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GEOACOUSTIC EXPERIMENTS
ICESHELF 97

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CONTRACTOR REPORT

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Abstract

A series of seismic and acoustic experiments were carried out at the Spinnaker Array site in April 1997 to determine geoacoustic properties of the ocean bottom and sea ice. Knowledge of these properties is required for reliable acoustic propagation modeling and matched-field processing. The experiments included an ice hammer seismic survey, ocean-bottom seismic refraction and interface wave surveys, and a seafloor reflectivity study. Three different sensor systems were used to measure propagation in the water column, ocean bottom, and ice cover due to impulsive sources deployed in each of these three media. The experiment, together with preliminary and proposed analysis methods, are briefly described in this report.

Résumé

En avril 1997, on a réalisé une série d'expériences sismiques et acoustiques au site Spinnaker Array afin de déterminer les propriétés géoacoustiques du fond océanique et de la glace de mer. Il faut connaître ces propriétés pour produire des modèles de propagation acoustique fiables et assurer le traitement par comparaison de champs. Les expériences comportaient un relevé sismique effectué à l'aide d'un marteau à glace, des relevés de réfraction sismique, des études d'ondes d'interface ainsi qu'une étude de la réflectivité du fond marin. Trois systèmes de capteurs différents ont servi à mesurer la propagation dans la colonne d'eau, sur le fond océanique et dans la couverture de glace à partir d'impulsions produites dans chacun des trois milieux. Ce rapport décrit brièvement les expériences ainsi que les méthodes d'analyse préliminaire et proposées.

Abstract

A series of seismic and acoustic experiments were carried out at the Spinnaker Array site in April 1997 to determine geoacoustic properties of the ocean bottom and sea ice. Knowledge of these properties is required for reliable acoustic propagation modelling and matched-field processing. The experiments included an ice hammer seismic survey, ocean-bottom seismic refraction and interface wave surveys, and a seafloor reflectivity study. Three different sensor systems were used to measure propagation in the water column, ocean bottom, and ice cover due to impulsive sources deployed in each of these three media. The experiments, together with preliminary and proposed analysis methods, are briefly described in this report.

1. Introduction

Geoacoustic properties of the ocean bottom and sea ice can significantly affect acoustic propagation in the ocean. Important properties include compressional and shear- speeds and density. In order to completely assess the geoacoustic environment at the Spinnaker Array site, a geoacoustic study was carried out at the array repair camp (Ice Camp Logion) as part of the Iceshelf 97 field project. The study involved four different experiments designed to measure ocean-bottom and sea-ice properties over a number of different spatial scales. To carry out these experiments, three different sensor systems were used to measure seismic and acoustic propagation in the water column, ocean bottom, and ice cover due to impulsive sources deployed in each of these three media. The sensors consisted of a vertical line array (VLA) of hydrophones in the water column, an ocean-bottom seismometer (OBS) on the seafloor, and a horizontal line array (HLA) of geophones on the ice surface. Sources consisted of explosive charges detonated on the seafloor, light bulbs imploded within the water column, and hammer blows on the ice surface. Each sensor system was particularly suited to a particular source; however, all systems were used to record all sources.

This report describes the geoacoustic experiments carried out during Iceshelf 97. At the time of writing of this report, data was available for only one of the sensor systems, the ice-mounted geophones. Hence, these recordings will be used to illustrate the arrivals for each of the three sources. The following section describes the sensor systems deployed at the Spinnaker Array site. Sections 3–6 describe the four distinct geoacoustic experiments carried out, together with the analysis that will be applied to the data from each experiment.

2. Sensor Systems

The three sensor systems used in the geoacoustic study are shown in plan view and in cross section in Fig. 1. Data from each of the sensor systems (HLA, VLA, OBS) were recorded on separate recording systems. The data from each sensor system were transfered via over-ice cables to a central (heated) tent which housed the three recording systems. In this section, each of the sensor/recording system is briefly described.

The HLA was comprised of a total of 11 geophones mounted on the surface of the sea ice. The inter-sensor spacing for the HLA was 25 m. The geophone positions were surveyed to high precision using a geodimeter. Each geophone was carefully planted on the ice by hand. This procedure consisted of removing up to 1.5 m of snow from the ice surface, and freezing the geophone to the ice using a small amount of water to provide good coupling. The first three geophones (G0, G1 and G2 in Fig. 1b) were three-component geophones which consisted of one vertical and two horizontal sensors. The horizontal sensors were oriented parallel and perpendicular to the HLA (x and y directions, respectively, in Fig. 1b). The remaining eight geophones were single (vertical or z) component sensors. The data from the geophone HLA was recorded using a Bison digital seismograph set to record 12 channels of data. Since the HLA was comprised of a total of 17 sensors, various subsets of the sensors were recorded depending on the particular experiment. The sampling rate at the seismograph could be selected from a number of options. Sampling rates of 1000–4000 Hz were used, again depending on the experiment.

The VLA was comprised of 24 hydrophones on a 600-m cable (the water depth at the experiment site was approximately 630 m). The inter-sensor spacing was 15 m for the bottom ten hydrophones, and 30 m for the top 14 hydrophones. The VLA was deployed through a 10-inch hole drilled through the $\sim$4 m ice with an ice auger powered by an electric drill motor. The data from the VLA was recorded on a pc-based recoding system at a (fixed) sampling rate of 1000 Hz.

The OBS consisted of four sensors: three geophones which measured the three-dimensional particle velocity of the ocean bottom, and one hydrophone which measured acoustic pressure in the water immediately above the seafloor. The OBS was deployed through a 36-inch hole cut through the ice using a hot-water drill. The data from the OBS was recorded on a pc-based system at a sampling rate of 128 Hz.

The amplifier gain for each of the three recording systems could be chosen from a number of options. Gains were selected based on the source strength and range. Only the recording system associated with the geophone HLA had the capability of displaying the data in the field. This display was used to ensure that the time-window of the recording included the arrivals of interest, and that the gains had been set to an appropriate level.

