OF 1519

PROCEEDINGS OF THE ACOUSTIC-GEOTECHNICAL CORRELATION WORKSHOP

"The Correlation of Acoustic and Physical Properties of Marine Sediments"

Sponsored by:

Gulf Canada, Esso Resources, Dome Petroleum, Home Oil,
Panel on Energy Research and Development and
The Geological Survey of Canada

Workshop held on April 16th and 17th, 1984
at Gulf Resources Canada, Calgary, Alberta

Edited by:

P.G. Simpkin
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Acoustic-Geotechnical Correlation Workshop

Welcome and Introduction

Steve Blasco

Workshop Chairman

Geological Survey of Canada
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

Ladies and Gentlemen, on behalf of Esso Resources Canada, Gulf Canada Resources, Home Oil, Dome Petroleum, the Panel on Energy Research and Development and the Geological Survey of Canada, I wish to welcome panel members and guests to this workshop entitled "The Correlation of Acoustic and Physical Properties of Marine Sediments". The quantitative determination of physical and engineering properties through the measurement of acoustic parameters is a topic of considerable interest from both the academic and applied viewpoints. By bringing together a small but diverse group of technical experts, including geophysicists, geologists, geotechnical engineers and theoreticians actively involved with the problem, an understanding of the state-of-the-art, present research trends and a perspective on future research directions and milestones will be achieved. The first day will consist of eighteen summary presentations by panel members from industry and research establishments. The second day will involve a structured discussion aimed at addressing the problems associated with the derivation of acoustic properties from the seismic response and the subsequent translation into sediment properties.

Over the past couple of years, we have been involved in compiling a synthesis of the seabed geology of the Canadian Beaufort continental shelf, and together with geophysicists, geologists and engineers have attempted to integrate a wide variety of multidisciplinary information. It is hoped that technical discrepancies that have arisen during the synthesis, related to the correlation of acoustic and physical properties, will be resolved at this workshop. Over the next two days, perhaps the engineers will be able to convey to the physicists just exactly what physical and engineering properties are required, and the physicists will be able to inform the engineers just what it is they can really measure.

I would like to thank in particular all those who have been involved in supporting this venture: Catherine Nelson from Esso Resources, Tony Stirbys from Gulf Canada, Kevin Hewitt from Dome Petroleum and Russell Parrott from the Atlantic Geoscience Centre who has been instrumental in co-ordinating logistics.

We have a special guest from the United Kingdom. Professor Denzil Taylor-Smith, Head of the Department of Earth Sciences at the University College of North Wales, Marine Science Laboratory, has been involved with the correlation of acoustic and geotechnical properties over the past twenty-two years. Denzil will be asked to summarize the proceedings of today's informal presentations by panel members and tomorrow's structured discussion. Larry Mayer will chair tomorrow morning's session concerning acoustics and Dick Campanella will chair the afternoon session related to geotechnical issues. As chairman of today's session, I would like to introduce the first presentation by Dr. Larry Mayer from Dalhousie University in Halifax, Nova Scotia.

Steve Blasco

Steve Blasco
Workshop Chairman

EDITORS NOTE

The many and varied topics presented and discussed in the two days of the Acoustic-Geotechnical Correlation Workshop can be fully appreciated only after reviewing the transcripts. The informal nature of the workshop stimulated discussion and it is hoped that these edited proceedings do justice to both the presentations by panel members and the ensuing debate.

In the following papers only the abstracts were submitted before the workshop took place. The texts have been prepared from the material presented by the original authors.

The format of these proceedings follows closely that of the workshop itself. The first day's formal presentations have been transcribed and edited. Where necessary, clarifications have been made and diagrams added. The second day's informal discussion sessions have been edited and clarified in order to accommodate deficiencies in the recorded dialogue.

All of the formal presentations have been reviewed by the original authors and should therefore, be accurate. However, for logistical reasons, the informal discussions of the second day have not been reviewed by the many contributors, therefore, the comments and opinions expressed and recorded may differ slightly from what was originally intended. Every effort has been made to present a flowing, accurate and interesting transcript of the discussions. However, the editor does not accept any responsibility for the views expressed in these proceedings.

It is hoped that the panel members and other contributors will benefit from these proceedings and that the cross fertilisation of ideas and techniques will help in a small way, to solve some of the many problems that face this sector of industry.

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ACOUSTIC-GEOTECHNICAL CORRELATION WORKSHOP

APRIL 16, 17, 1984

FUNDING & EXPENDITURES STATEMENT

FUNDING:

Dome Petroleum	2,000.00
Esso Resources	3,000.00
Gulf Canada	6,750.00
Home Oil	500.00
Geological Survey of Canada/PERD	17,000.00
Registration Fees	810.00
TOTAL	$30,060.00

EXPENDITURES:

Transportation	12,912.80
Panel Members Expenses	5,392.93
Hospitality, Meals and Receptions	2,883.90
Publication Costs	8,628.77
Miscellaneous	241.60
	$30,060.00

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RESEARCH AND RELATED ACTIVITIES IN THE CORRELATION OF ACOUSTIC-GEOTECHNICAL PROPERTIES

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DAY TWO - TUESDAY, 17TH APRIL 1984

HIGH RESOLUTION ACOUSTIC PROFILING AND REMOTE SEDIMENT PROPERTY DETERMINATION USING, AMONG OTHER THINGS, A DEEPLY TOWED BROAD-BAND SOURCE

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ABSTRACT

Researchers at Dalhousie University are currently involved in a number of research programs aimed at improving our ability to use remotely collected acoustic data to characterize deep-sea sediments with specific reference to paleoceanographic problems. In particular we have been developing (with U.S. O.N.R. support), a quantitative, extremely high resolution, deep-towed, sub-bottom profiler (the Chirp Sonar) that uses a long (typically 100 milliseconds) 2-5 kHz swept FM pulse to drive a specially designed transducer. The system provides the bandwidth and energy output necessary for high resolution with substantial sub-bottom penetration. After processing (which includes pulse compression, and calculation of and correction for, sediment attenuation), the resulting record should be a near artifact-free image of the impulse response of the sediment column. A shallow water prototype has been deployed in Narragansett Bay in an area of established geologic structure, and reflection coefficients and sediment attenuation have been calculated from the chirp data. A deep water system has been integrated with the Lamont Sea MARC I side scan vehicle and successfully field tested in 3,000 m of water. The system will soon be "ground truthed" in 4,600 m of water at the site of an 1,800 m deep, nearly continuously cored, Deep Sea Drilling Project hole at which physical property measurements are available at 1.5 m intervals. We have collected seismic data with 13 different systems at this site during the first stage of a seismic intercalibration experiment and compared the results of each system to each other and to the ground truth data provided by drilling.

We are also exploring means of using remote high resolution seismic data to identify sediment properties. Our approach uses an understanding of the processes responsible for the deposition of sediment in a particular environment to predict what the impedance curve for that environment should look like. Pattern discrimination techniques are used to identify depositional environment. Then relationships established for that environment are used to predict properties. Finally, we are investigating the use of broadband side scan information to generate real-time topographic, backscatter and roughness data that may be used quantitatively to characterize the seafloor.

INTRODUCTION

This presentation discusses several research projects aimed at improving our ability to use remotely collected acoustic data to characterize marine sediments and to address paleoceanographic problems. The first project involves a study of the geologic significance of high-frequency sub-bottom seismic reflectors, the second, the development of a quantitative 'chirp' sub-bottom profiling system, the third, a 'depositional-process oriented' impedance model for marine sediments, and fourth, a seismic intercalibration experiment, conducted in the western North Atlantic.

GEOLOGICAL SIGNIFICANCE OF HIGH-FREQUENCY REFLECTIONS

In order to understand the origin and geologic significance of high-frequency (4 kHz) sub-bottom reflections, the Scripps Institution of Oceanography's Deep Tow geophysical instrument package (Figure 1) was used to collect high-resolution profiles within several meters of the position at which 10-meter-long piston cores were recovered. The acoustic returns were digitized and processed in real time (Figure 2) for later comparison to sediment physical properties. Closely-spaced measurements of sound velocity and saturated bulk density, made on these cores (deep-sea carbonates) were used to calculate acoustic impedance (Figure 3) and reflectivity. Detailed analysis of other physical and stratigraphic properties revealed that variations in acoustic impedance in these cores were the direct result of glacial/interglacial climate fluctuations. A comparison of the calculated reflectivity with the field-record revealed that the seismic profile showed little correspondence to the calculated reflectivity (Figure 4). Convolving the outgoing pulse of the Deep-Tow with the calculated reflectivity series, however, generated a synthetic seismogram that closely matched the field record (Figure 5) (Mayer, 1978a).

These results indicated that even with high-resolution profiling systems, the observed reflectors do not necessarily represent discrete lithologic horizons, but rather, are interference composites, the result of interaction of the outgoing pulse with very fine-scale geologic layering. If we wish to use sub-bottom profiles to generate quantitative sediment property estimates, we must remove such artifacts and increase the resolution of our profiling systems.

THE CHIRP SONAR

Our approach towards achieving the goal of high resolution, without compromising sub-bottom penetration, was to develop a broadband, near bottom profiling system that uses a long (typically 100 ms) outgoing pulse and sweeps through a wide range of frequencies (2-5 kHz) (Figure 6). The returned signals are correlated with a replica of the outgoing pulse which effectively collapses the returned signal into a narrow, high-resolution impulse. The matched filter output is a correllogram with impulses representing the reflectors in both time and amplitude (Figure 7). The resolution is a function of the width of the correlation peaks which are, in turn, a function of the original bandwidth of the outgoing signal. With careful scaling, the amplitude of the correlation peaks should be directly proportional to the sediment reflection coefficients, if attenuation, spherical spreading loss, and other amplitude-degrading factors can be accounted for. The correlation process is fairly insensitive to noise, and spherical spreading loss can be corrected for by time-varying gain. Sediment attenuation, however, presents a much more difficult problem. We can, however, use the bandwidth of the system to estimate attenuation and then to make corrections. In order to estimate attenuation, we use a 'two-band' correlation technique which calculates the ratio of the amplitude between low pass and high pass filtered correllograms (Figure 8). From this ratio, a frequency-dependent attenuation coefficient can be calculated. The practicality of the technique was demonstrated two years ago (ed. note: 1982) when a shallow water prototype system was built and subjected to field trials in Narragansett Bay where bore hole and geologic data were available. Although only a 250 watt power amplifier was used to drive the transducers, penetration up to 12 meters in sand was obtained. Figures 9 and 10 show some test results of these trials. Table 1 shows a comparison between calculated values of reflection coefficient compared with predicted values from Hamilton's (1970) data.

A deep water chirp sonar, interfaced to Lamont Doherty Geological Observatory's SeaMARC I side scan vehicle has been constructed and successfully deployed in 3,000 m of water on the Laurentian Fan. "Ground truthing" of this instrument awaits the seismic intercalibration experiment to be discussed later.

SEDIMENT PROPERTY RELATIONSHIPS

An interactive data bank with over 90,000 entries of sediment physical and acoustic properties has been established to aid in the remote identification of sediment properties by acoustic means, In addition, a 'depositional process-oriented impedance model' for marine sediments is being developed. This model uses an understanding of the processes responsible for the deposition of sediment in a particular depositional environment to predict the expected shape of the impedance curve for a particular depositional environment. Inversely, the model can be used to identify depositional environment for an impedance profile from an unknown sediment type.

For example, from earlier studies on the deep-sea carbonate curves discussed before (Mayer, 1979b), it was established that the variations in acoustic impedance variations were the result of contrasts in saturated bulk density (rather than velocity) which, in turn, were caused by fluctuations of calcium carbonate content (Figure 11).

Fluctuations in calcium carbonate can be directly linked to glacial/interglacial climatic cycles, and thus the impedance signal is climatically forced and will therefore have a very cyclic appearance (Figure 12a). In other depositional environments, different mechanisms are responsible for impedance contrasts (eg., there appears to be no major impedance contrasts in deep sea clays and very sharp, spikey impedance contrasts for deep sea turbidites). This technique allows for the application of simple pattern recognition schemes to impedance profiles for the identification of depositional environment (Figure 13).

SEISMIC INTERCALIBRATION EXPERIMENT

The deep water chirp sonar, along with 13 other seismic sources (or source combinations) including sparkers, airguns and waterguns will be tested at a site in 4,600 m of water off Cape Hatteras where the Deep Sea Drilling Project's vessel, Glomar Challenger has collected continuous cores to a depth of 1,800 m below the seafloor. The experiment will provide a unique opportunity to compare many seismic systems to each other as well as to "ground truth" provided by the bore hole. In addition, collecting seismic data over a wide range of frequencies should provide a unique perspective on the origin of the lower Continental Rise off North America.

Table 1 - Narragansett Bay Sediment Properties

	Reflection Coefficient		Attentuation Coeff. db/kHz/m	
Interface	Predicted	Calculated	Predicted	Calculated
Sediment/Water	0.24	0.20	0.51-0.7	0.46
Sand/Till	0.47-0.12	0.10		

REFERENCES

Mayer, L.A., "The Origin of Fine-Scale Acoustic Stratigraphy in Deep-Sea Carbonates", Jour. of Geoph. Res., 84, No. B11, 1979a, pp. 6177-6184.

Mayer, L.A., "Deep Sea Carbonates: Acoustic Physical and Stratigraphic Properties", Jour. Sed. Pet., 49, No. 3, 1979b, pp., 819-836.

Hamilton, E.L., "Prediction of In-Situ Acoustic and Elastic Properties of Marine Sediments", Geophysics, 36. No. 2, April 1970.

QUESTIONS

Q. Not recorded.

A. The penetration is a function of the time and bandwidth product so the larger the time-bandwidth product the deeper the penetration. You can think of the correlation process as collapsing all the energy in the long pulse back into the spike so the longer that pulse the larger that correlation peak is going to be in terms of energy.

