort required to produce a signal on the seafloor. To make an equivalent source safer for animals at the surface, to generate shear-waves, and to do more detailed refraction experiments, however it is desirable for the source to be on or near the seafloor ([3] – [13]). Accurately timed and navigated seafloor shots have been used in our lab for a number of years in refraction experiments to image sub-bottom structure [11], [12], and in Scholte wave studies of the upper few tens of meters of sediment [5], and [13] – [18]. The explosive energy sources for these studies have become increasingly difficult to use because of regulation and safety issues. This motivated us to develop our non-explosive seafloor source.

With funding from NSF (Ocean Technology), we developed an explosive-free seismic source that can be used on the seafloor. This has the advantage of concentrating seismic energy at lower frequencies than explosives, and eliminating most of the safety and regulatory concerns. It can replace small explosives in usages such as generating Scholte (sea-floor interface) waves. Advantages of having the source directly on the bottom include shrinking the footprint area of ray entry and the enhanced excitation of shear waves in comparison with a source higher up in the water column.

The next step in our imploder's development is to make it capable of being refired on or near the seafloor without having to haul it to the surface between shots, as presently required. Our new design calls for a compressed air powered, larger-volume version for increasing its output-energy level. Its design parameters can be modeled to concentrate its output energy into the seismic frequency band of interest (1 to 200 Hz). Our goal is to make a source effective for refraction studies while minimizing the harm to the marine ecosystem. Among other considerations, this requires it being able to refire within one to two minutes. Its is clear that its ability to directly generate shear waves will benefit many seismic studies. These include imaging methane-hydrate structures and hydrothermal systems and the determination of the shear-velocity structure around Ocean-Seismic Network Observatories.

II. SCIENTIFIC RATIONALE

Why do we think it is worthwhile to design a new marine seismic source? Aren't airguns sufficient? Their main drawback is that they fire at the surface - separated from their sub-sea target area by an intervening water layer hundreds to thousands of meters thick. The energy released at the surface spreads out as acoustical waves, devoid of shear energy, since shear waves cannot propagate through a fluid. Land sources have evolved from explosives to controllable electromechanical devices (e.g. Vibroseis) in response to safety issues, the proximity to urban areas, and imaging advantages. So too, marine sources have evolved from explosives to airguns, which are non-explosive, impulsive sources with limited control over the source waveform. Marine source evolution has not reached a culmination point yet, not with most-commonly used sources firing far above the seafloor.

Airgun arrays fire loud enough to raise issues about possible harm to marine mammals, who all spend the majority of their time near the surface. Recent news items have featured marine seismic exploration in a less-than-perfect light because of association with the beaching of whales. In the November, 2002 Gulf of California incident [19], two Cuvier's beaked whales (Ziphius cavirostris) were found beached during a seismic survey. Although it is arguable whether the R/V Maurice Ewing's airguns caused these whale deaths, the US District for Northern California found sufficient probable cause to issue a court order stopping the survey. The marine Mammal Protection Act established allowable sound-level generation values. The limits, however, are neither frequency dependent, nor species specific. More experimentation and observation needs to be done in this area. The Bahamas stranding event of 2000 [20] consisted of 17 cetaceans, including 2 species of beaked whales. Six of the whales died. The stranding is attributed to tactical naval sonars operated by several nearby naval vessels. These operate at frequencies centered at 2.6, 3.3, 6.8, and 8.2 KHz - frequencies much higher than are recorded and used in reflection and refraction seismic surveys. These incidents, and others, should prompt us to look at our marine sources in the light of environmental considerations.