3. Ice Hammer Seismic Survey

The first geoacoustic experiment to be described is the hammer seismic survey. This experiment was designed to determine compressional and shear speeds of the sea ice. The experiment consisted of using a sledge hammer to strike wooden four-by-four posts frozen into the ice, and recording the seismic-wave arrivals at the HLA geophones. A total of four posts were frozen into the ice endfire to the HLA at ranges of 25, 100, 175, and 250 m from geophone G0 (ranges were measured using the geodimeter). The time of the hammer blow

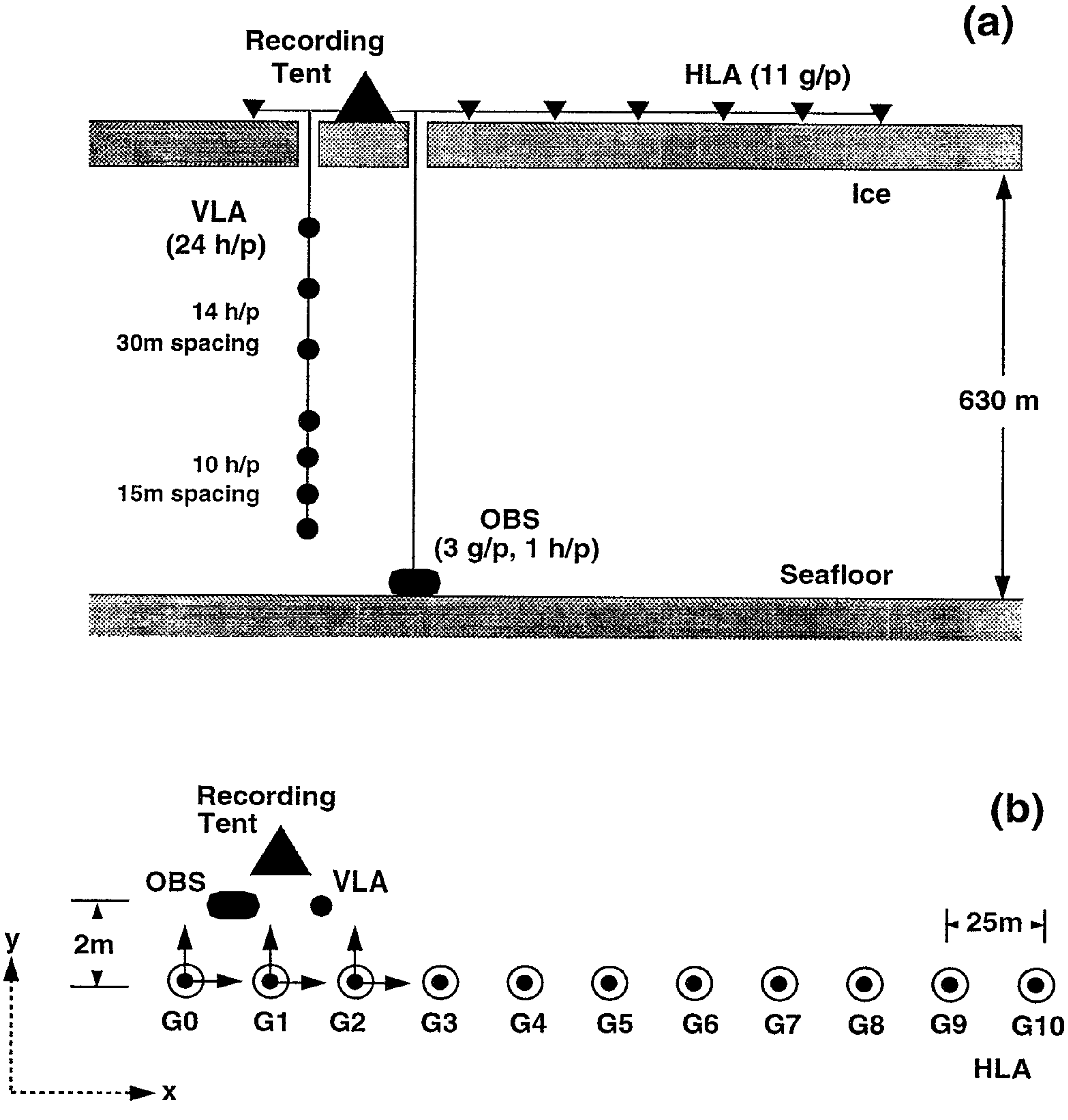

Fig. 1. Schematic diagram of the sensor systems used in the geoacoustic study, (a) cross-section, (b) plan view. H/p indicates hydrophone, g/p indicates geophone. The arrows in (b) indicate the orientation of the horizontal geophone components.

(source instant) was measured by attaching a trigger geophone directly to the post: this allowed absolute traveltimes to be measured. The 12 channels that were recorded on the seismograph consisted of the three components of geophones G0, G1 and G2, and the single (vertical) components of geophones G3, G4 and G5.