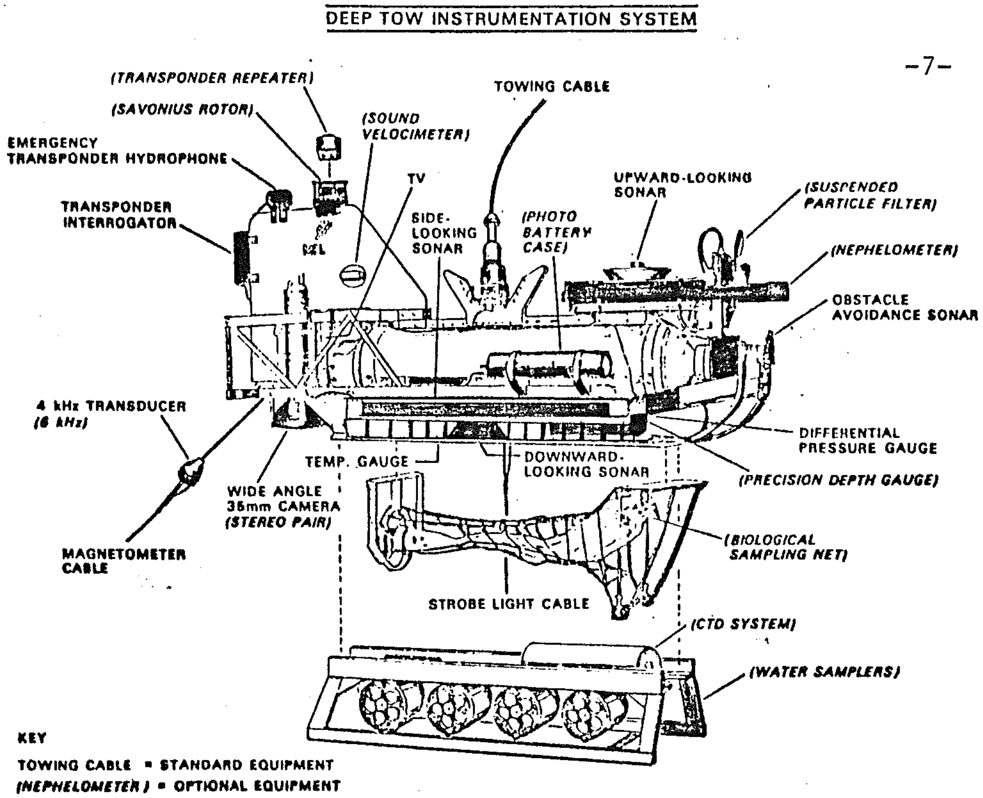


Figure 1 The Scripp's Institution of Oceanography's deep tow geophysical instrumentation package

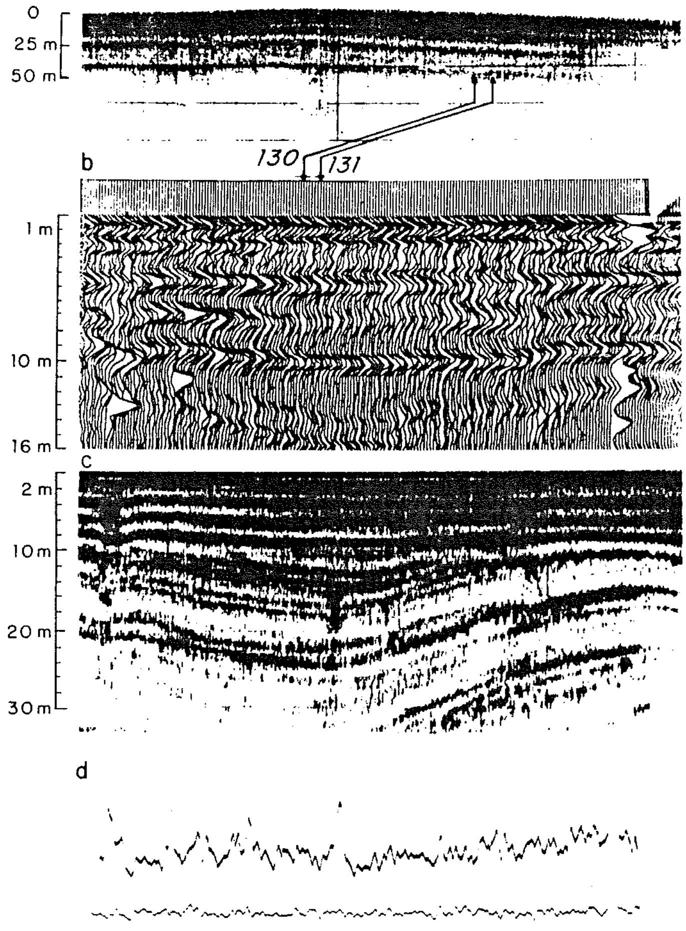


Figure 2 Raw and processed acoustic signatures

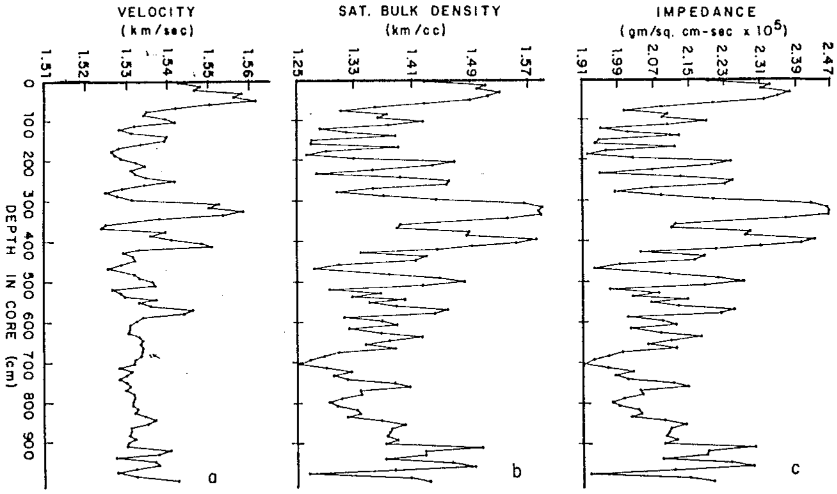


Figure 3 Acoustic Impedance profiles from a deep sea core

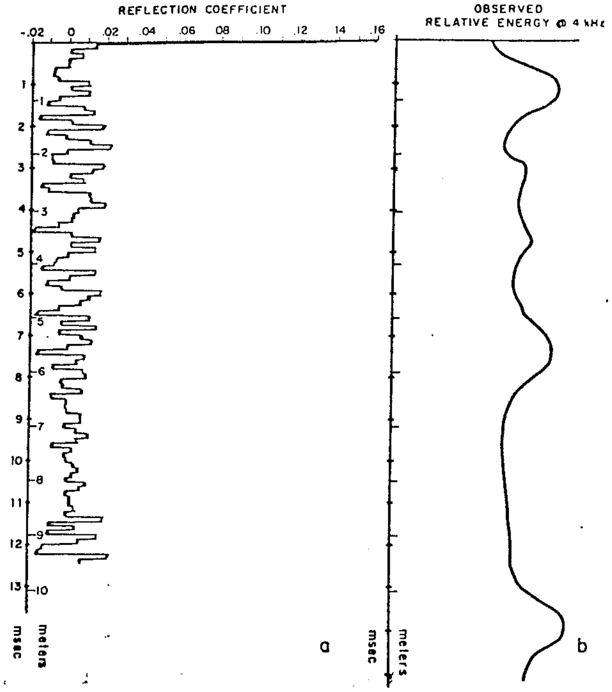


Figure 4 a) Reflection coefficient log calculated from impedance profile for 10 micro second thick layers. (Represents 1246 reflection coefficients)

b) Deep-Tow 4 kHz reflection profile at core site -- from computer-processed equivalent intensity display.

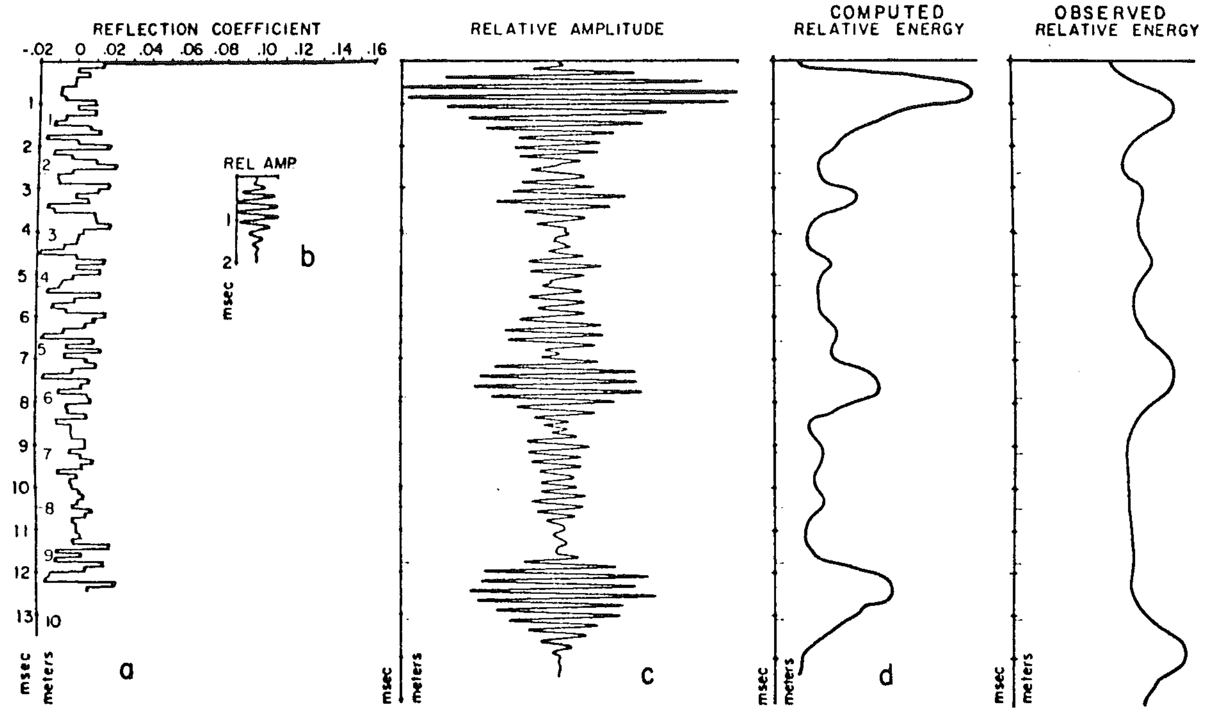


Figure 5 a) Reflection Coefficient log
b) Digitized outgoing 4 kHz pulse of the Deep-Tow
c) Output of the convolution of Figures 5a and 5b (amplitude)
d) Output of the convolution of Figures 5a and 5b (energy)
e) Deep-Tow 4 kHz profile (reflection)

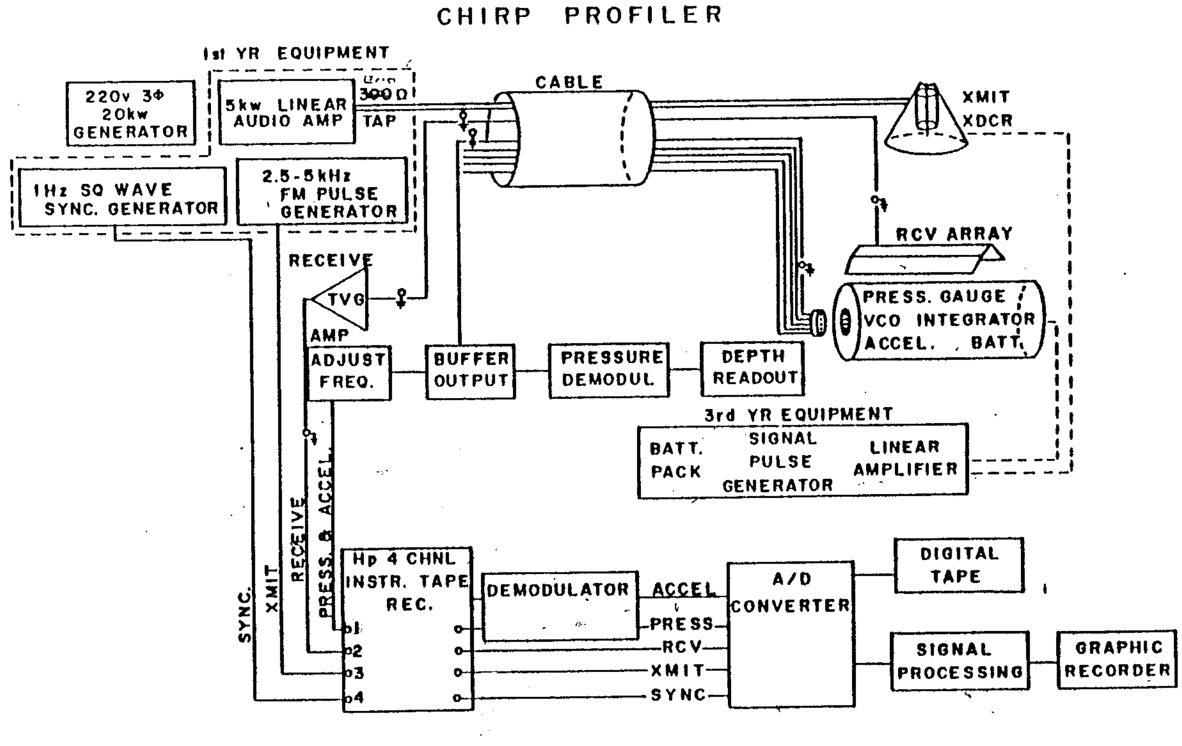
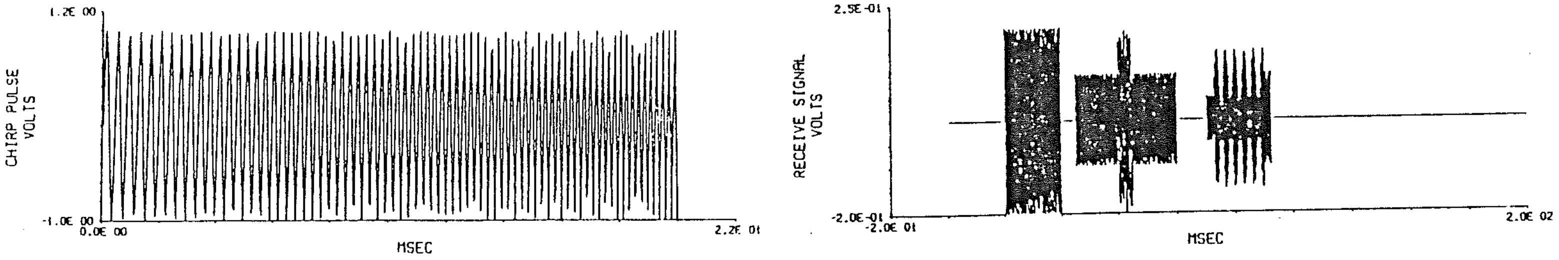
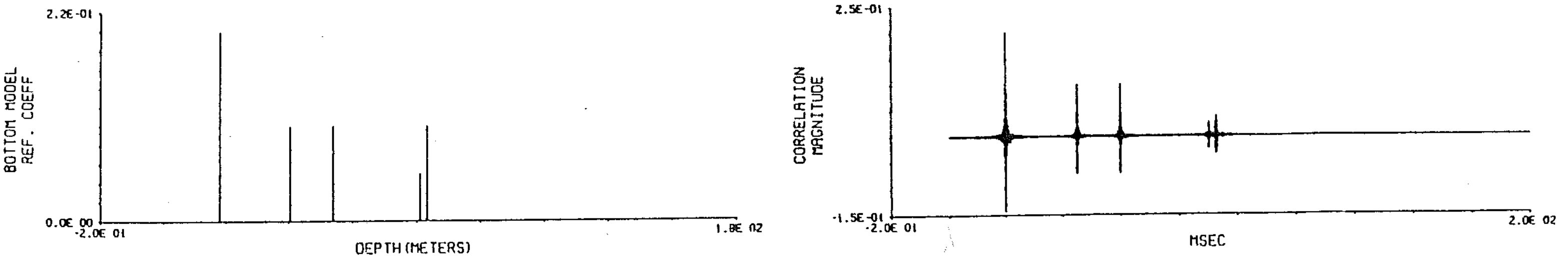


Figure 6 Schematic Diagram of the Chirp Sonar system



a) Linear 2.5 - 5 kHz chirp

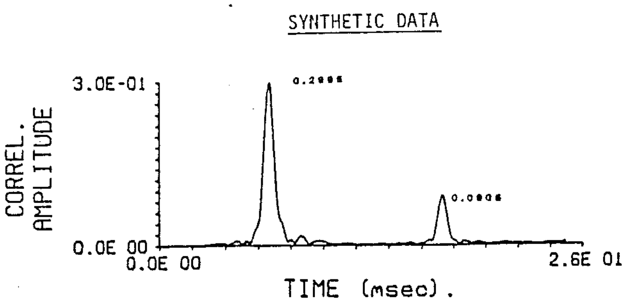
b) model sediment structure



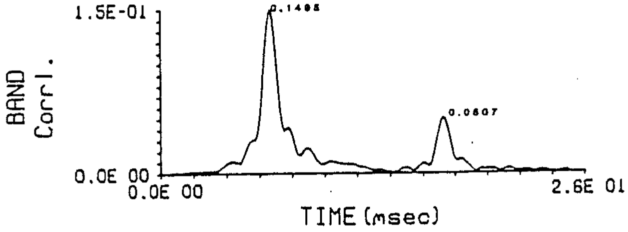
c) Convolution of a) & b) Note resonance in deep structure

d) Matched filter correlation

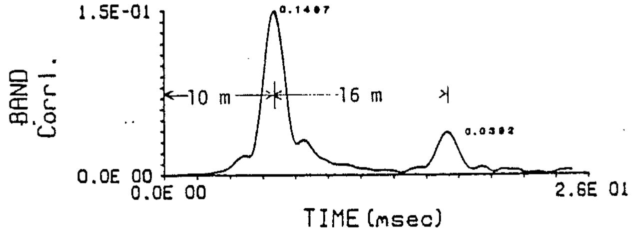
Figure 7 Chirp Sonar signal processing



a) full band correlation



b) low-pass filter correlation



c) high-pass filter correlation

Figure 8 Two-Band method of estimating attenuation coefficient - time domain plot. (Returned signal)