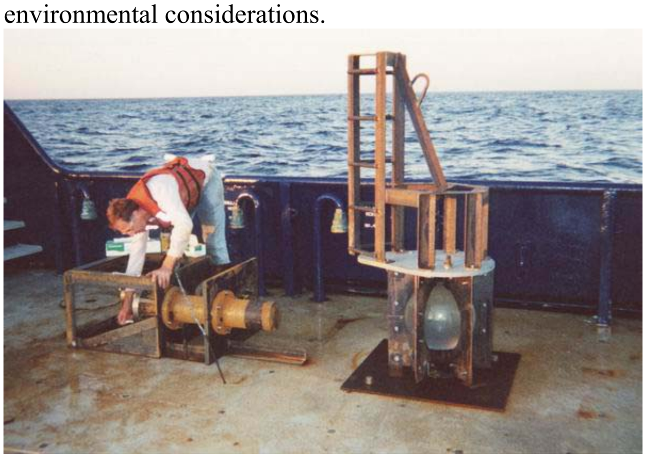

Fig. 1. Cylindrical and spherical imploder configurations

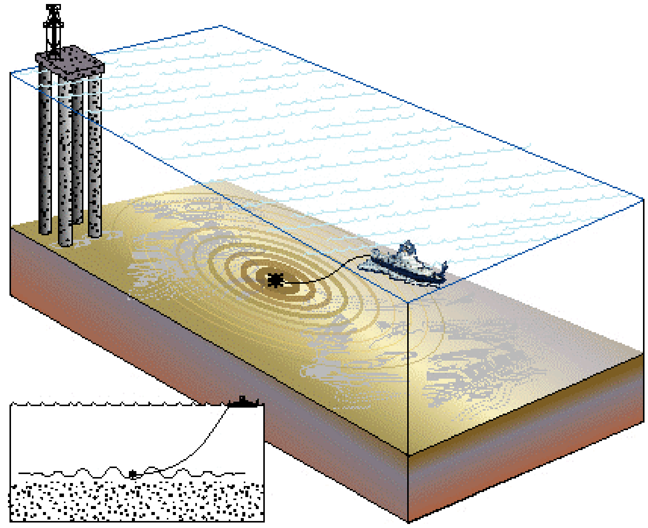

Fig. 2. Generating Scholte waves on the seafloor with a seafloor source.

It is desirable to bandlimit the output so that the majority of energy released is below 250Hz. As we increase the distance between the source and the surface, we lessen its effect on marine mammals because sound intensity decreases with distance from the source.

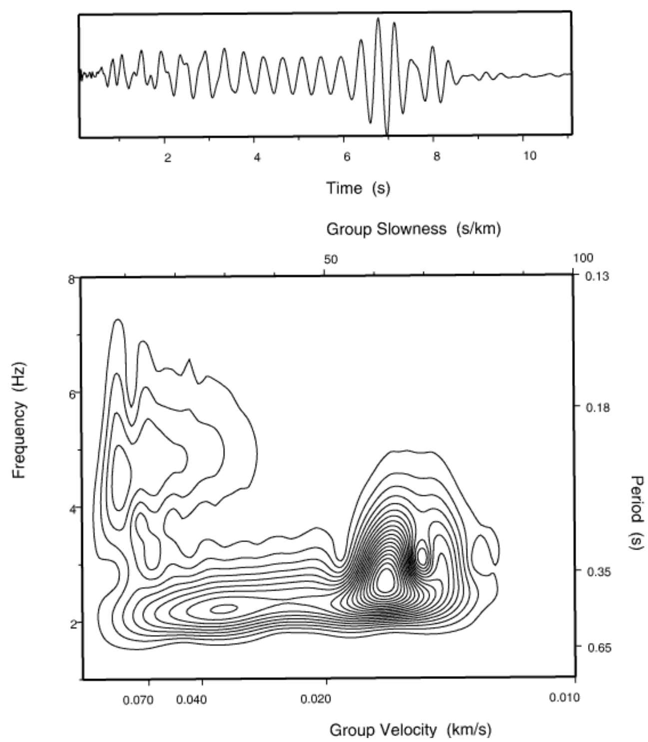

Fig. 3. Scholte interface wave generated by cylindrical imploder in the San Diego Trough – February 2001