Hammer blosw in different directions provided a simple method of preferentially generating different types of waves in the ice. Horizontal hammer blows directed toward to the array ($+x$ direction) were used to excite plate waves. Plate waves involve particle motion parallel to the direction of propagation and travel at a speed slightly less than the bulk compressional speed of the ice. Figure 2 shows an example of the plate waves recorded on the x-component geophones. The move-out (slope) of the first-break arrival times provides an estimate of the plate-wave speed. A least-squares fit of the first breaks in Fig. 2 yielded a plate-wave speed of 3080 ± 20 m/s. From this, the ice compressional speed was estimated to be approximately 3200 m/s [1]. Hammer blows directed perpendicularly to the array ($+y$ direction) were used to excite horizontally polarized shear waves, which involve particle motion perpendicular to the direction of propagation and travel at the bulk shear speed of the ice. Figure 3 shows an example of the shear waves recorded on the y-component geophones. A least-squares fit of the first breaks in Fig. 3 yielded a shear speed of 1780 ± 10 m/s. Finally, vertical hammer blows were used to excite flexural waves in the ice. Flexural waves are dispersive waves which involve (prograde) elliptically polarized particle motion in the radial-vertical plane. Figure 4 shows an example of the flexural waves recorded on the z-component geophones. The dispersion of the flexural wave depends on the shear and compressional speeds and thickness of the ice. Figure 5 compares the flexural-wave dispersion properties, computed with a moving Fourier transform technique [2], to the theoretical dispersion curve computed for an ice layer 3.5-m thick with compressional and shear speeds of 3200 m/s and 1780 m/s, respectively (the dispersion curve was computed with a normal mode model). The reasonably good agreement supports the measured compressional and shear speeds.

4. Refraction Survey

The refraction survey was carried out to determine a compressional-speed profile for the ocean-bottom sediments. The survey consisted of detonating 0.8-kg SUS charges on the seafloor at 17 ranges from 50 m to (nominally) 5000 m (see Table 1). The ice holes used for the source deployments were positioned using the geodimeter and a skidoo out to a range of 1000 m. Beyond this range, rough ice prevented line-of-sight measurements and over-ice travel, and a helicopter and GPS were employed. The procedure for these long-range shots was to navigate the helicopter to approximately the correct location using the onboard GPS, and choose a landing site with suitable ice. The actual shot location was then determined using a hand-held P-code GPS. The range between the shot and sensors was subsequently calculated from the coordinates of each site.

The SUS charges deployed had previously been modified to withstand the hydrostatic pressure of water depths in excess of 600 m by fitting a machined aluminum diaphragm over

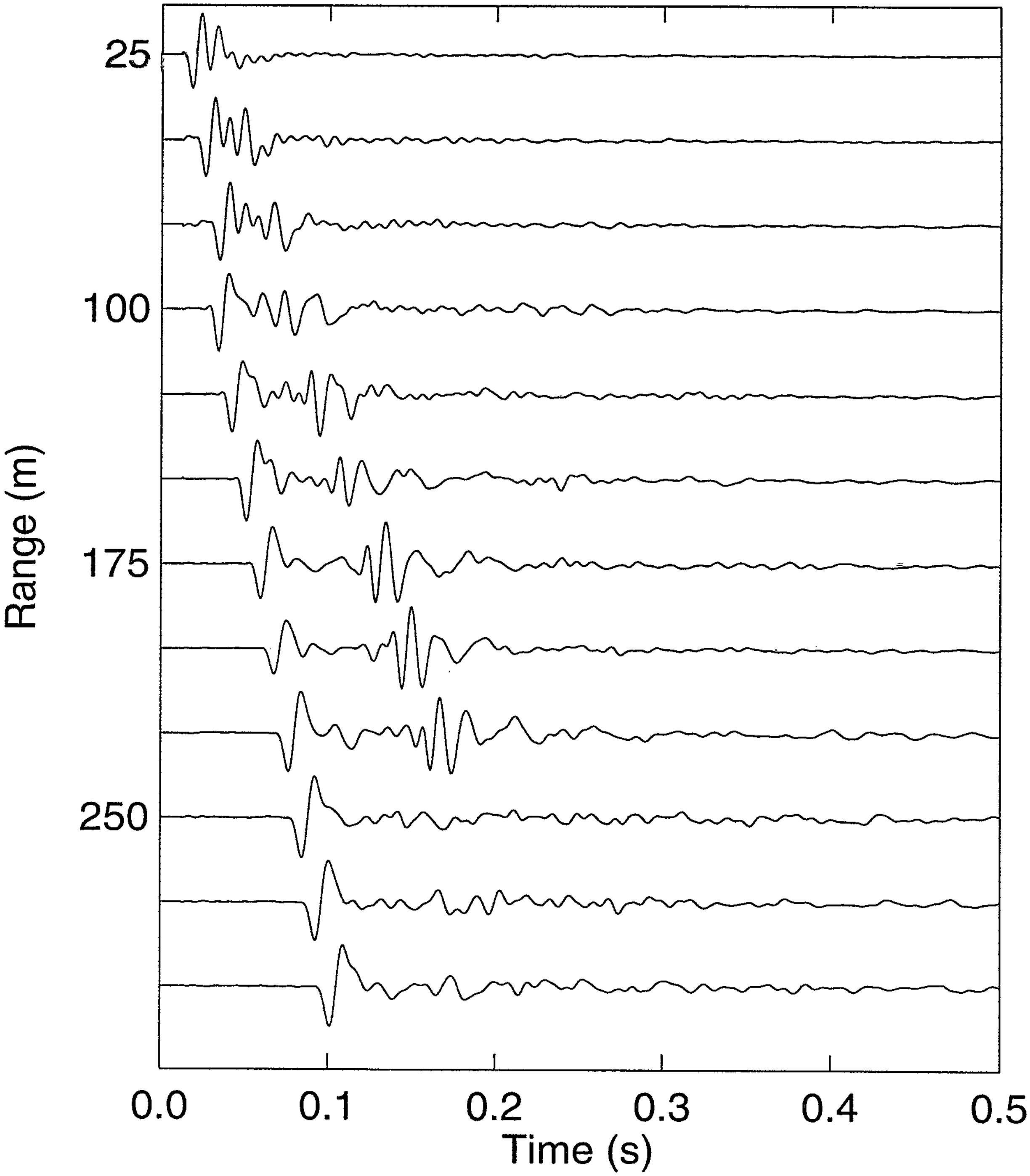

Fig. 2. Seismograms recorded at the x-component sensors of the HLA for x-direction hammer blows. The strong first arrival is the plate wave.