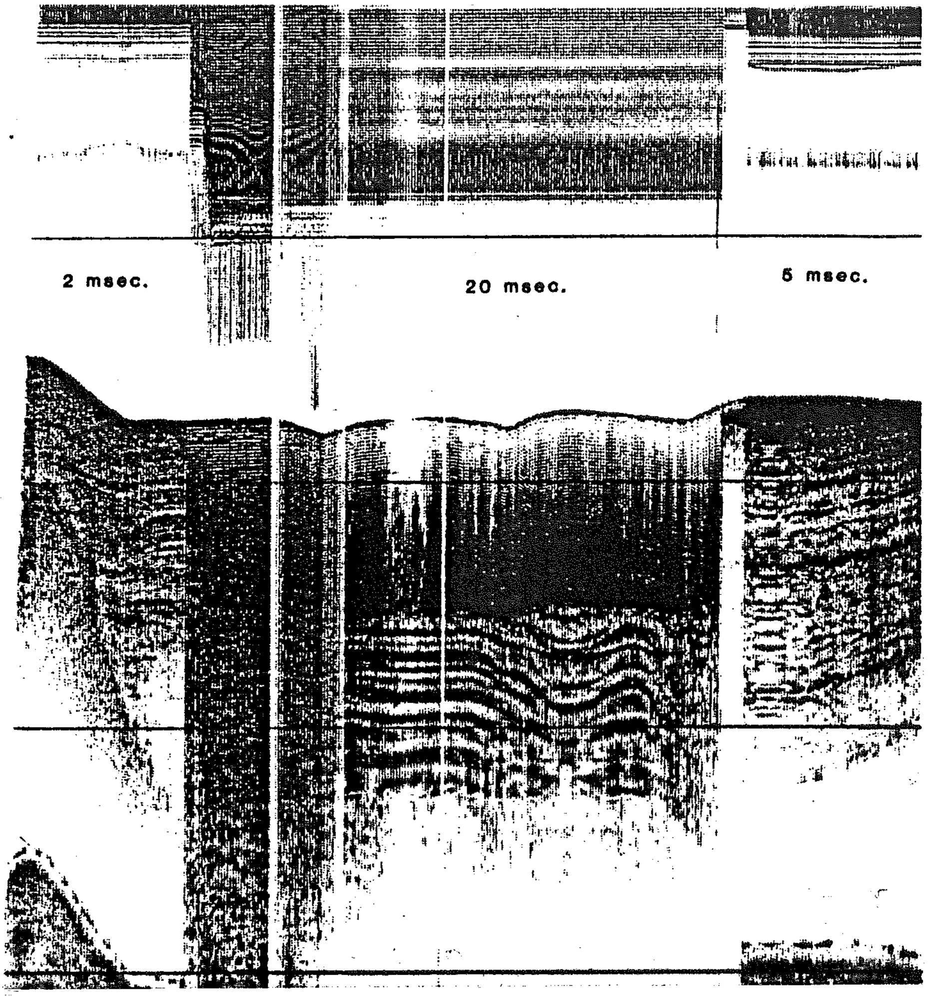


Figure 9 a) Field trials in Narragansett Bay examining penetration as a function of pulse length. Steeply sloping surface in 2 ms record is edge of bedrock valley near Jamestown Bridge.

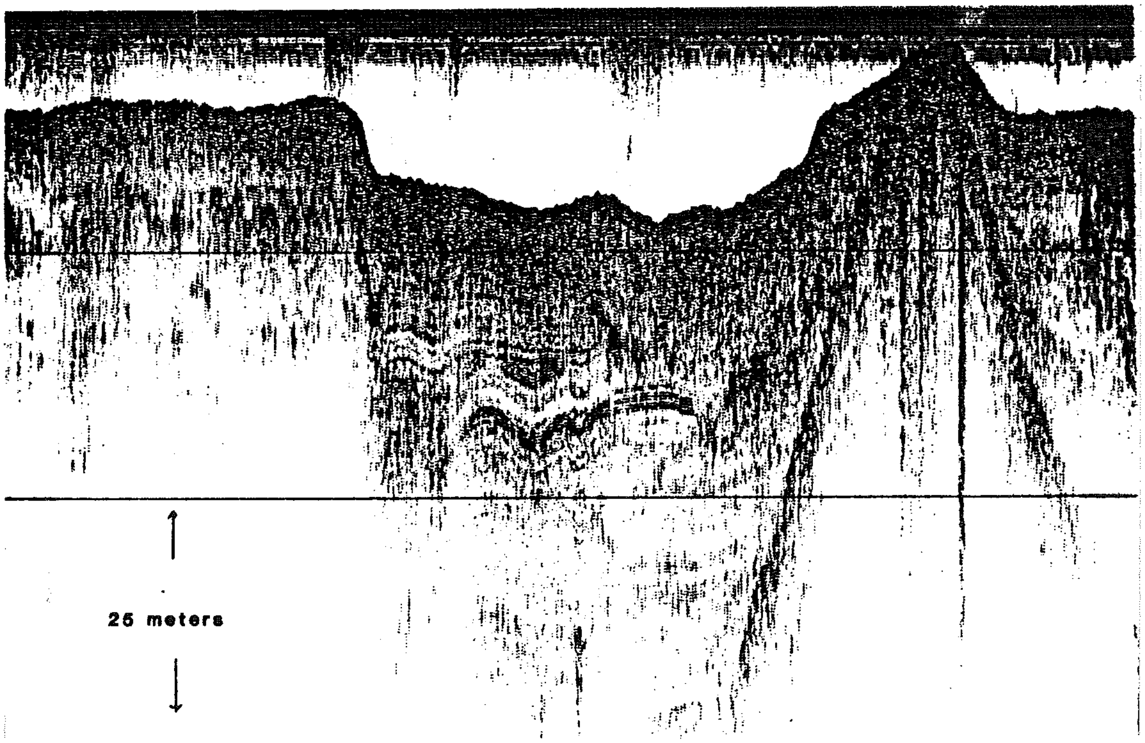


Figure 9 b) Unprocessed, high power 2 ms chirp profile from Dutch Island to School of Oceanography. While resolution is increased, processing is still necessary to achieve theoretical resolution.

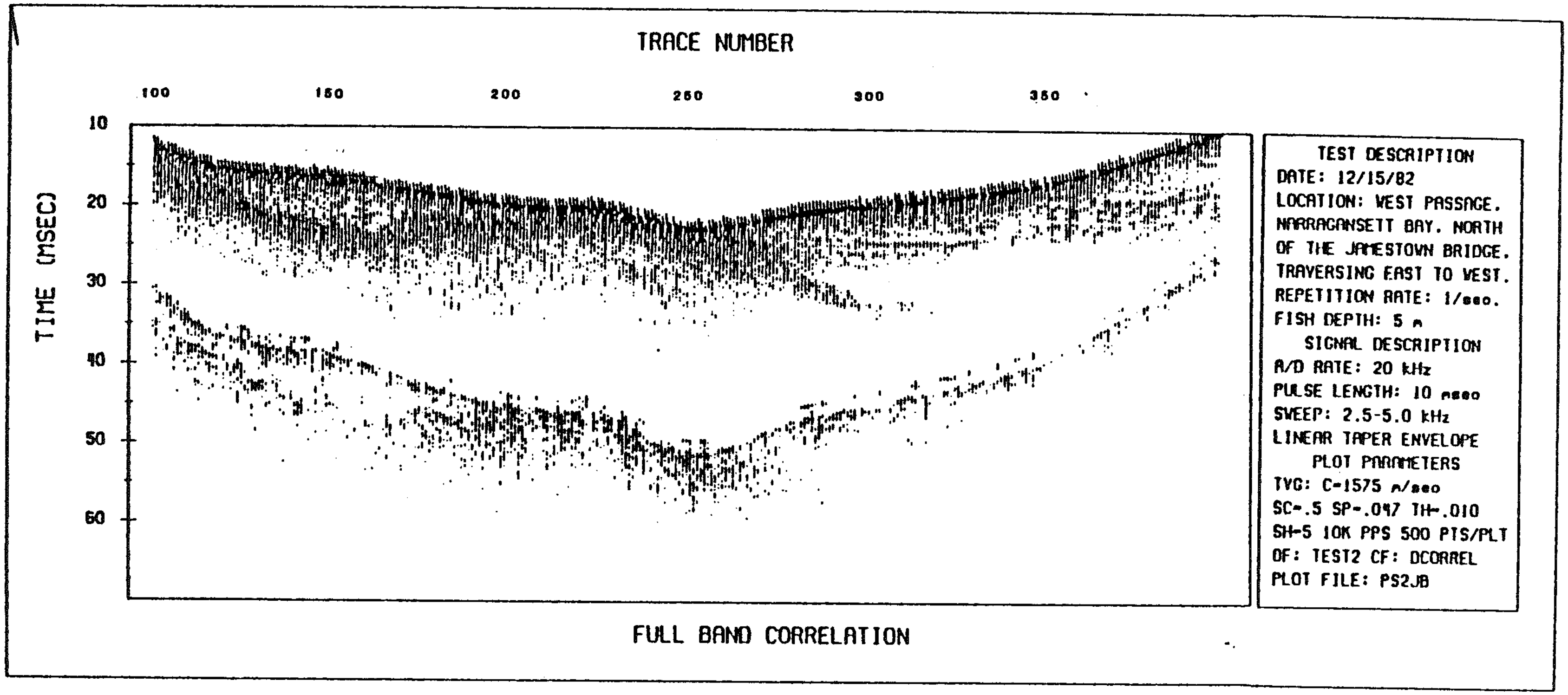


Figure 10 Photo-reduced "filled trace" display of correlation processed chirp sonar data from Narragansett Bay. Digitally recorded 15 Dec. 1982

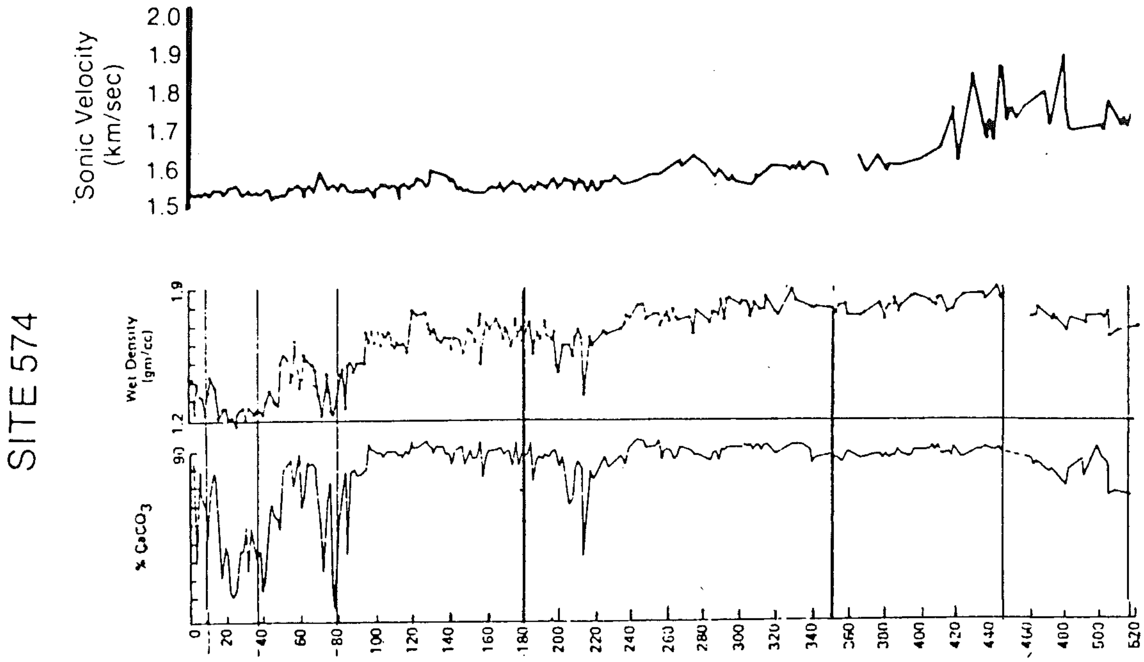


Figure 11 Down-core velocity, density and carbonate values from 520 m long DSDP Site 574 in Equatorial Pacific

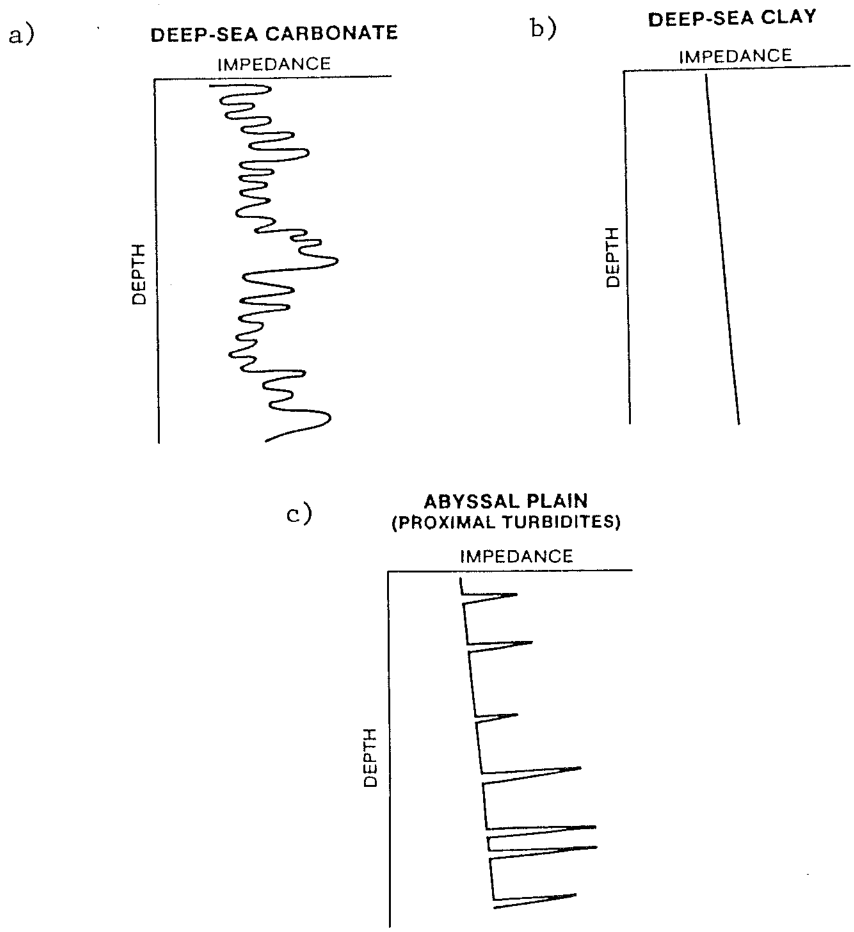
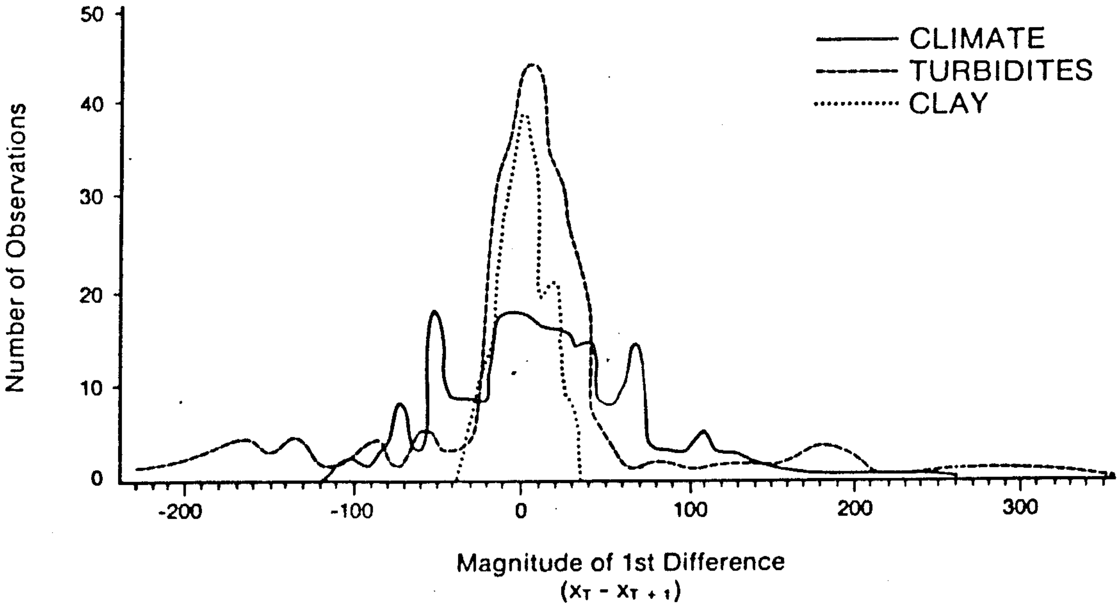


Figure 12 Impedance models for a) deep-sea carbonates, b) deep-sea clay and c) deep sea turbidite environments.



a) Histograms of the magnitudes of the first differences of impedance data from equatorial Pacific and North Atlantic cores.