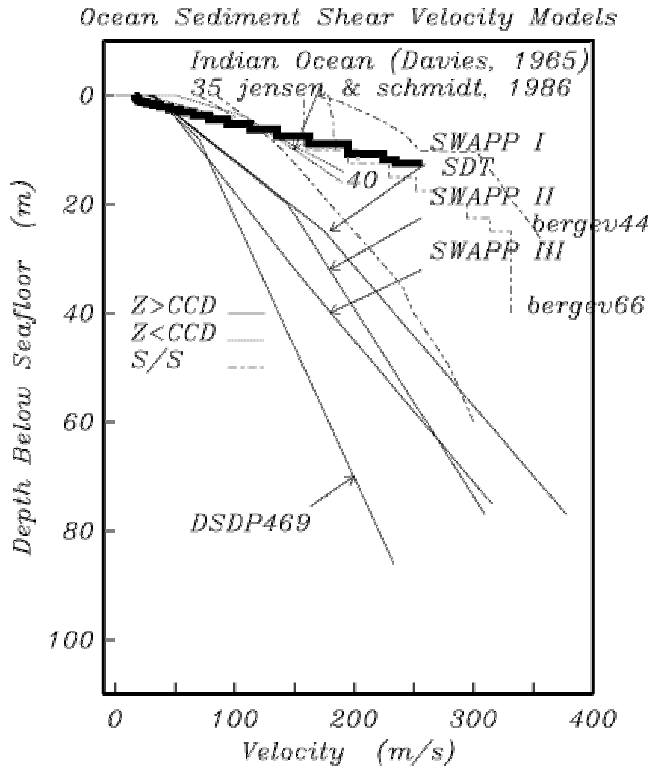

Fig. 4. Compilation of shear velocity determinations from in situ measurements – CCD – Calcium Carbonate Compensation depth, below which the rate of CaCO3 solution exceeds deposition, S/S – Shallow water silts and sands. The darkest line is the model that best fits the data in Fig. 3.

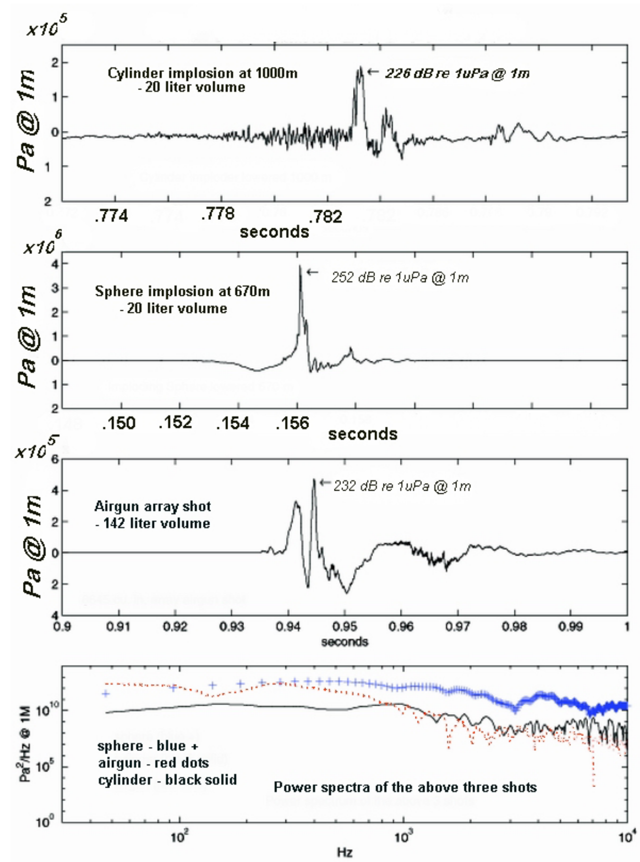

Fig. 5. Comparison of airgun array and implosions measured in October 2000 off the R.V. Ewing in deep water.

What then, do we need from a source? A useful marine seismic source will have the following characteristics: able to produce signals of the desired bandwidth and amplitude for seismic prospecting; robust, source-signature repeatable, firing-time controllable, and able to be fired repeatedly on the order of one or two minutes; it should not produce much high-frequency energy outside the frequency range of seismic interest. We have made substantial progress in designing a seismic deep-towed bottom source that meets these requirements.

II. PREVIOUS WORK

Much of what we have learned with our present imploder can be applied to this project. To date, our imploder (shown in both its cylindrical form and its spherical form at right in Fig. 1) has demonstrated that it generates shear waves on the seafloor (Figs. 2 and 3) and we have used that information to invert for sediment velocities (Figs. 3 & 4). This is useful for engineering and gas-producing (methane hydrate) site studies.