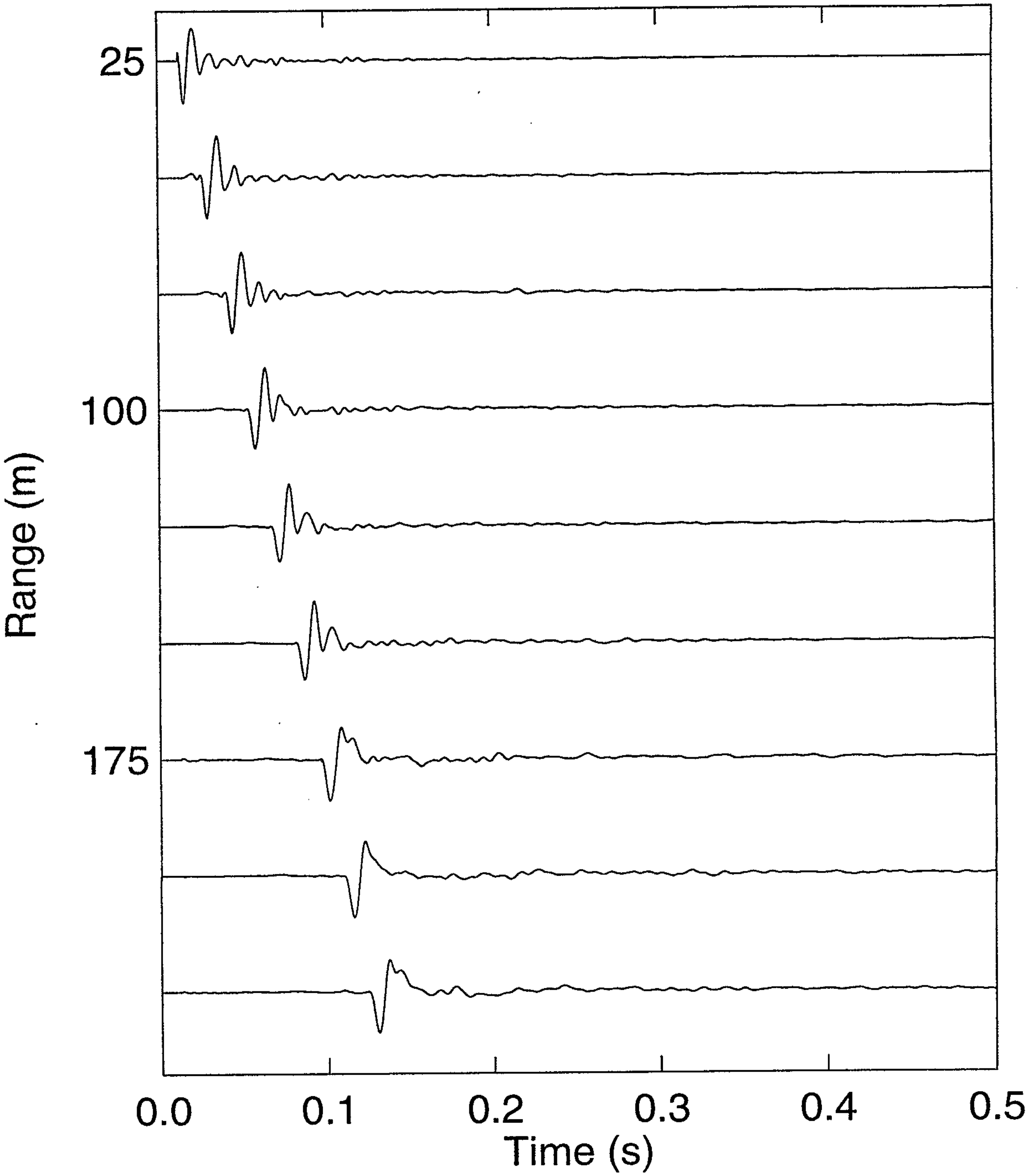

Fig. 3. Seismograms recorded at the y-component sensors of the HLA for y-direction hammer blows. The strong first arrival is the shear wave.