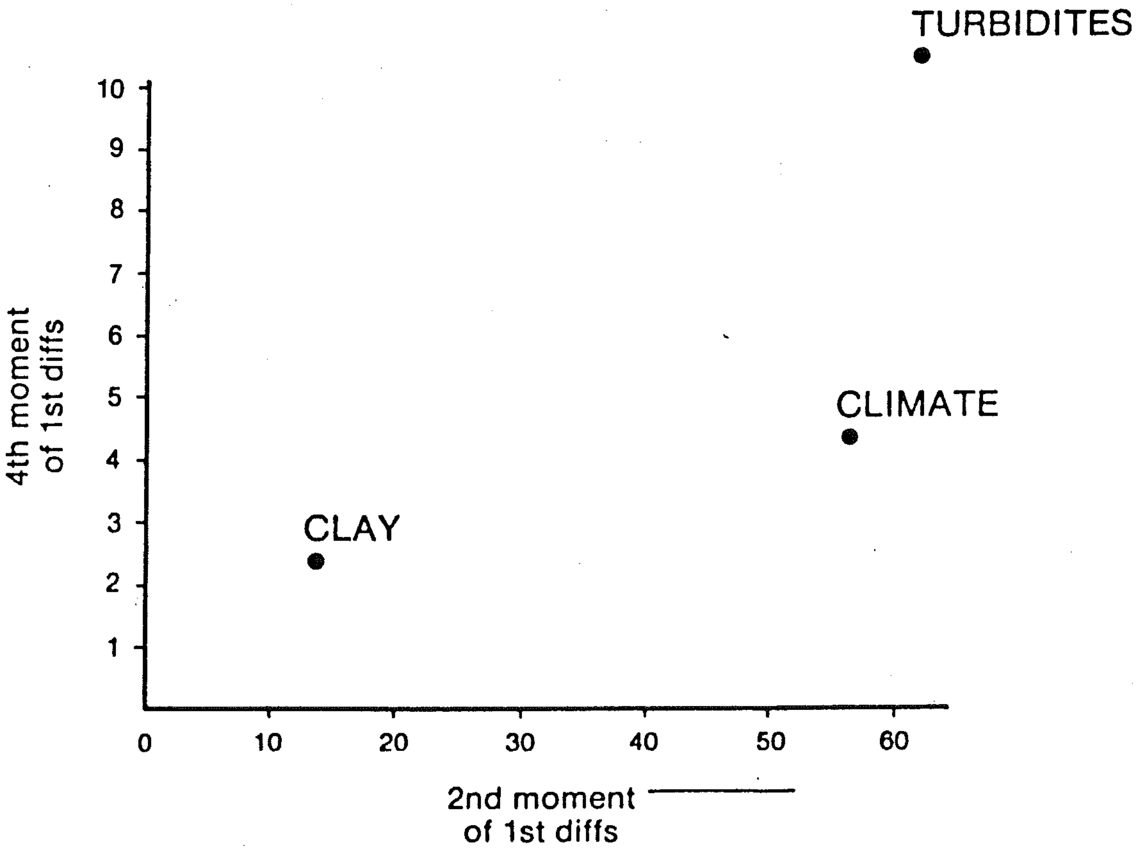


Figure 13b Plot of Second against Forth moment of above histograms

ACOUSTIC WAVE PROPAGATION IN FROZEN AND CLATHRATE HYDRATE-BEARING SEDIMENTS

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Expressions for acoustic wave velocities, based on the scattering theory proposed by Kuster and Toksoz (1974), have been developed for partially frozen water-saturated sediments. The original two-phase model has been modified to account for the three phases found in permafrost: ice, water, and solid matrix material. The first stage in development of the three-phase model is the development of an ice matrix in which water inclusions form. The elastic properties are calculated for a complete spectrum of ice/water ratios. The elastic constants of this ice/water mixture can then be employed in a second model of a matrix of varying ice/water content with quartz inclusions. Thus the elastic properties of the three-phase system are obtained.

The physical reasoning behind the suggested model is discussed in terms of water absorbed on a silicate surface and the silicate/ice/water interface. Application of the model to clathrate hydrate-bearing sediments is also discussed. Zimmerman's (1984) recent work on a new self-consistent theory for the elastic properties of two-phase systems appears to confirm validity of the Kuster and Toksoz (1974) scattering theory.

The results of laboratory measurements of acoustic-wave velocities in frozen and unfrozen sediments are presented. Agreement of the laboratory data with predictions from the proposed theory, and certain departures from it, are discussed.

INTRODUCTION

In this presentation, I am going to discuss a theoretical model for partially frozen, water-saturated sediments. This model has recently been developed to fit acoustic data on permafrost that I originally collected on permafrost over a 15 year period while at the University of Saskatchewan (King, 1984).

THREE PHASE MODEL

Figure 1 shows the basic three-phase model to be a matrix of mineral grains with the intergranular water in both the unfrozen and frozen states. The model assumes that around each grain there exists a continuous unfrozen film of adsorbed water which gets thinner as the temperature is decreased, to the extent that eventually grain-grain contact develops, particularly at the sharp corners. The important aspect of the above model is the continuous film of water around each grain. The reported research attempts to develop the acoustic wave propagation characteristics for a complete spectrum of ice/water/quartz ratios.

As a basis for this three-phase model, a two-phase model has been used which was originally developed by Kuster and Toksoz (1974) in terms of elastic wave scattering theory, the validity of which has been more recently confirmed by Zimmerman (1984) using a rigorous, self-consistant analysis of the elastic properties of a solid material with inclusions.

For permafrost the Kuster and Tuksoz theory is modified to account for three phases:

1. For consolidated permafrost sediments the first stage is to consider an ice matrix in which spherical water inclusions form.
2. The elastic properties (bulk and shear moduli) are calculated for a complete spectrum of ice/water ratios.
3. The elastic constants for this ice/water mixture are then employed in a second model of a matrix of varying ice/water content with quartz inclusions.

In this way the elastic properties for the three-phase system are obtained.

The results of this procedure on a three-phase system are summarized in Figure 2 where the predicted compressional wave velocity relationship with porosity is plotted for different fractions of ice in the pore space.

Other three phase systems could also be modelled in a similar manner. However, no laboratory measurements have been made to confirm their validity. When hydrates are present in place of saline water in the model a small difference in predicted velocity exists. It is however felt that on the basis of this model it would be difficult to distinguish between clathrate hydrate saturation and complete ice saturation.

FIELD AND LABORATORY MEASUREMENTS

Figures 3, 4 and 5 show results of compressional wave velocity measurements made on core samples of permafrost. The specimens were stored at -9°C and transported from the Arctic in their original state. The tests were performed at temperatures in the range of -15°C to +5°C. with the temperature being increased in steps. Figure 6 shows similar results of shear wave velocity measurements.

For temperatures less than 0°C we discovered a linear relationship between compressional wave velocity and the fraction of clay-sized particles for the different ranges of porosities. This relationship can be seen in Figure 7. Using these data the fraction of ice in the pore space can be predicted, as indicated in Figure 8.

Above 0°C we found that the compressional wave velocity bore no relationship to the fraction of clay-sized particles (Figure 9). The Kuster-Toksoz theory appears to provide a lower bound to the velocity/porosity relationship. Calculations of compressional wave velocity through a sphere pack under hydrostatic stress, using Biot's theory to predict the effect of water saturation, show better agreement with the data.

CONCLUSIONS

The Kuster-Toksoz wave-scattering model when extended to a three-phase system, provides a good estimate of compressional wave velocity in permafrost where the clay content is small. Where appreciable fractions of clay-sized particles are present in the permafrost, the compressional wave velocity is found to correlate well with the water-filled porosity. The model predicts only small differences in velocity when the ice in the pore space is replaced by clathrate hydrates.

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King, M.S., "The Influence of Clay-sized Particles on Seismic Velocity For Canadian Arctic Permafrost", Canad. J. Earth, Sci., 21, 1984, pp. 19-24.

Kuster, G.T. and Toksoz, M.N., "Velocity and Attenuation of Seismic Waves in Two-Phase Media, Part I, Theoretical Formulations", Geophysics, 39, 1974, pp. 587-606.

Zimmerman, R.W., "The Effect of Pore Structure on the Pore and Bulk Compressibilities of Consolidated Sandstones", Unpublished Ph.D. Thesis, University of California, Berkeley, 1984, pp. 116.

QUESTIONS

Q. (from the floor) Under what conditions were the velocity measurements on the core made at temperatures above 0°C?

A. These were performed under drained conditions. Upon unfreezing, the water expelled from the pore spaces by the confining pressure was collected. Upon refreezing, the resulting velocities are usually slightly higher than the original ones because of the generally lower water content of the specimen.

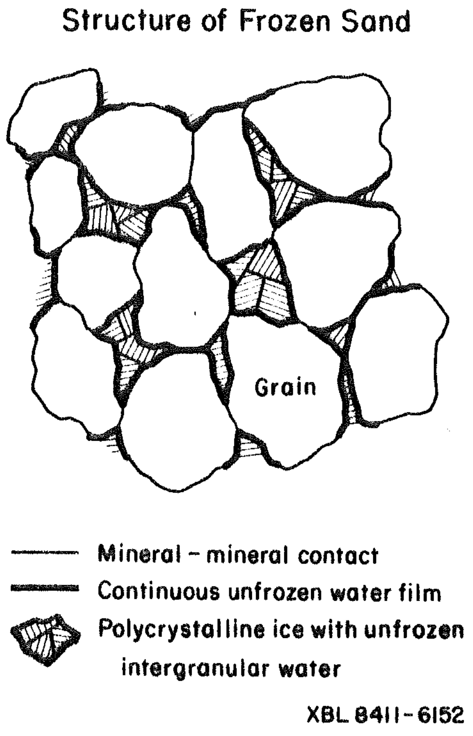
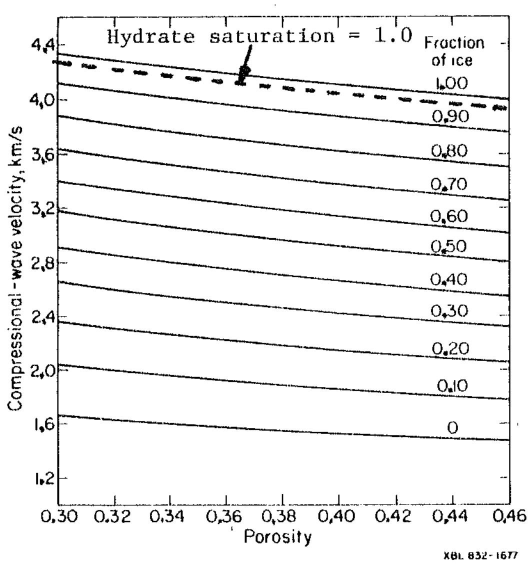


Figure 1 Structure of the proposed three phase model of frozen sand



Elastic properties of constituents of 3-phase system

	Ice	Water	Quartz	
K	8.4	2.0	44.0	10^9Pa
μ	3.7	-	37.0	10^9Pa
ρ	920	1000	2700	Kg/m^3

Figure 2 Theoretical Compressional wave velocity versus porosity for various ice contents