In October 2001 on the R.V. Ewing we recorded the source signals from several sources: our cylindrical imploder, imploding 43-cm glass spheres, and a 20-gun airgun array using a hydrophone of known calibration (-194dB re 1uPa@ 1m) lowered a few meters into the water. Fig. 5 shows the time series and spectra for representative shots. For a given source, shot signals from different firings were very similar; shot signals from different sources differed, as can be seen in the three upper time series. The top trace is a recording of our cylindrical pressure gun imploding at 1000 meters depth. Infilling of the main cylinder begins around .778 seconds. We suspect that the inflow is turbulent because of the high-frequency nature of the signal between .778 and .783 seconds. This is caused by the constriction at the cylinder's collar. The peak pressure of 226 dB re 1uPa @ 1m is generated when the cylinder finishes filling and the water suddenly deaccelerates. In comparison, a relatively clean implosive signal is recorded in the next plot down, generated by the breaking glass sphere. From .154 to .156 seconds, water rushes into the broken sphere's center, creating a negative pressure field that propagates outward. Then shortly after .156 seconds, the water and broken glass meet in the center and motion comes to an abrupt halt creating a large deacceleration peak of 252 dB re 1uPa @ 1m. The third plot down shows the pressure time series of a shot from the

20-gun airgun array. The 232 dB peak compares well with published values [21].

Power spectra for the 3 shots are shown in the bottom plot of Fig. 5. We recorded the hydrophone on a TEAC RD145T DAT recorder sampling at 48K samples per second, thus the high frequency component of the signals was preserved. The airgun spectrum begins dropping off shortly after 200 Hz, sooner than the breaking sphere or cylinder. The drop-off is facilitated by the array, since each gun's bubble oscillates at a different frequency, canceling much of the energy following the initial burst. The two implosion spectra exhibit high-frequency energy not because of bubble oscillations, but because of the sudden deacceleration of water at the end of the process. In the next section we will outline an approach that could lessen this effect and boost the low frequency output at the same time. One puzzling aspect of the sphere and cylinder spectra is that by theory [18] we expect the lowest frequency power levels of the two to be the same, since the same volume of water was displaced in each case. However, the breaking sphere produces more low-frequency energy by something like a factor of 100. We suspect that the cylinder implosion did not convert the turbulent flow into a radiating pressure signal as effectively as did the more laminar spherical flow. The main point is that our cylinder flow geometry was not optimized for producing a seismic signal. We will address this with our new design.

III. A NEW SEAFLOOR SOURCE

The seafloor is an extremely harsh environment. It is corrosive and the high pressure readily deforms precision parts out of tolerance, very much complicating mechanical tasks. So it is not surprising that a non-explosive, towable seafloor source has not yet been developed, though its utility is widely appreciated. Since air at pressure higher than 13.8MPa (2000 PSI) is not normally supplied on UNOLS ships, it makes sense to design the first air-powered repeatable seafloor imploder to operate at 13.8MPa. Though this limits its operating depth to 1300 meters or shallower, there are many interesting areas that it can be used to explore, including much of the Gulf of Mexico and several hydrothermal sites.

We will describe the source system from top down. Many ships already have compressors for airgun operations, and nothing more will be said about them here, other than that the R.V. Ewing compressors can supply air at a rate sufficient to fill our target volume of 200 liters in less than a minute. The major investment required, apart from the imploder, is 2000 meters of high-pressure hose. Parker Polyflex makes armored hose with large inner diameters that can easily contain the working pressure. Given an inner diameter of 1.27 cm, and a usual mean velocity in the hose of 10 m/s [23], the hose will be able to deliver 5 liters/s to the imploder. With a 2.54 cm inner diameter, delivery will be 20 liters/s. This rate is adequate for an array of seafloor imploders. The hose will be towed in tandem with an armored cable that will support the weight of the imploder and supply it with electrical control. A skid cage will surround the imploder, ensuring its vertical orientation and positioning it above the bottom. Regions with rough bathymetry should be avoided, or it will be necessary to attach a downward-looking sonar one hundred meters above the imploder to enable us to see it in relation to the seafloor. This is the method we used successfully with explosive shots to image the topographically-rough Jasper Seamount and Hess Deep [11,12].

The imploder will be designed with Solidworks CAD software. Tolerance and strength requirements will be analyzed using Cosmos, a finite-element modeling program. We will begin by modeling its acoustical source-effect and use that information to optimize its design. We have already used Solidworks and Cosmos to design our working imploder to ensure repeated operation free of seizing or breaking. One thing we began to appreciate when designing it is how difficult it is to make a large-diameter cylinder retain tolerances so that a piston can move when subjected to a high differential pressure. Instead our approach will be to use a multi-cycle, small-bore piston pump to fill a large-volume tank that does not need to keep its shape and can be internally buttressed.