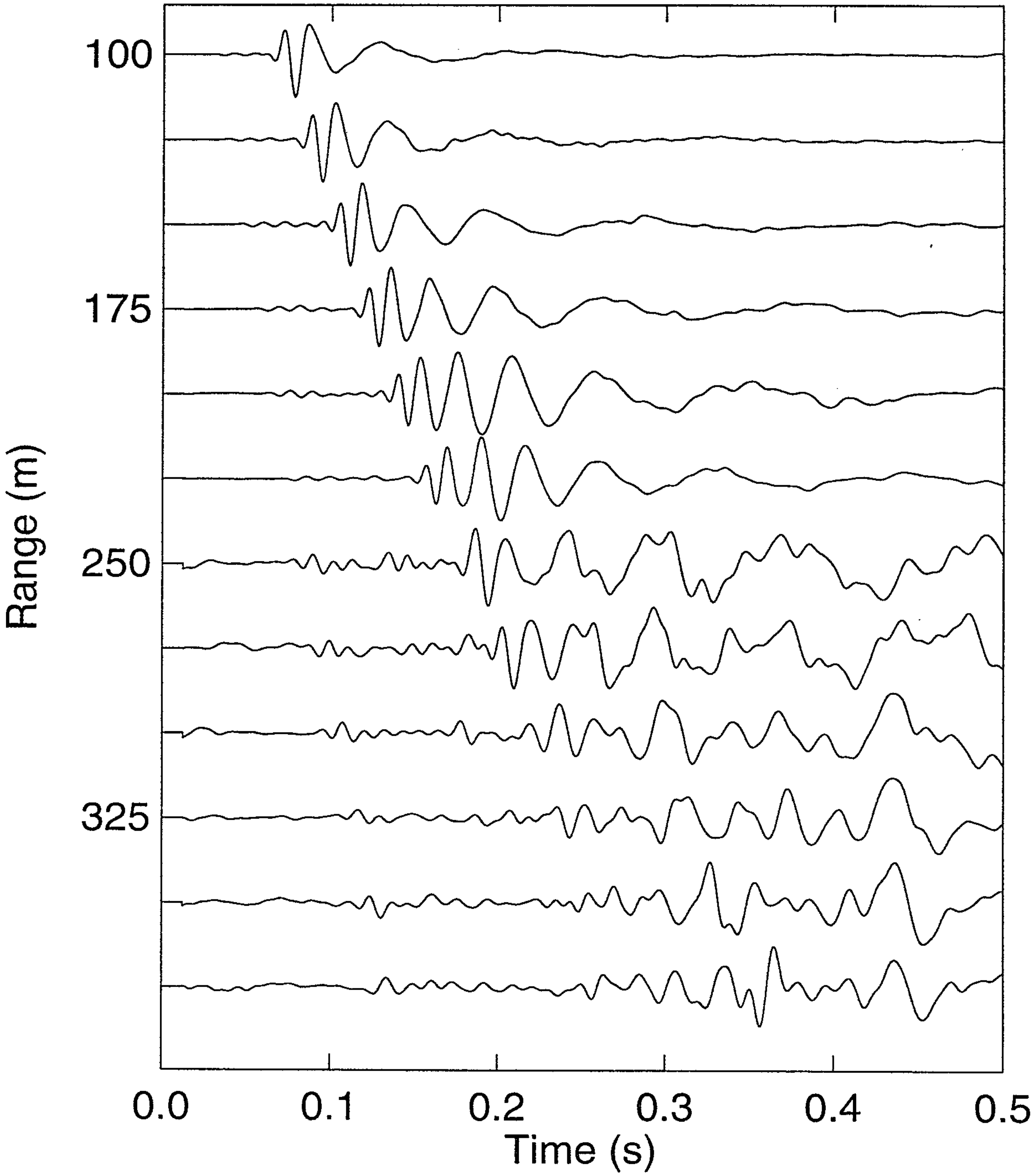

Fig. 4. Seismograms recorded at the z-component sensors of the HLA for vertical hammer blows. The strong dispersive arrivals are flexural waves.

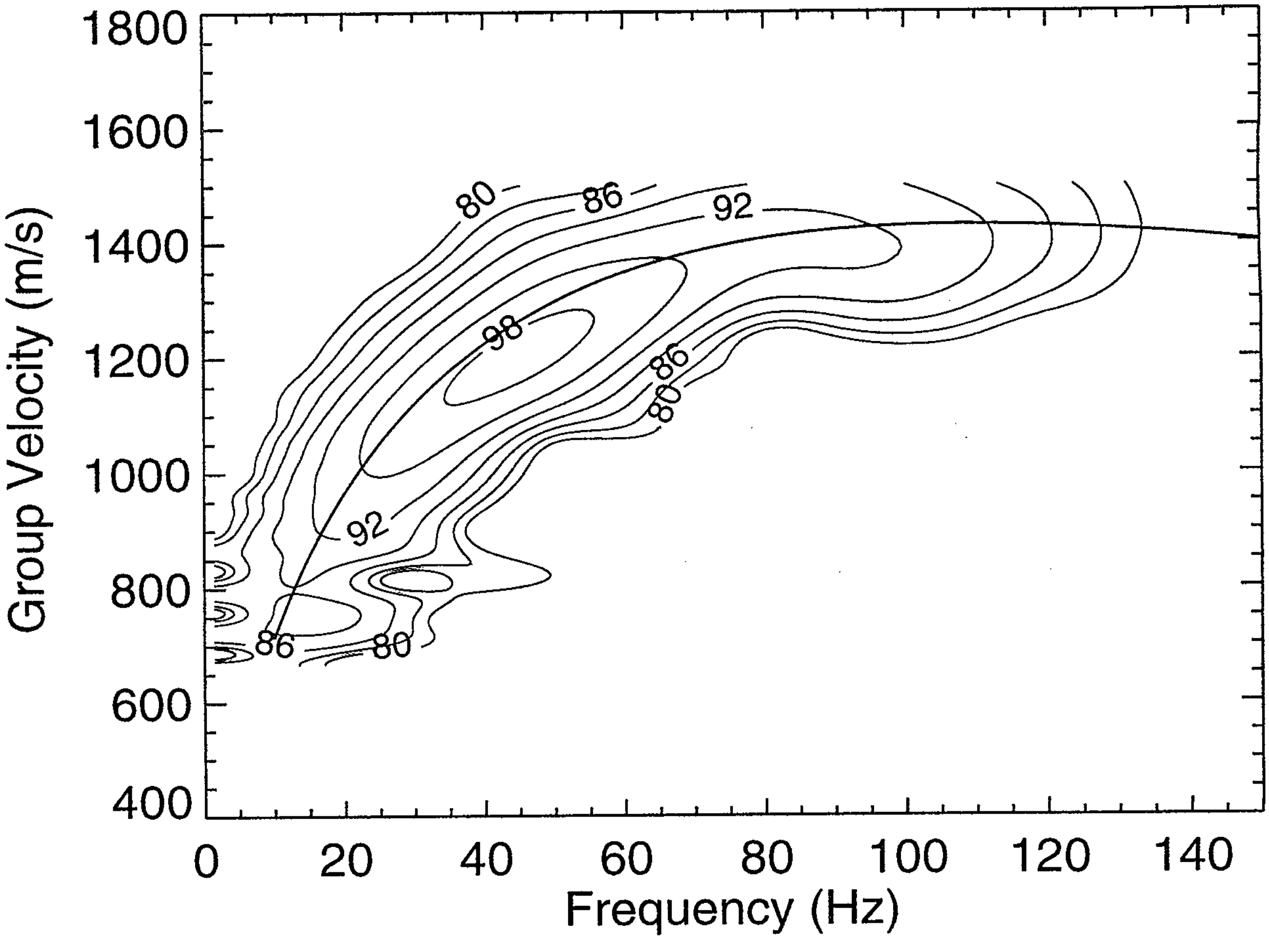

Fig. 5. Observed dispersion characteristics of the flexural wave (contours) and theoretical dispersion curve (solid line).