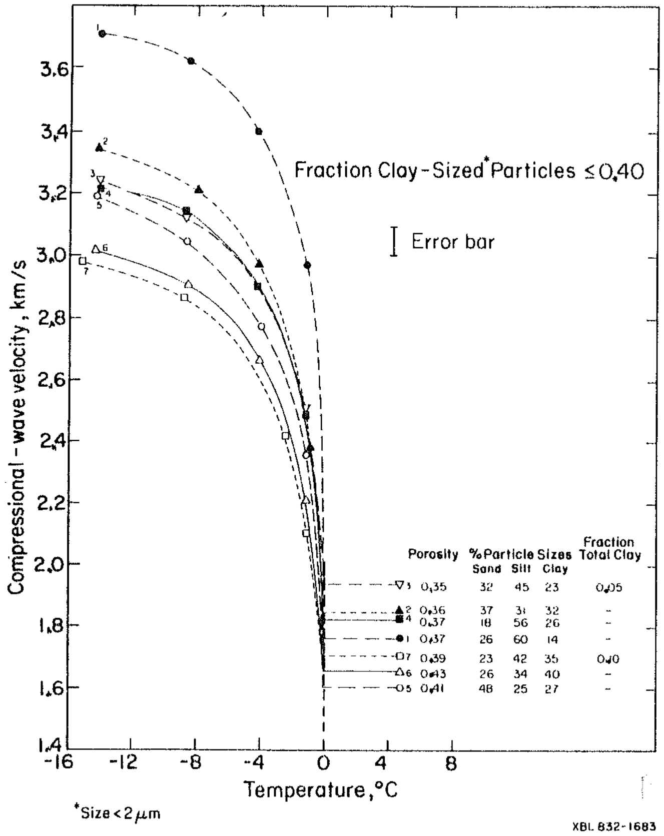


Figure 3 Compressional wave velocity versus temperature

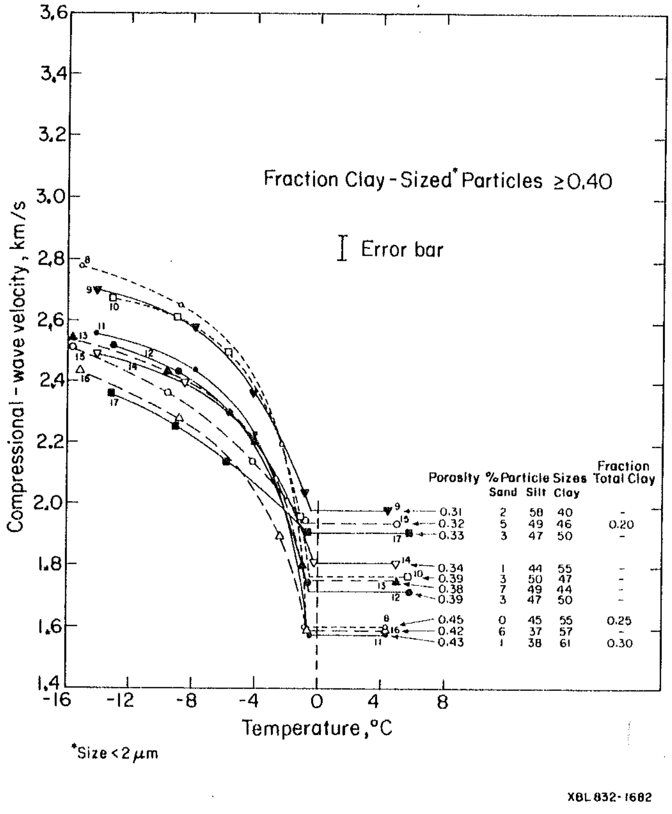
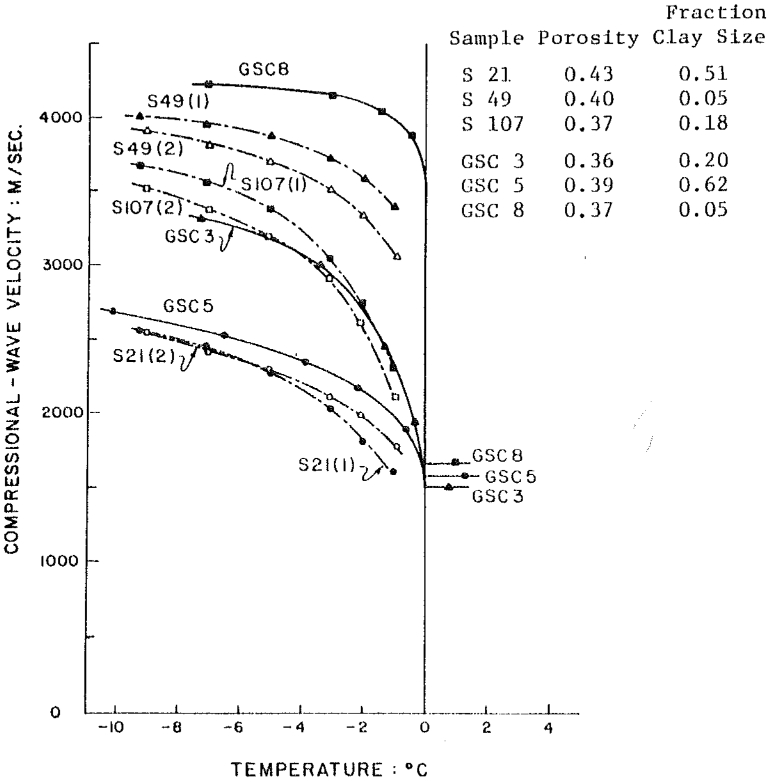


Figure 4 Compressional wave velocity against temperature



Sample	Porosity	Fraction Clay Size
S 21	0.43	0.51
S 49	0.40	0.05
S 107	0.37	0.18
GSC 3	0.36	0.20
GSC 5	0.39	0.62
GSC 8	0.37	0.05

Figure 5 Compressional wave velocity against temperature

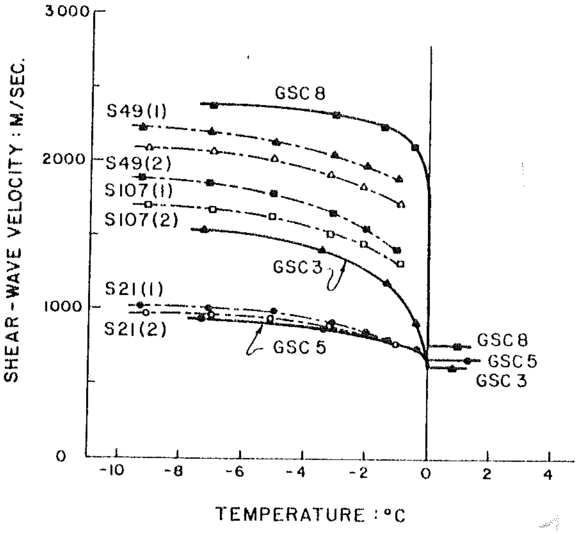
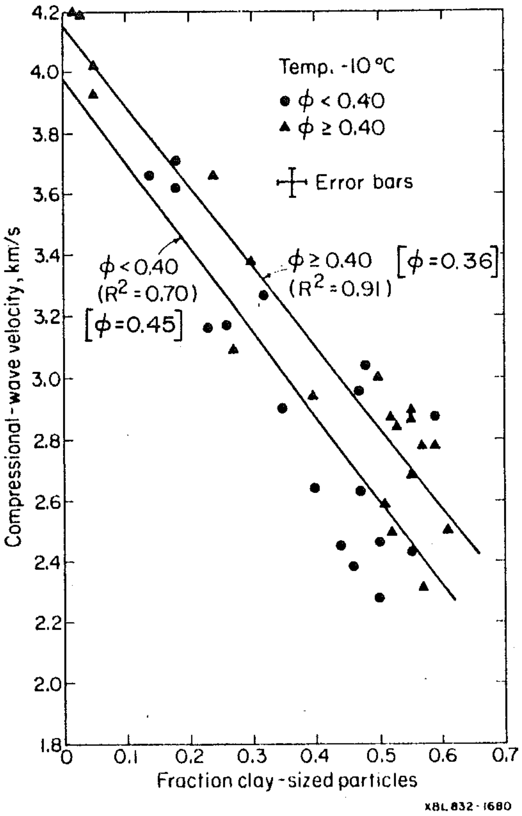


Figure 6 Shear wave velocity against temperature



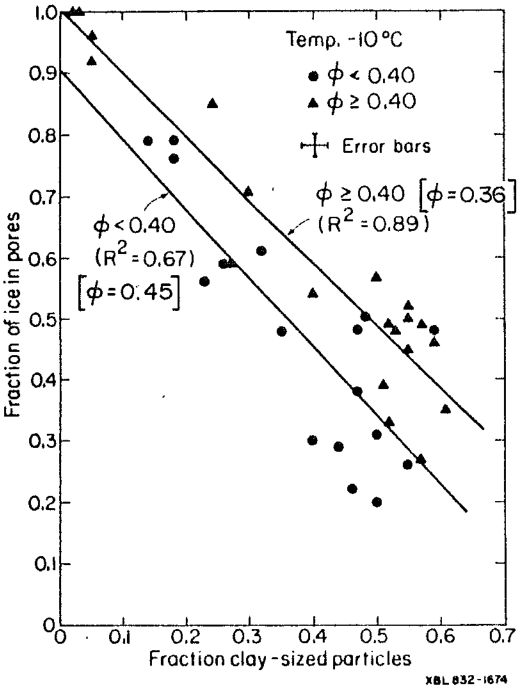


Figure 7 Compressional wave velocity versus fraction of clay-sized particles at temp. of -10°C.

Figure 8 Fraction of ice in pores versus fraction of clay-sized particles at temp. of -10°C.

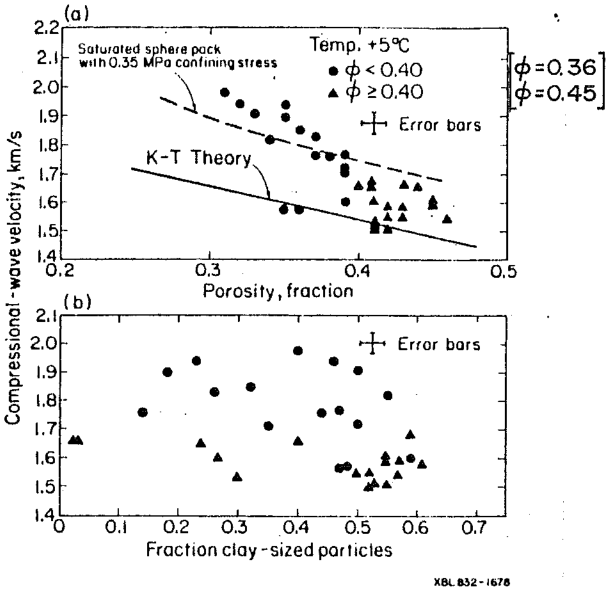


Figure 9 Compressional wave velocity versus (a) porosity, and (b) fraction of clay-sized particles at temperature of $+5^{\circ}$C.

USE OF SHEAR AND COMPRESSIONAL WAVES TO DETERMINE LIQUEFACTION RESISTANCE OF SAND.

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Sand liquefaction is a potential problem for offshore structure foundations subjected to significant storm-wave loading or earthquakes. Current techniques for estimating liquefaction potential are based on empirical correlations with penetrometer resistance. Direct testing of specimens in the laboratory is not usually done because the in-place grain structure of the sand is destroyed during sampling. The long-term objective of this study is to develop a down-hole tool for measuring shear (S) and compression (P) wave velocities in situ, using this data to reconstitute samples for laboratory testing. Transducers were developed to measure P and S wave velocities in laboratory specimens which were then liquified under cyclic loading. Results show that characteristics relationships between elastic wave velocities and liquefaction can be established for each sand tested. On the other hand, velocity measurements alone will not quantify liquefaction resistance, since the resistance/velocity relationship is material-dependant. Current emphasis is on developing a prototype for the in situ tool. Studies of source/receiver type and configuration are in progress.

INTRODUCTION

In this presentation I shall be describing the work that has been undertaken in the Mechanical and Civil Engineering Departments of the University of New Hampshire over the last four and one half years. Our long term objective is to develop an in situ probe to measure S and P wave velocities in a sand deposit and to use this information to reconstruct samples in the laboratory. Since conventional sampling techniques tend to destroy natural grain structure, a measure of a physical property such as S or P wave velocity of a material in its undisturbed natural state may allow the reconstruction of an identical state in the laboratory following a sampling operation.

Our approach has been twofold:

1. A laboratory study to investigate the relationship between acoustic parameters and liquefaction resistance.
2. A feasibility study of transducer type and orientations for a prototype tool.

PHASE I

Phase 1 involved the modification of a triaxial liquifaction cell and the development of acoustic transducers followed by experiments to establish the correlation between velocity data and liquefaction resistance. As no suitable transducers that could easily fit into the end caps of a triaxial cell were commercially available a transducer capable of generating both P and S waves had to be developed.

A thickness expanding transducer is the normal method of generating and detecting P waves and construction presents few problems. However shear (S) wave generation and detection is more difficult because propagation depends entirely on the structure of the medium. Of five methods of shear wave generation (mode conversion devices, resonant column, radial expander, shear plate and bender bimorph), the bender bimorph was selected for use in these studies. The principal of operation of the bender bimorph is shown in Figure 1. The advantages of the bender bimorph over the other type of shear wave generators is that the relatively low mechanical impedence matches that of typical saturated sediments. The mechanical arrangement of each end cap of the triaxial cell is shown in Figure 2.

The second part of Phase I involved a testing program on the six types of sand described in Table 1 with grain size distribution plotted in Figure 3. Two methods of sample preparation were used:

1. Raining the dry material ("dry pluviation").
2. A tamping technique using moist material with compaction in thin layers ("moist tamping").

These methods allowed relative density values in the range 43-89% to be obtained. The samples were prepared in the mold, flushed with carbon dioxide and then saturated under back pressure greater than 0.92 atmospheres. This ensured that saturation was at least 99.9% complete.

Figure 4 shows the laboratory equipment arranged for sample testing. The P and S wave velocities were obtained as the specimen was subjected to undrained cyclic loading until $\Delta_u/\sigma_o^1 = 1$, where Δ_u equals residual pore pressure increase and σ_o^1 equals initial effective stress.

RESULTS FROM PHASE I

The results shown in Figures 5 through 10 can be broken down into two general categories.

1. Liquefaction resistance versus elastic wave velocity for different sands and one preparation method (Figures 5-8).
2. Fabric-Stress History effects on velocity for one sand and different preparation methods (Figures 9-10).

The important message in these relationships is that a measure of velocity alone does not define a sand's physical characteristics i.e., the graph of liquefaction cyclic stress ratio (normalized back to 10 cycles) against P or S wave velocity is not a unique solution for all sands. Further, when loaded to failure each sand had a different stress ratio depending both on its relative density and the preparation method (Figures 9 and 10). The interesting point here is that two distinct answers for both S and P wave velocities are obtained depending on the method of preparation. The question that the above raises is: Is there a unique liquefaction/elastic velocity relationship for a given sand? We are willing to answer "Yes, for a given sand" in a given deposit.

Figure 11 indicates that the cyclic stress ratio versus S wave velocity for the Dover 40-50 sand falls on one line for both preparation techniques. Likewise, when cyclic stress ratio is plotted against saturated P wave velocity, a relationship that we consider unique exists (Figure 12). From our Phase I effort we conclude the following:

1. Characteristic V_s or V_p versus liquefaction resistance curves for a given sand include stress-history effects
2. Field measured V_s, V_p provide two independently measured indicators for specimen reconstitution.
3. Field velocities alone do not provide an unambiguous measurement.
4. Additional work must be done on signal shape.

Item 4 deserves further discussion. It is easily understandable that different relative densities, different water contents and different methods of preparation will give a different mechanical response which affects the shape of the received signatures. Essentially, the same amount of energy is being transmitted on the sample each time and contingent upon the material we therefore obtain a different response. Some responses display a well defined envelope whereas others give a broad response. These data are presently undergoing further study.

PHASE II

The Phase II program for the in situ tool based on a wireline, self-boring pressuremeter concept is underway. Testing has been conducted on various transducers and configurations. The idea is to drill a prescribed distance ahead of a drill string with a self-boring tool, perform the acoustic measurement, advance the tool and repeat the measurements until the maximum tool extension has been reached. At this point, the tool will retract into the drill string and the drilling will continue until the next position for a testing sequence has been reached. Phase II is still in its conceptual stage, no construction has yet taken place.

TRANSDUCER DEVELOPMENT

As far as transducer development is concerned a torsional method of producing shear waves using a pair or protruding fins was tested in a sediment chamber. This proved unsuccessful because of structure borne noise. Experiments using the triaxial cell transducers mounted side by side and flush to the tube wall indicated that a surface wave along the sediment/wall interface was being produced. There was also a problem with directionality. We are now experimenting with single bimorph bender probes deployed from the side of the tube. These will be mounted one above the other and will retract when the probe position is changed. Table 2 summarizes the Phase II feasibility study.

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Roe, G., "An Acoustic Method for Identifying Sand Fabric and Liquefaction Potential", Ph.D. Dissertation, University of New Hampshire, Durham, NH, June 1981.

Roe, G.V., DeAlba, P.A. and Celikkol, B., "Acoustic Identification of Liquefaction Potential", Proceedings of the International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri-Rolla, Vol. 1, Rolla, MO, May 1981, pp. 199-202.

Janoo, V.C., "A Study of the Liquefaction Resistance of Various Sands Using Shear and Compression Wave Velocities", Masters Thesis, University of New Hampshire, Durham, NH, Sept. 1982.

QUESTIONS

Q. (from floor) When you were talking about the shear wave measurements, I think you mentioned 3.5 kHz for the resonant frequency. For the laboratory measurements how do you measure the time of the first arrival and what error bar do you put on your S wave velocity measurement?

A. We are measuring the arrival times from a digital oscilloscope with a 5 microsecond sampling interval. Several signals can be stored and an average taken. I have no information on the measurement errors involved.