Fig. 6 shows the major components of the imploder. This is a conceptual design and does not show valves, fittings, skid cage, or umbilical attachments. The bottom funnel is open to the sea and is inverted so that pumped-in buoyant,

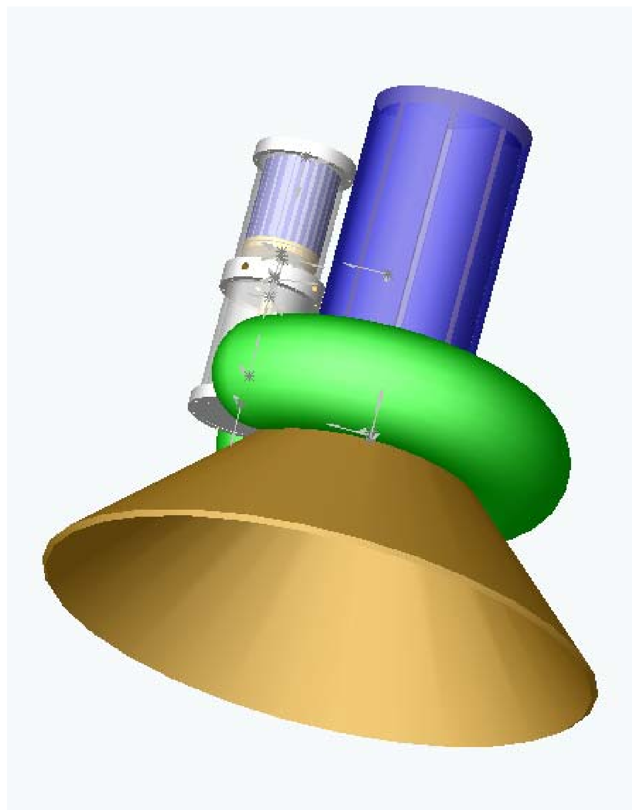

Fig. 6. New design for seafloor imploder – Tan: funnel imploding chamber; Blue: venting tank; Green: pump-water bladder; White: four-chamber, two-piston pump assembly

compressed air remains within the funnel. While the funnel is being filled with air, the reciprocating action of the pump is transferring water out of the blue venting tank and into the green bladder, creating a low-pressure void within the venting tank. A high-pressure differential potential between the tank and the gas bubble in the funnel is converted to kinetic, sound-radiating energy when a valve opens between the two. We can see from the second plot in Fig. 5 that the sudden inrush of water creates a sizeable signal at about 200 Hz (.154 to .156 seconds). For the collapse of a larger volume gas bubble in the funnel, it is reasonable to expect a larger signal of lower frequency.

The funnel allows nearly unconstricted flow. Then, by constricting the opening at the right time and rate, the large deacceleration slap and bubble oscillation can be minimized, effectively band-limiting the source signal. The cross-section of the funnel may also be important in shaping the outgoing signal. A firing cycle is completed by using the pump assembly to refill the venting tank with water from the bladder while releasing tank air to the sea.

As stated earlier, this is a preliminary design and some parts, most notably the valve between the funnel and the venting tank, need careful thought. For the valve, we presently favor a setup similar to the shuttle in an airgun - where a small solenoid trips a large shuttle that retracts to form a large opening [2]. Shielding and a wiper to remove solids such as is used in borehole equipment will be necessary for firing directly on the seafloor. Also unknown at this time is how advantageous an array approach will be for producing an optimum seafloor signal. Obviously, the funnel could be replaced with a "muffin pan" arrangement having several smaller funnels with the added complexity of having more valves. We think to start with it is better to concentrate on optimizing the signal from a single implosion. Recent comparisons between airgun records from a small array of large guns versus a larger array of smaller guns favor the larger-displacement guns for producing useful signals out to greater ranges [24].

IV. CONCLUSION

We have shown that there are many advantages to producing seismic noise directly on the seafloor related to imaging improvements, shear wave generation, and marine mammal remediation measures. Although its design will present several challenging engineering problems, they are not insurmountable, as our previous working versions have provided guidance for an improved seafloor source. We look forward to using it to further exploration into the world beneath the seas.

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References

[1] J. L. Worzel and M. Ewing, Explosion sounds in shallow water, *Geological Society of America Memoir 27*, 1948.

[2] W. M. Telford, L. P. Geldart, R. E. Sheriff, D. A. Keys, *Applied Geophysics, Cambridge University Press*, 1976.

[3] D. Davies, Dispersed Stoneley waves on the ocean bottom, *BSSA*, Vol. 55, 1965, pp. 903-918.