Table 1. Summary of ranges and water depths for SUS and light-bulb sources.

Name	Range (m)	Water Depth (m)
S50	50	627
S100	100	627
S150	150	627
S200	200	625
S250	250	625
S300	300	625
S400	400	612
S500	500	608
S600	600	608
S800	800	606
S1000	1000	600
S1500	1680	586
S2000	2130	573
S3000	2810	556
S3500	3470	558
S4000	3821	529
S5000	5030	495

the standard SUS diaphragm. A sharp aluminum "dagger" was placed with its point against the aluminum diaphragm. The SUS charges were lowered to the seafloor on a Greenlee string, and a section of steel pipe dropped along the string. When the pipe struck the dagger, the dagger pierced the aluminum diaphragm and the SUS charge exploded.

The purpose of the seafloor sources was to generate compressional waves in the bottom which are refracted upward by increases in compressional speed with depth and emerge from the bottom to be detected the sensor systems [3]. The observed moveout of the bottom-refracted arrivals can the be interpreted in terms of a layered compressional-speed model of the ocean bottom. The primary sensor systems for the refraction experiment are the OBS and VLA. However, since data for these systems were not available at the time of writing, an example of the seismograms recorded on the geophones of the HLA for a SUS charge at ~5000-m range is shown in Fig. 6. This figure clearly shows the direct arrival together with three reflected arrivals. The arrivals of interest for the refraction experiment consist of low-amplitude precursors that arrive prior to the direct signal as a result of following high-speed refracted paths through the ocean bottom. Figure 7 shows an example of the precursors recorded for the 5000-m SUS charge (the direct arrival, labeled 'D', is purposely clipped in order to enhance the low-amplitude precursors). A number of precursor arrivals are evident. For instance, the moveout of the arrival labeled 'A' in Fig. 7 indicates a propagation speed of 2400 m/s, corresponding to a sub-bottom layer. Unfortunately, the HLA recordings are difficult to interpret fully in terms of bottom-refracted arrivals due to the presence of refracted waves in the ice. A complete interpretation of the refraction experiment must await the OBS and VLA data.

5. Interface Wave Experiment

The most effective method of determining the sediment shear-speed profile is through a dispersion analysis of seismic interface or Scholte waves [3]. The interface wave is a retrograde elliptically-polarized wave which propagates along the water-sediment boundary, decaying exponentially away from the interface in either medium. Hence, to effectively generate and detect interface waves, the sources and receivers are required to be on or near the seafloor. The SUS charges detonated on the seafloor for the refraction survey described above are also ideal for generating interface waves. The OBS is the optimal sensor for measuring interface waves; however, these waves may also be evident at the lowest hydrophones of the VLA. There is no evidence of the interface wave on the recordings at the ice-mounted geophones (e.g., Fig. 6), and hence no examples are shown in this report. Since interface waves are generally strongly attenuated, the SUS charges at short ranges (50–500 m) should produce the best recordings. A shear-speed profile for the upper sediments can be determined by matching the dispersion properties of the interface wave, as quantified by a moving Fourier transform analysis [5], such as is illustrated in Fig. 5 for the ice flexural wave.

6. Plane-wave Reflectivity Experiment

Compressional and shear speeds and density of the suficial sediments can be determined by inverting measurements of the seafloor reflection loss as a function of grazing angle. The reflection loss can be determined by comparing the amplitude of the direct and bottom-reflected arrivals (corrected for geometric spreading) generated by an impulsive source in the water column. Sediment properties consistent with the reflection loss can then be determined by forward modelling [6]. The plane-wave reflectivity experiment carried out at the Spinnaker Array site consisted of imploding glass light bulbs at 50-m depth in each of the holes used for the SUS charges in the refraction and interface wave experiments (Table 1). Light bulbs provide a simple, repeatable impulsive source which has little or no bubble-pulse oscillation [7]. The depth of implosion was controlled by lowering the light bulbs on a line to 50 m,