Q. (from floor) Have you tried measuring the shear wave velocity in the samples after they have liquefied?

A. I don't believe so. This work was undertaken as PhD and Masters theses prior to my appointment.

Table 1

MATERIAL CHARACTERISTICS

Material	Characteristic Diams. mm.		Cu^1	Dry Unit Weight (pcf) ^{2}		$D_r{}^3$- Range Tested (%)	Particle Description
	D_{50}	D_{10}		Maximum	Minimum		
Ottawa 30-40	0.50	0.44	1.2	95.2	113.3	52 - 77	Rounded Quartz Sand
Monterey 0	0.41	0.31	1.4	89.5	105.7	47 - 89	Subrounded Quartz Sand Feldspars. Ferromagnesians
<u>Dover Sands</u>:							
40 - 50	0.35	0.30	1.2	82.9	103.4	52 - 76	Subangular - Angular Quartz Feldspars, Ferromagnesians Mica.
5%	0.29	0.095	4.2	92.0	119.6	58 - 66	5% Passing #200
15%	0.22	0.058	5.2	89.8	122.7	43 - 53	15% Passing #200
Holliston 00	0.42	0.23	2.0	88.2	107.4	56 - 83	Subangular Quartz Sand Feldspars, Ferromagnesians

Notes: 1: Cu = Coefficient of Uniformity D_{60}/D_{10} 2: by ASTM D 2049-69; one pcf = 0.16 kN/m^3

3: D_r = Relative Density (%)

Comment 1: Two specimen preparation techniques - Dry Pluviation: Pouring Technique - Moist Tamping: Compacting

Comment 2: Relative Density D_r - Major range of interest $50\% \leq D_r \leq 80\%$. Actual Values $43\% \leq D_r \leq 89\%$

Table 2 - Transducer Feasibility Study

<u>Mechanical/Electro Mechanical Sources</u>	<u>Laboratory Transducers</u>	<u>Miniature Single Bender Probe</u>
● Torsional Fin	● Flush mounted in pipe wall	● Move in and out perpendicular to tool longitudinal axis
● Piston	● Transducer directionality -	● Talk to each other in a direct fashion as in laboratory apparatus
Neither successful	Not favourable	

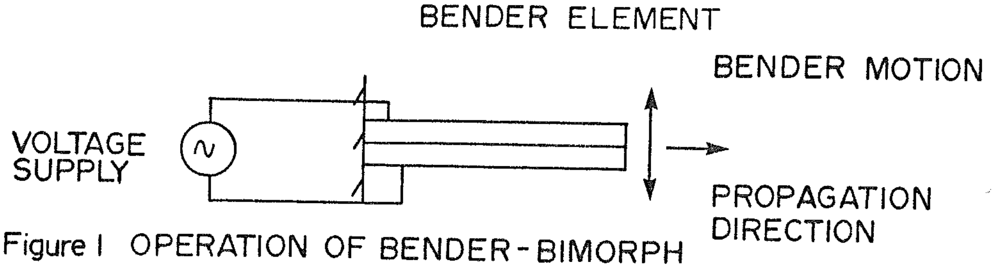
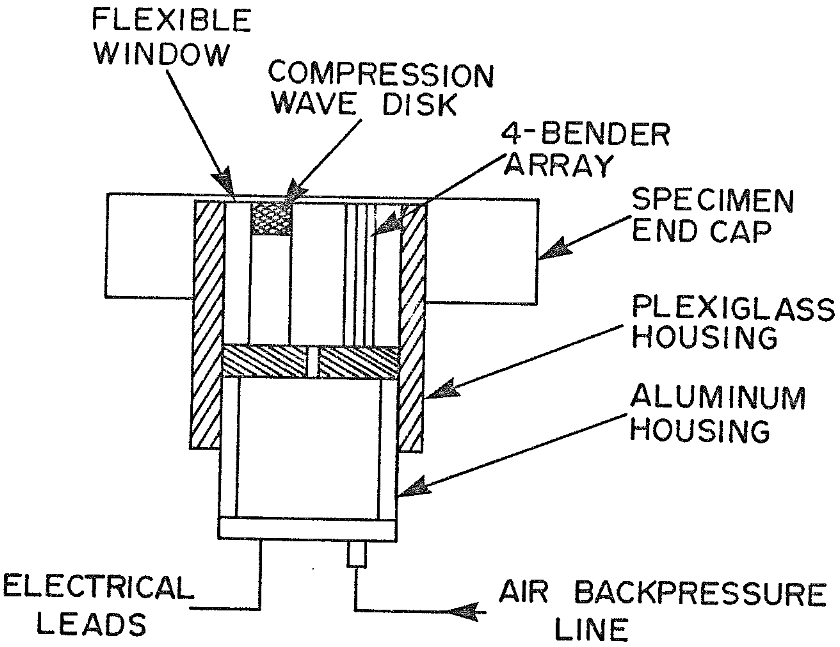


Figure I OPERATION OF BENDER-BIMORPH



BALDWIN-DE ALBA

- BOTH S AND P WAVE
- SELF CONTAINED WITH COMPLIANT ACOUSTIC WINDOW
- PRESSURE COMPENSATED TO AOID WINDOW AND BENDER FAILURE
- ADAPT TO VARIOUS SAMPLE DIAMETERS
- SURVIVES LOADS IN CYCLIC TRIAX TEST

Figure 2 DETAILS OF THE TRIAXIAL CELL ENDCAP

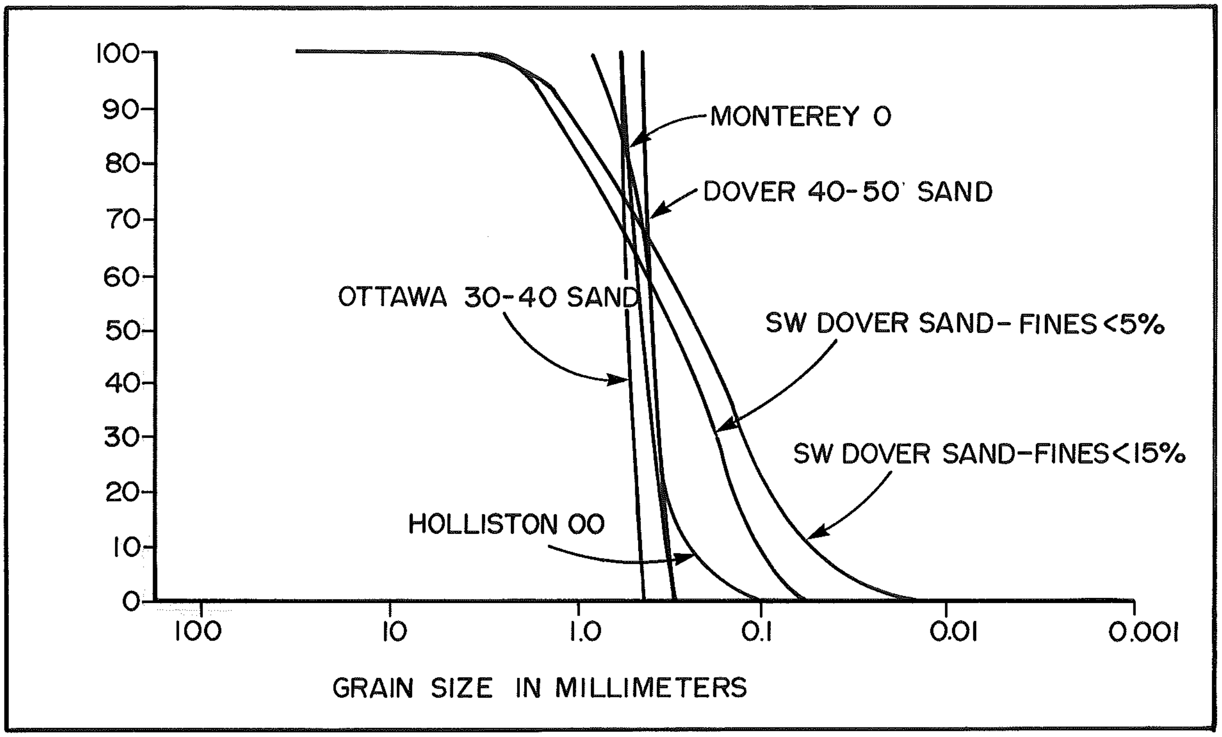


Figure 3 Grain Size Distribution of sand samples

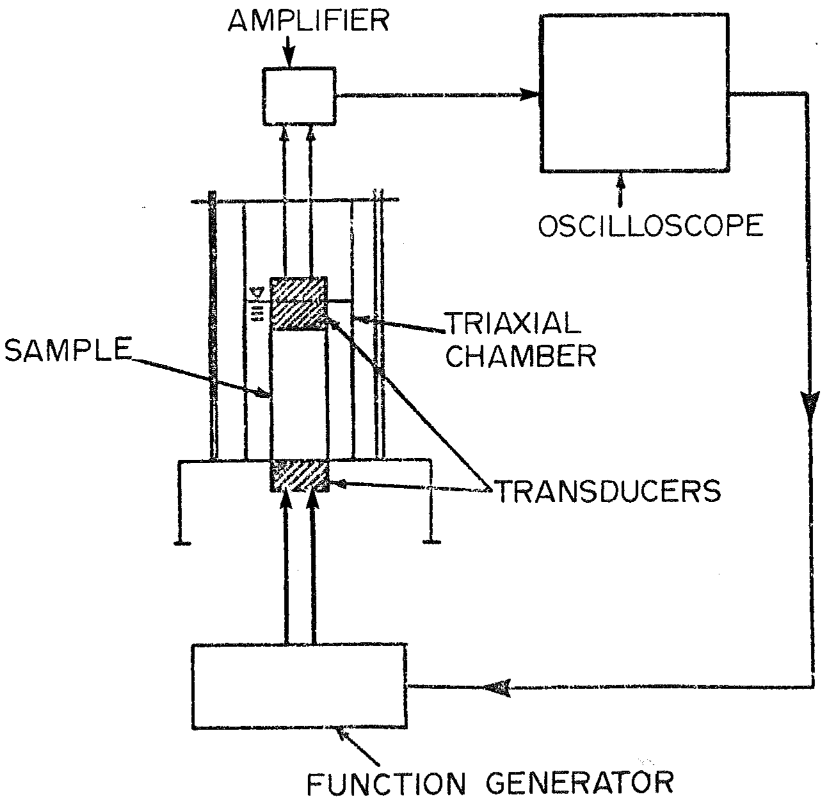


Figure 4 Laboratory equipment used for sample testing

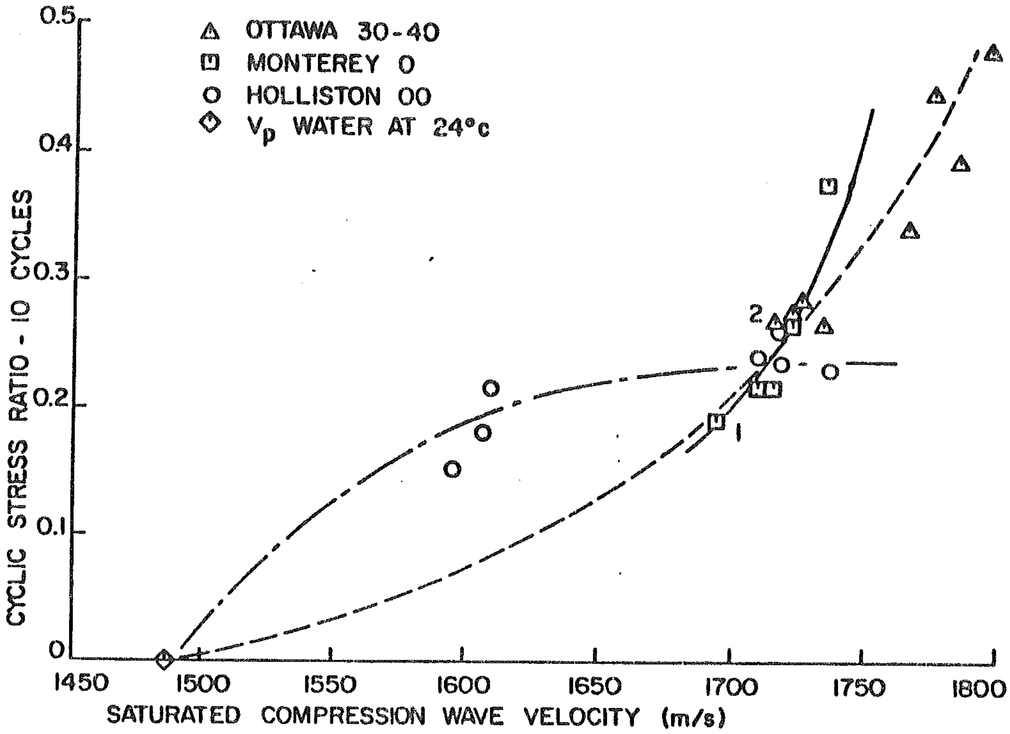


Figure 5 Cyclic Stress ratio against saturated compressional wave velocity for various sands

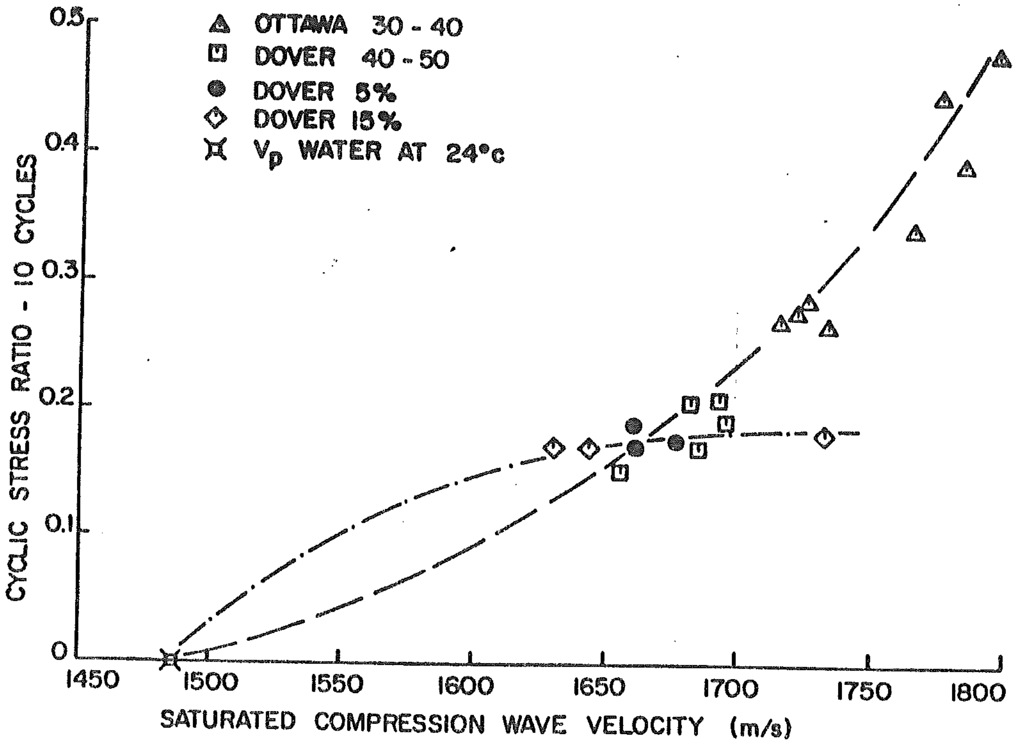


Figure 6 Cyclic Stress ratio against saturated comprssional wave velocity for various sands