[4] R. B. Whitmarsh and R. C. Lilwall, A new method for the determination of in-situ shear-wave velocity in deep-sea sediments, in *Proceedings of Conference: "Oceanology International*, 1982", 1982, p. OI82.

[5] A. W. Sauter, L. M. Dorman, and A. E. Schreiner, A study of seafloor structure using ocean bottom shots, in *Ocean Seismo-acoustics, Low-frequency Underwater Acoustics*, edited by T. Akal and J.M. Berkson, 1986, pp. 673-681.

[6] R. D. Stoll, *Sediment Acoustics*, vol. 26, 1989, *Springer-Verlag, Berlin*.

[7] P. A. Berge, S. Mallik, G. J. Fryer, N. Barstow, J. A. Carter, G. H. Sutton, J. I. Ewing, In situ measurement of transverse isotropy in shallow-water marine sediments, 1991, *Geophys. J. Int*., 104, pp 241 – 254.

[8] N. R. Chapman, Estimation of geoacoustic properties by inversion of acoustic field data, in *Shear Waves in Marine Sediments*, edited by J. M. Hoven, M. D. Richardson, and R. D. Stoll, 1991, *Kluwer, Dordrecht*, pp. 511-520.

[9] G. L. Christeson, G. M. Purdy, G. J. Fryer, Structure of young upper crust at the East Pacific Rise near 9° 30' N, *Geophys. Res. Lett*., 19, 1992, pp 1045-1048.

[10] G. L. Christeson, G. M. Purdy, G. J. Fryer, Seismic constraints on shallow crustal emplacement processes at the fast spreading East Pacific Rise, *J. Geophys, Res*., 99, 1994, pp. 17957-17973.

[11] P. T. C. Hammer, L. M. Dorman, J. A. Hilderand, B. Cornuelle, Jasper Seamount Structure: Seafloor Seismic Refraction Tomography, *J. Geophys. Res*, 99, 1994, pp. 6731-6752.

[12] S. Wiggins, L. M. Dorman, Cornuelle, B. D., Hildebrand, J. A., Hess Deep rift valley structure from seismic tomography, *J. Geophys. Res*, 1996, pp. 22335-22353.

[13] L. M. Dorman, Chapter 37: Propagation in Marine Sediments, in *Encyclopedia of Acoustics*, edited by M. J. Crocker, Vol. 1, 1997 *John Wiley, New York*, pp. 409-416.

[14] A. E. Schreiner, L. M. Dorman, Coherence lengths of seafloor noise: effects of seafloor structure, *J. Acoust. Soc. Am*., 1990, Vol. 88, pp. 1503-1514.

[15] L. M. Dorman, A. E. Schreiner, L. D. Bibee, The effects of shear structure on seafloor noise, in *Shear Waves in Marine Sediments*, J. Hovem, R. Stoll, and M. Richardson, eds. 1991, *Kluwer, Dordrecht*, pp. 239-245.

[16] A. E. Schreiner, L. M. Dorman, L. D. Bibee, Shear wave velocity structure from interface waves at two deep water sites in the Pacific ocean, in *Shear Waves in Marine Sediments*, 1991, *Kluwer, Italy*, pp. 231-238.

[17] L.D. Bibee, and L. M. Dorman, Full waveform inversion of seismic interface wave data, in *Full Field Inversion Methods in Ocean and Seismo-acoustics*, ed.

O. Diachok, A. Caiti, P. Gerstoft, and H. Schmidt, 1995, *Kluwer, Dordrecht, the Netherlands*, pp. 377-382.
[18] G. Nolet, and L. M. Dorman, Waveform analysis of Scholte modes in ocean sediment layers, *Geophys. J. Intl*., 1996, pp. 385-396.
[19] G. Peterson, Whales beach seismic research, *Geotimes,* January 2003, AGI.
[20] Anonymous, Joint interim report, Bahamas marine mammal stranding event of 15-16 March, 2000, *NOAA, Department of the Navy, Washington, DC*, 2001.
[21] W. J. Richardson, C.R. Greene, Jr., C. I. Malme, D. H. Thomson, *Marine Mammals and Noise*, 1995, *Academic Press*.
[22] J. B. Diebold, personal communication.
[23] H. L. Hydraulik, GmbH, personal communication.
[24] D. Wiens, personal communication.