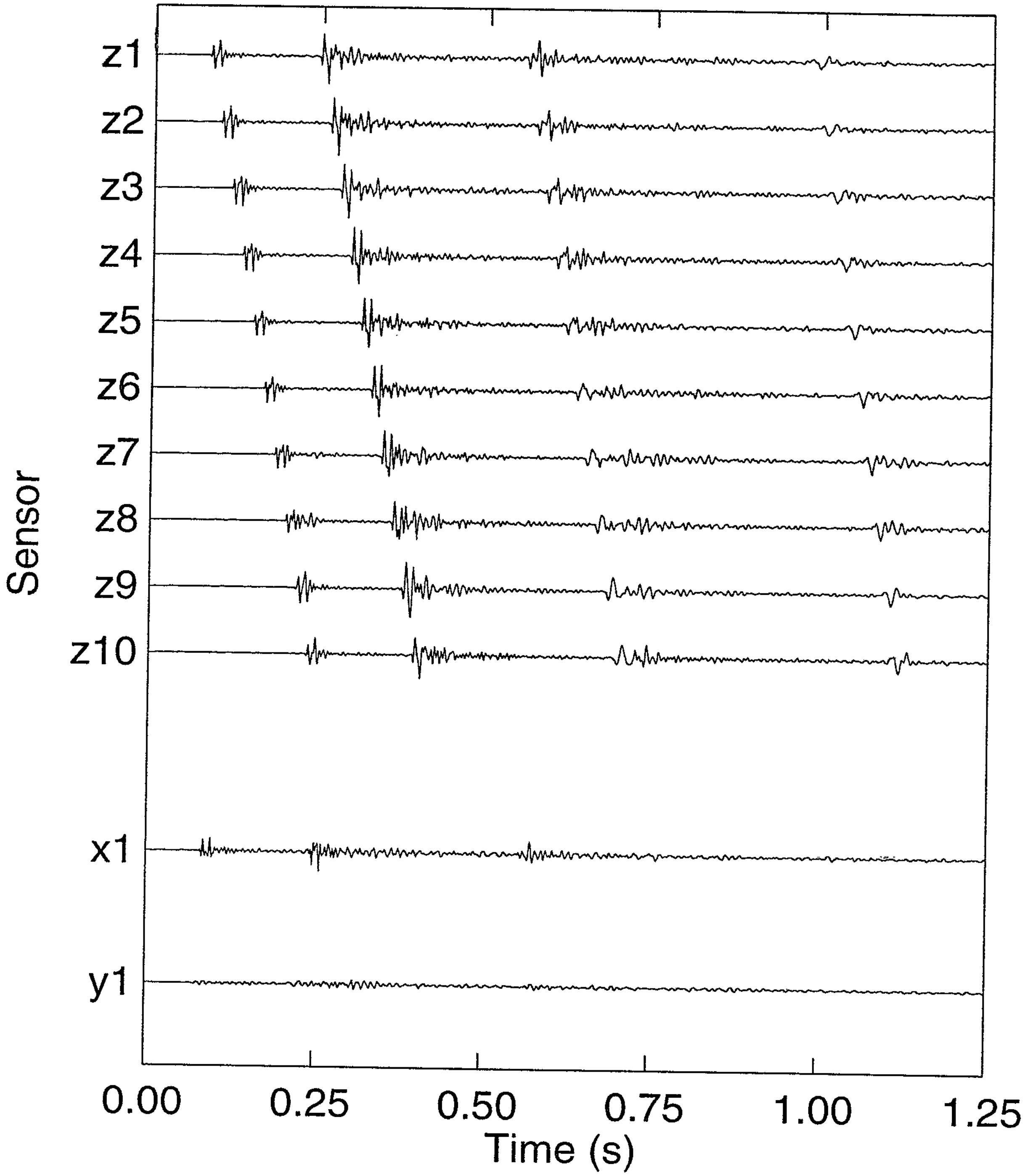

Fig. 6. Seismograms recorded using the geophone HLA for a SUS charge on the seafloor at 5000-m range.

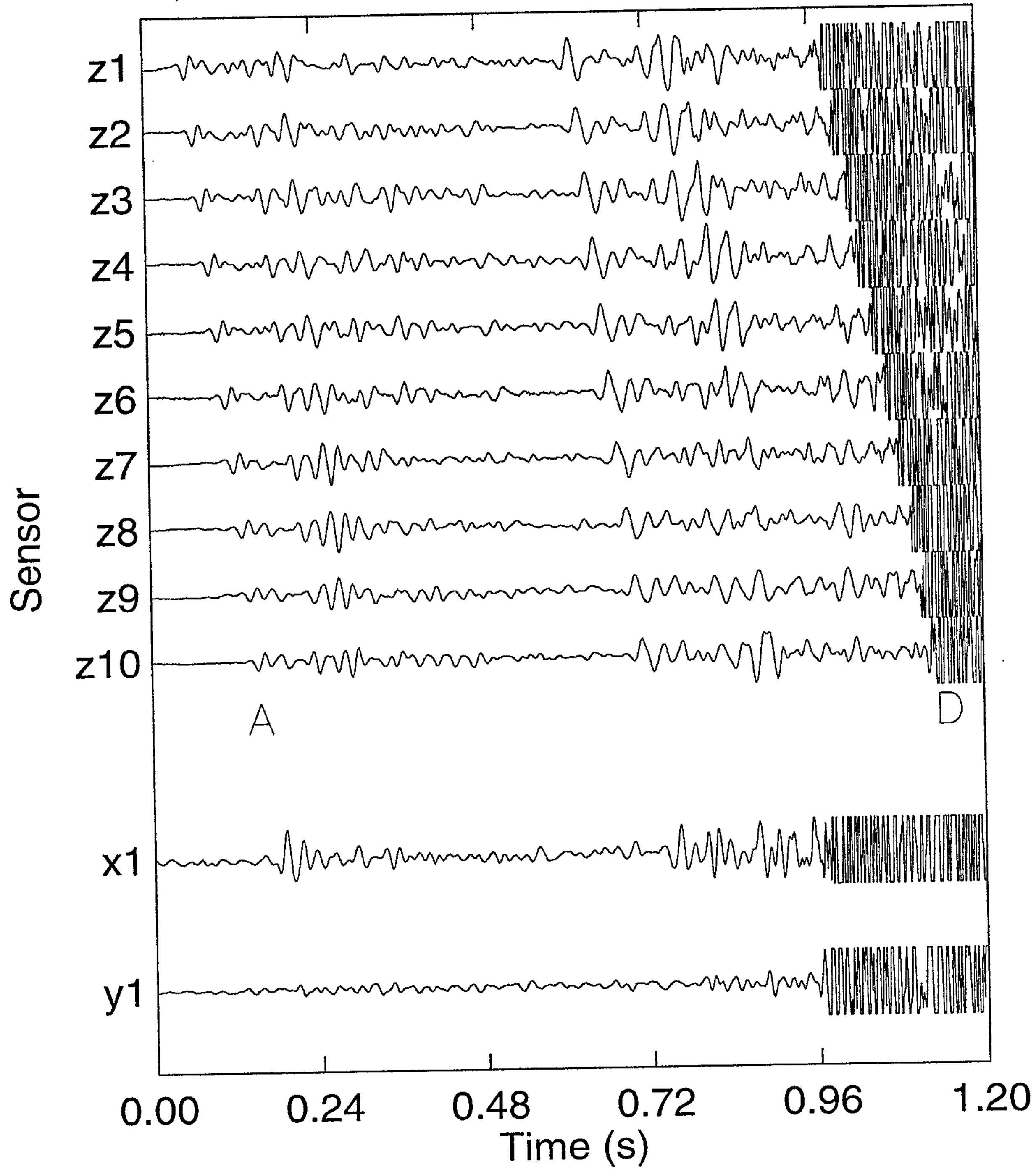

Fig. 7. Precursor arrivals recorded using the geophone HLA for a SUS charge on the seafloor at 5000-m range. 'D' indicates the direct arrival (purposely clipped), 'A' indicates a precursor arrival with moveout indicating a speed of 2400 m/s.