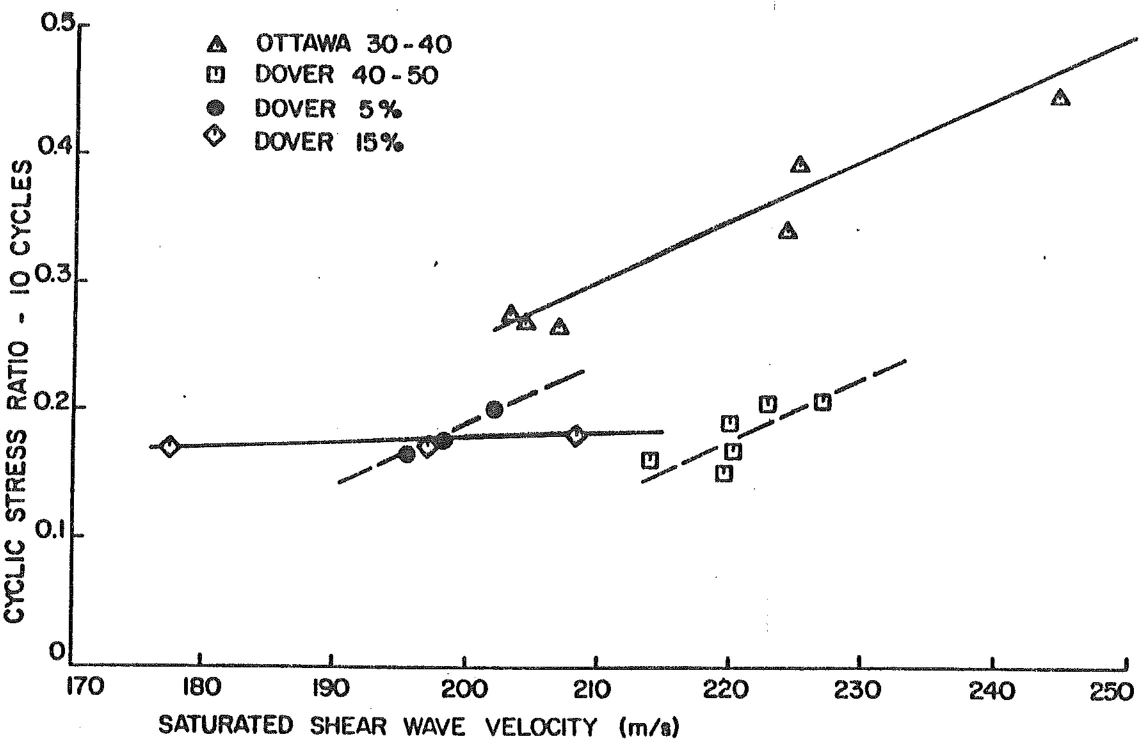


Figure 7 Cyclic stress ratio against saturated shear wave velocity for various sands

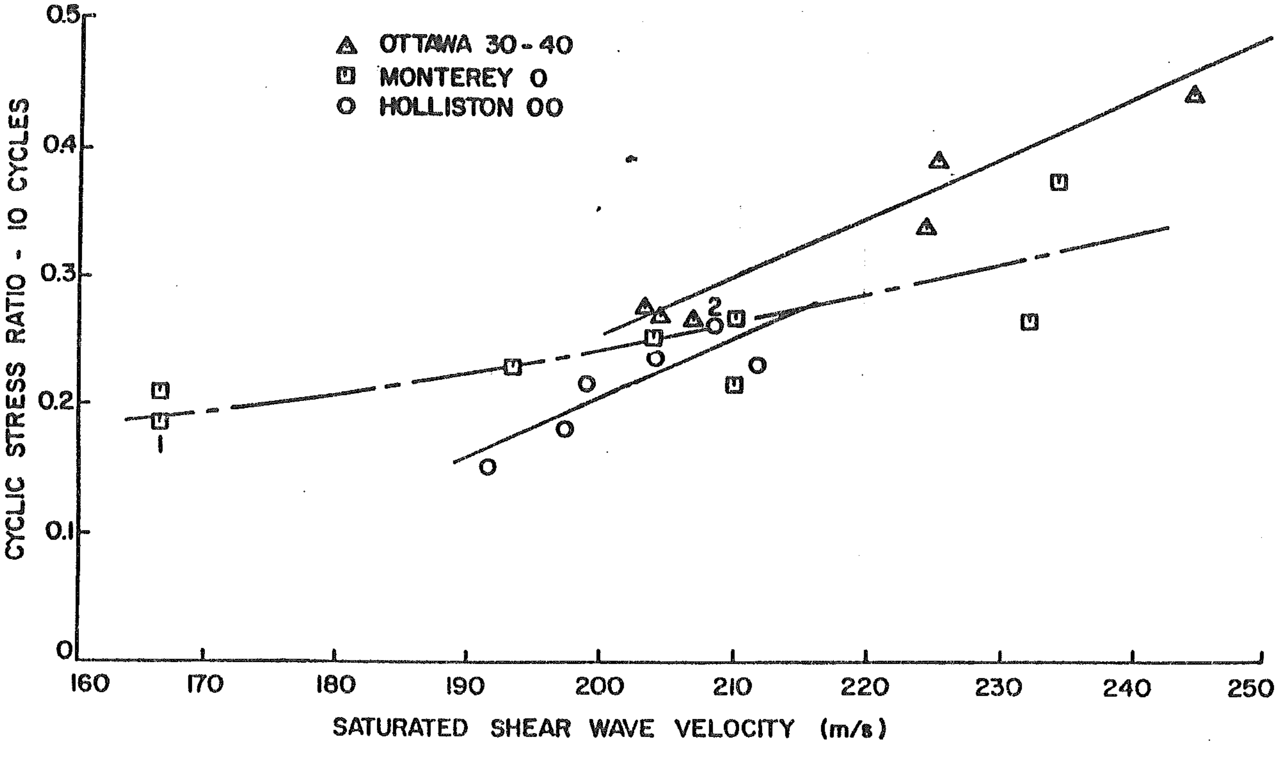


Figure 8 Cyclic stress ratio against shear wave velocity for various sands

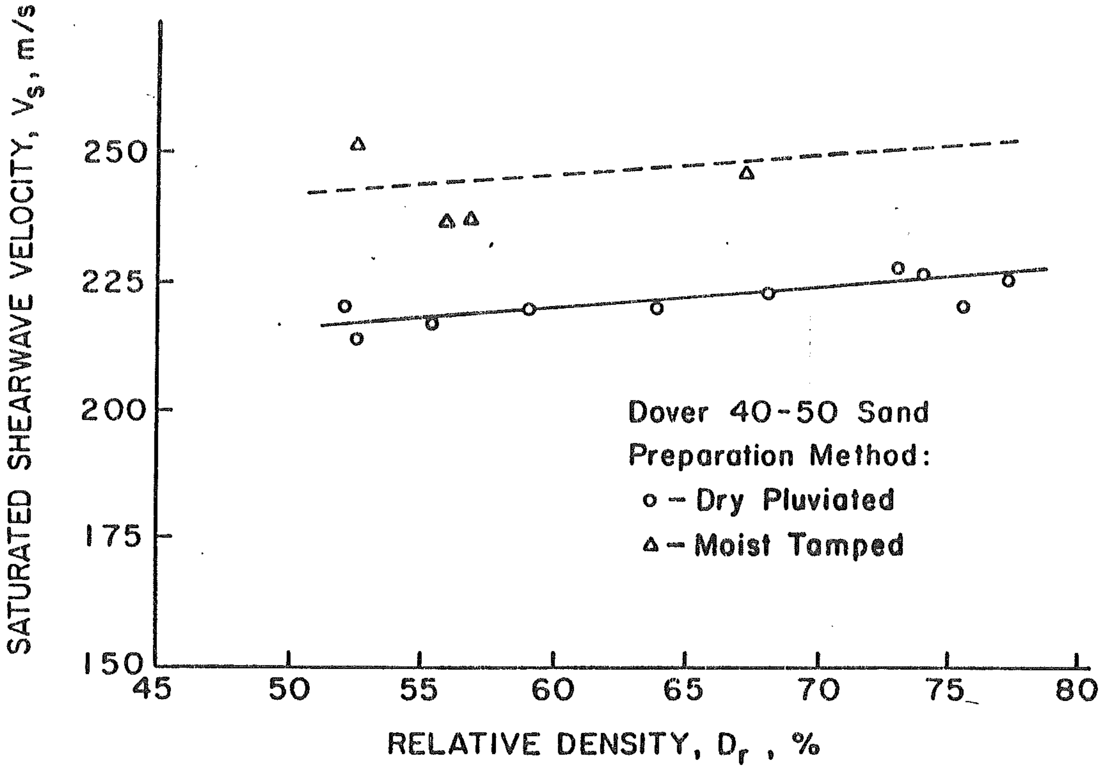


Figure 9 Saturated shear wave velocity against relative density

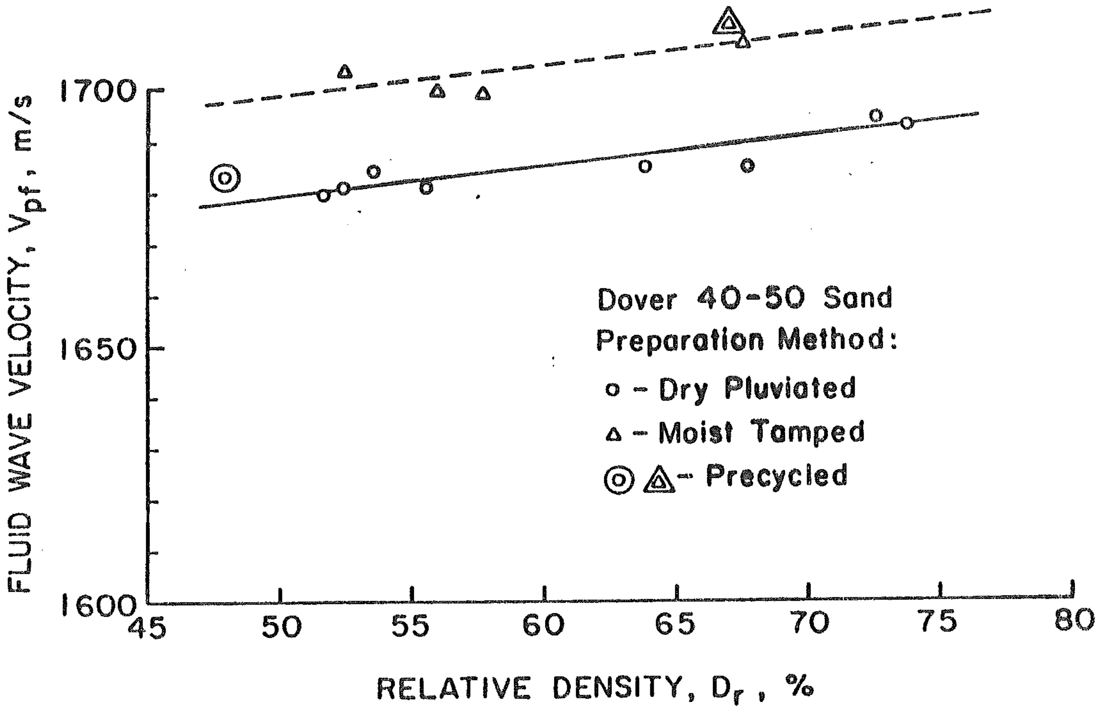


Figure 10 Fluid wave velocity against relative density

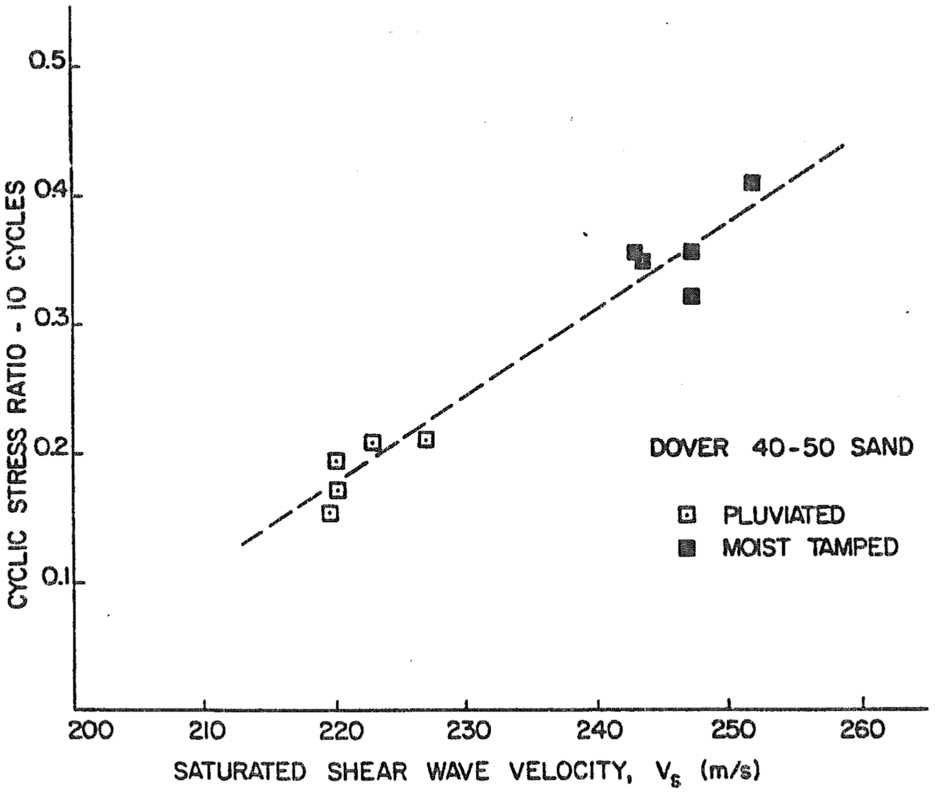


Figure 11 Cyclic stress ratio against shear wave velocity for 40-50 Dover sand

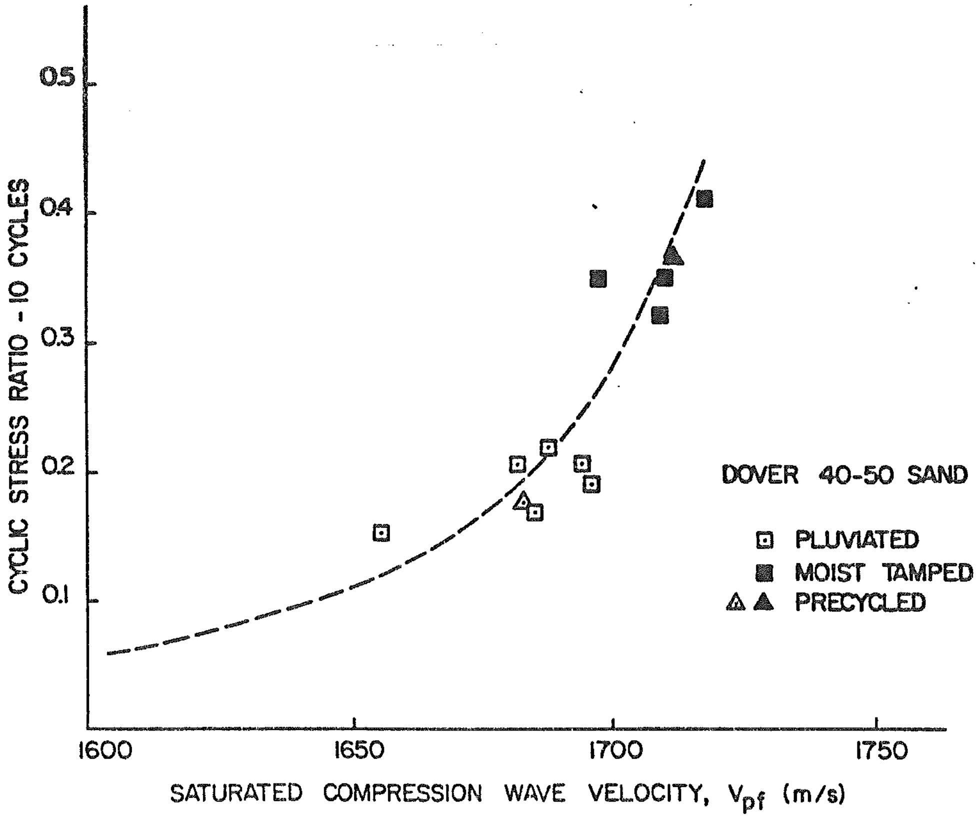


Figure 12 Cyclic stress ratio against saturated compressional wave velocity for Dover 40-50 sand

SEDIMENT PHYSICAL PROPERTY MEASUREMENTS

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Naval Ocean Research and Development Activity (NORDA)
NSTL Station, Mississippi

The Sediment Physics Lab of Seafloor Geoscience Division, NORDA, is interested primarily in the physical/elastic properties of marine sediments. As part of our applied research program, the geoacoustic environments of test locales are being extensively studied and defined in order to extrapolate seafloor geoacoustic parameters to other locales where few data are available. Piston cores, diver-collected cores, and seismic reflection profiling and 3.5 kHz profiling methods are currently being used to collect data. In situ probes to measure compressional and shear wave velocities and electrical resistivities are being developed and tested in our basic research program with the goal of obtaining measurements more quickly and accurately. The Honeywell-Elac (15 kHz and 30 kHz) Sea Bottom Classifier is being evaluated as a rapid survey tool for classifying sediment type (acoustic reflectivity) in real time. We are currently developing plans to utilize these techniques to obtain sediment and ice elastic property measurements in the Arctic.