then dropping a section of pipe along the line which burst the bulb on impact. The primary sensor system for the reflectivity experiment is the VLA. However, since data from this system were not available at the time of writing, an example of the recorded light-bulb arrivals at the geophone HLA is shown in Fig. 8. The records in this figure clearly show a sharp direct arrival, followed approximately 0.3 s later by bottom-reflected and surface-bottom-reflected arrivals. The light-bulb arrivals were clearly evident on all the geophone recordings, including the maximum range of $\sim$5000 m.

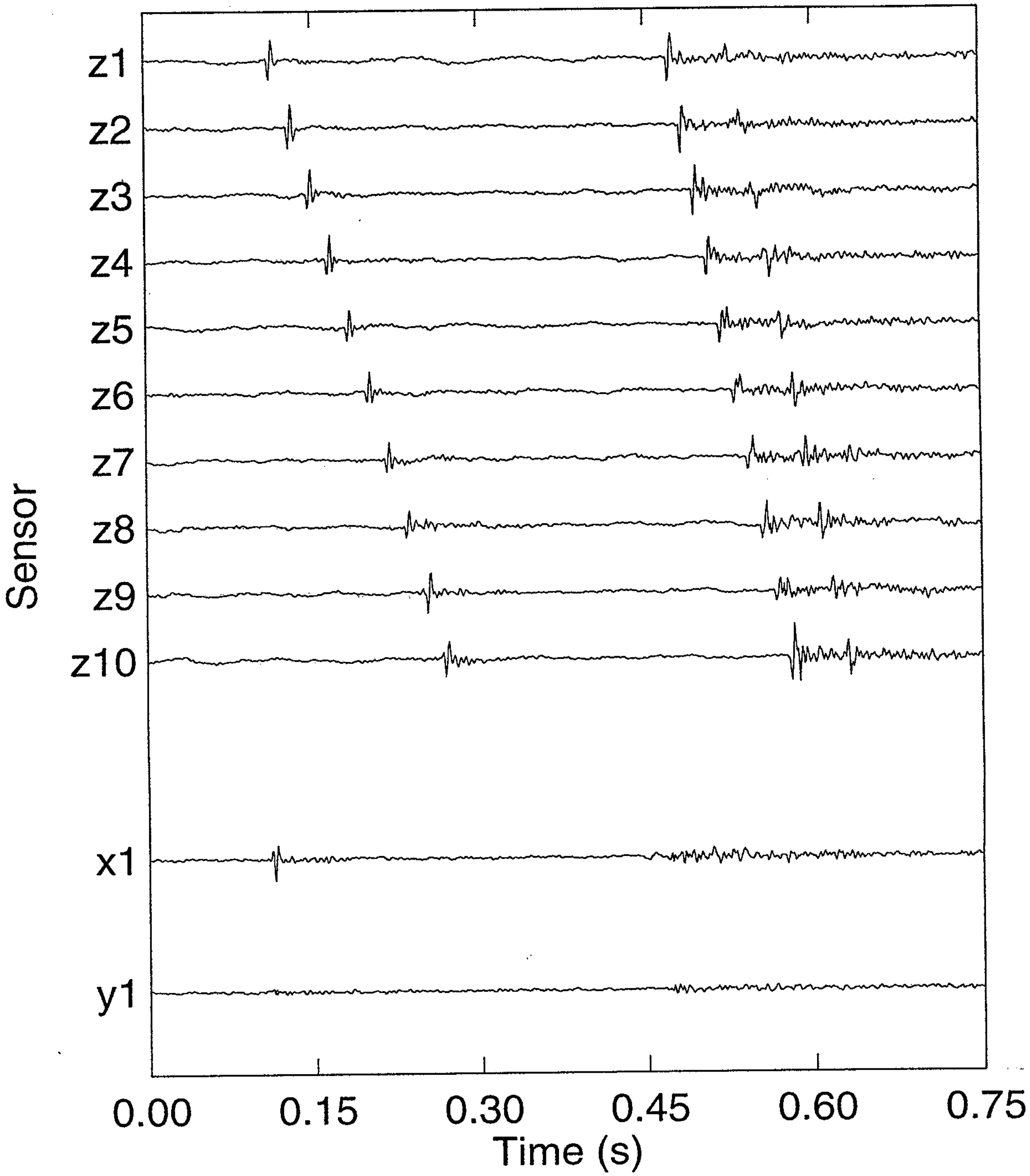

Fig. 8. Seismograms recorded using the geophone HLA for a lightbulb source at 50-m depth and at 1000-m range.

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A series of seismic and acoustic experiments were carried out at the Spinnaker Array site in April 1997 to determine geoacoustic properties of the ocean bottom and sea ice. Knowledge of these properties is required for reliable acoustic propagation modelling and matched-field processing. The experiments included an ice hammer seismic survey, ocean-bottom seismic refraction and interface wave surveys, and a seafloor reflectivity study. Three different sensor systems were used to measure propagation in the water column, ocean bottom, and ice cover due to impulsive sources deployed in each of these three media. The experiments, together with preliminary and proposed analysis methods, are briefly described in this report.

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