INTRODUCTION

This paper describes research work undertaken by the Geotechnical Branch of the Seafloor Division of NORDA in Mississippi, U.S.A. Rather than presenting large amounts of data we are going to describe the two main programs; an applied research program and a basic research program.

The objective of the applied research program is to define the geoacoustic environment within a series of type locales. These type locale studies will then be used to extrapolate geoacoustic parameters as a function of depth below the seafloor in areas where only surface sediment measurements, or estimates of surface sediments measurements exist. Our definition of type locales is: those areas where the seafloor is as close to one sediment type and one grain size as can be resolved by one measurement. The most important physical parameters that are of interest to us are the compressional and shear wave velocity and attenuation and bulk density. By necessity most of our measurement data is derived from laboratory analysis. The laboratory methods will be discussed further in this presentation.

THE APPLIED RESEARCH PROGRAM

Compressional wave measurements are made on collected core samples by a transverse scanning method. Figure 1 shows a core undergoing tests. The two transducers are enclosed in "earmuffs" which are filled with oil. The core is slowly moved through the transducer "earmuffs".

A modified "Hamilton Frame" is used for both compression and shear wave measurements (Figure 2). The shear wave measurements are made in the 1-10 kHz range, while the compressional wave measurements are made in the 100-500 kHz range. We have two sets of compressional and shear wave transducers which can be selected as desired. Figure 3 shows a set of shear wave velocity data from a well sorted fine sand. Figure 4 shows attenuation data measured using a 100 cm attenuation tube made on the same well sorted fine sand used earlier. We have also developed field versions of the compressional and shear wave transducer so that measurements can be made on cores as soon as possible after collection. These instruments include transducers that can be inserted into the core through holes bored in the liner. Standard geotechnical methods are used to obtain the grain size distribution, bulk density, porosity, total carbonate content and organic carbon content.

THE BASIC RESEARCH PROGRAM

Our basic research program is aimed at quantifying the relationships between sediment physical properties and sediment diagenetic processes. This involves obtaining the compressional and shear wave velocity of various sediments as functions of pressure, temperature and depth of burial. Several diver-operated probes have been developed to make these measurement in situ. Figure 5 shows a compressional wave probe with the transducer removed. Figure 6 shows a similar shear wave probe.

Both these instruments are mounted on water tight boxes which can withstand pressures at 100 feet (30m). Presently underwater cables are used to transmit signals to and from the surface equipment. However, diver-operated data storage methods are under consideration.

Our basic research program is also aimed at rapid survey techniques and to this end, we have acquired a Honeywell Elac Sea Bottom Classifier which is presently undergoing evaluation. This Classifier uses a 30 kHz transducer mounted in a portable fish which can be deployed from a small boat. The Echo Strength Measuring Unit provides absolute depth and reflection strength.

Figure 7 describes this measurement of echo strength. The analog signal (echo) is divided into 10 equal time intervals and an estimate of reflection strength in these time windows is computed and recorded. Ultimately we hope to process the reflection strengths in real time. Presently software is being developed and the instrument outputs are being evaluated (Figure 8).

Ground truthing of all our in situ measurements is of primary concern, and we are using divers to collect core samples with as little disturbance as possible. Areas of gravel and coarse sand create difficulty. Laboratory measurement of shear and compressional wave velocities on such coarse sediments are less reliable than with finer sediments. We are looking at alternate techniques that may give us more confidence in our results.

QUESTIONS

Q. (from floor) We have lots of problems with earmuffs? Do you feel confident?

A. Actually yes. Our results are pretty reproduceable. We get fairly similar results to those that Mike Richardson (of NORDA CODE 333) gets.

Q. Have you measured the same samples with the earmuffs and then on the Hamilton frames?

A. Yes.

Q. (to Jim Matthews) "Do you know what the actual differences are?

A. They are very slight. We do not use the Underwater Systems Inc. electronics. We use only the transducers and we find them quite rapid and quite good. We have compared measurements through liner cores against probes. We have taken box cores and hand cut a liner core and then used the probes with very good agreement.

Q. Have you used it on piston cores? The problem I found was the separation of the sample from the liner and a thin layer of water.

A. If you have disturbance of the core, then you do get phony readings. Most differences can be accounted for on a basis of core disturbance and void spaces and separation and distortion, not in the technique.

(Comment by Dawn Lavoie) That's why we are going to the diver-collected cores.

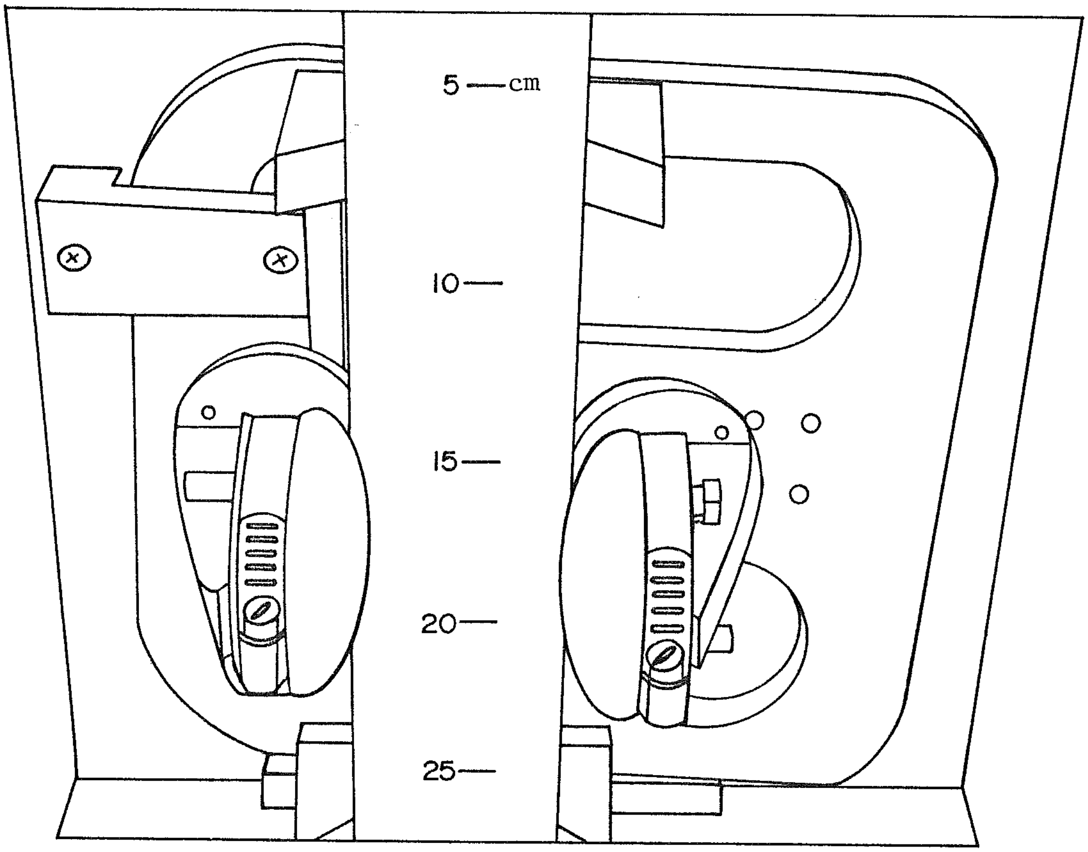

Figure 1 Core Testing using earmuffs

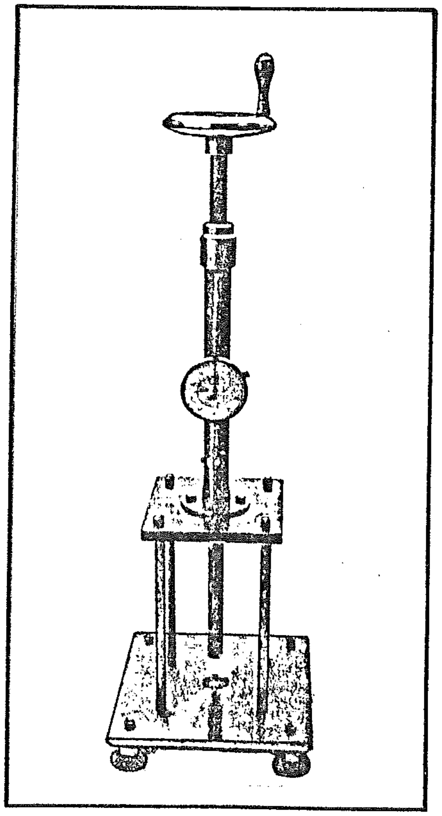

Figure 2 A modified Hamilton Frame

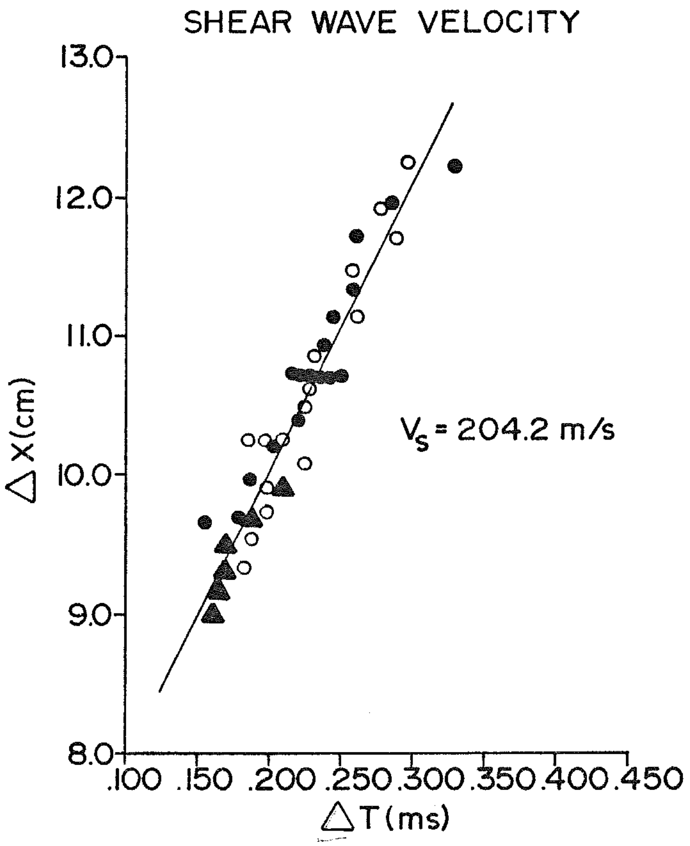

Figure 3 Shear wave velocity data for a well sorted fine sand

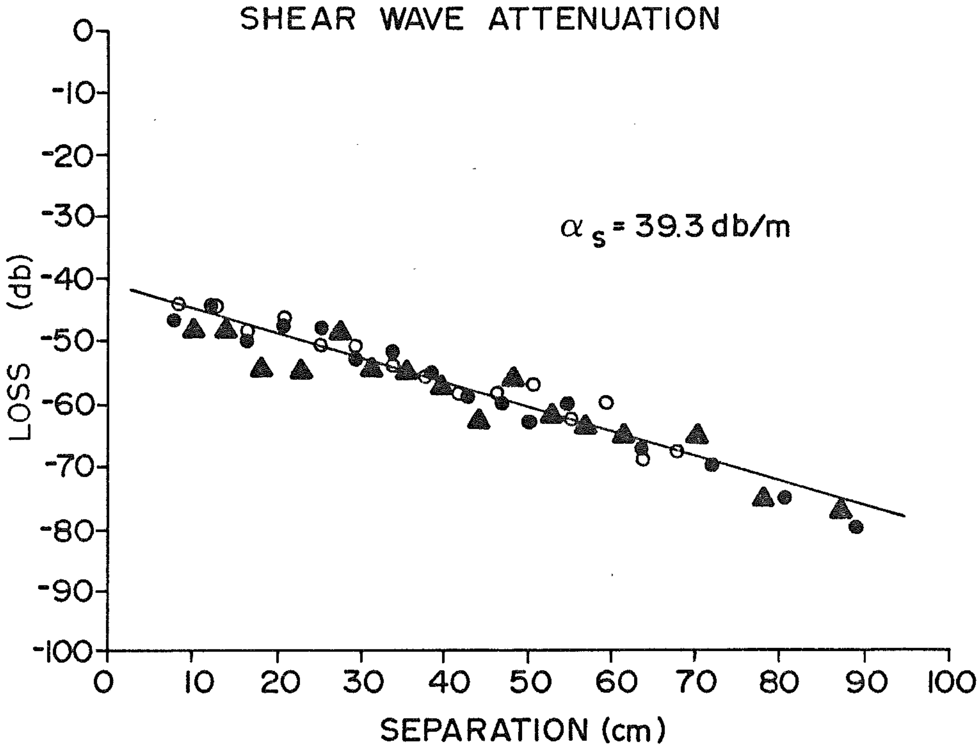

Figure 4 Shear wave attenuation data for a well sorted fine sand

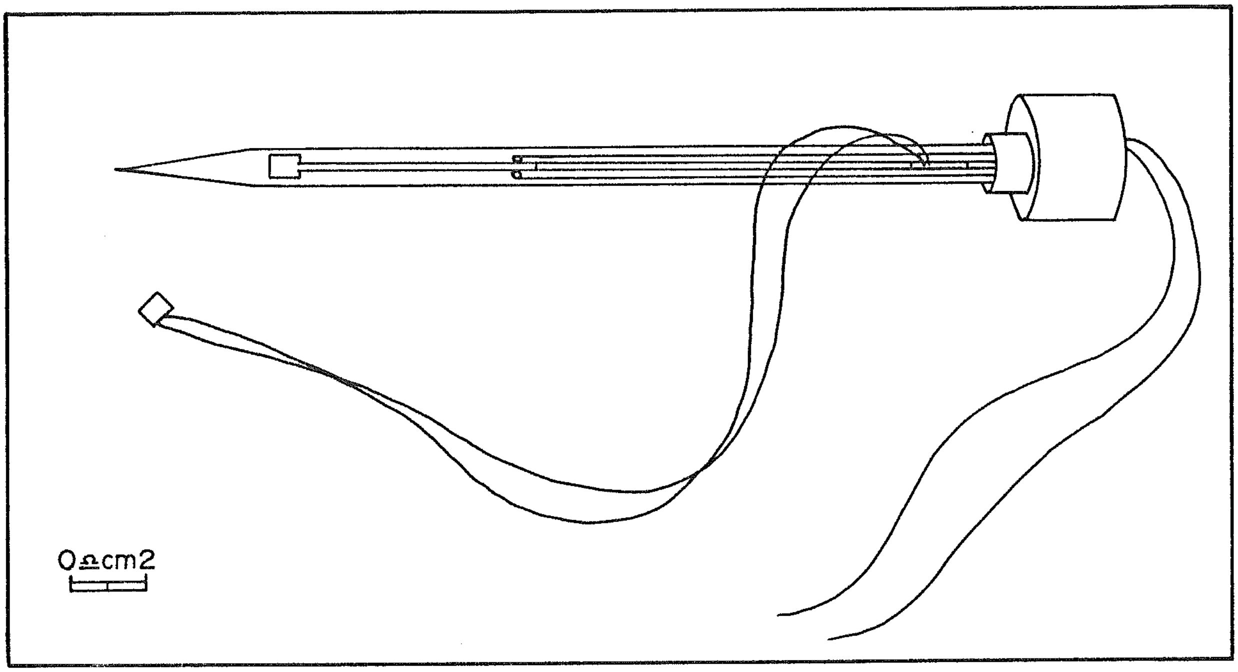

Figure 5 Diver operated compressional wave probe

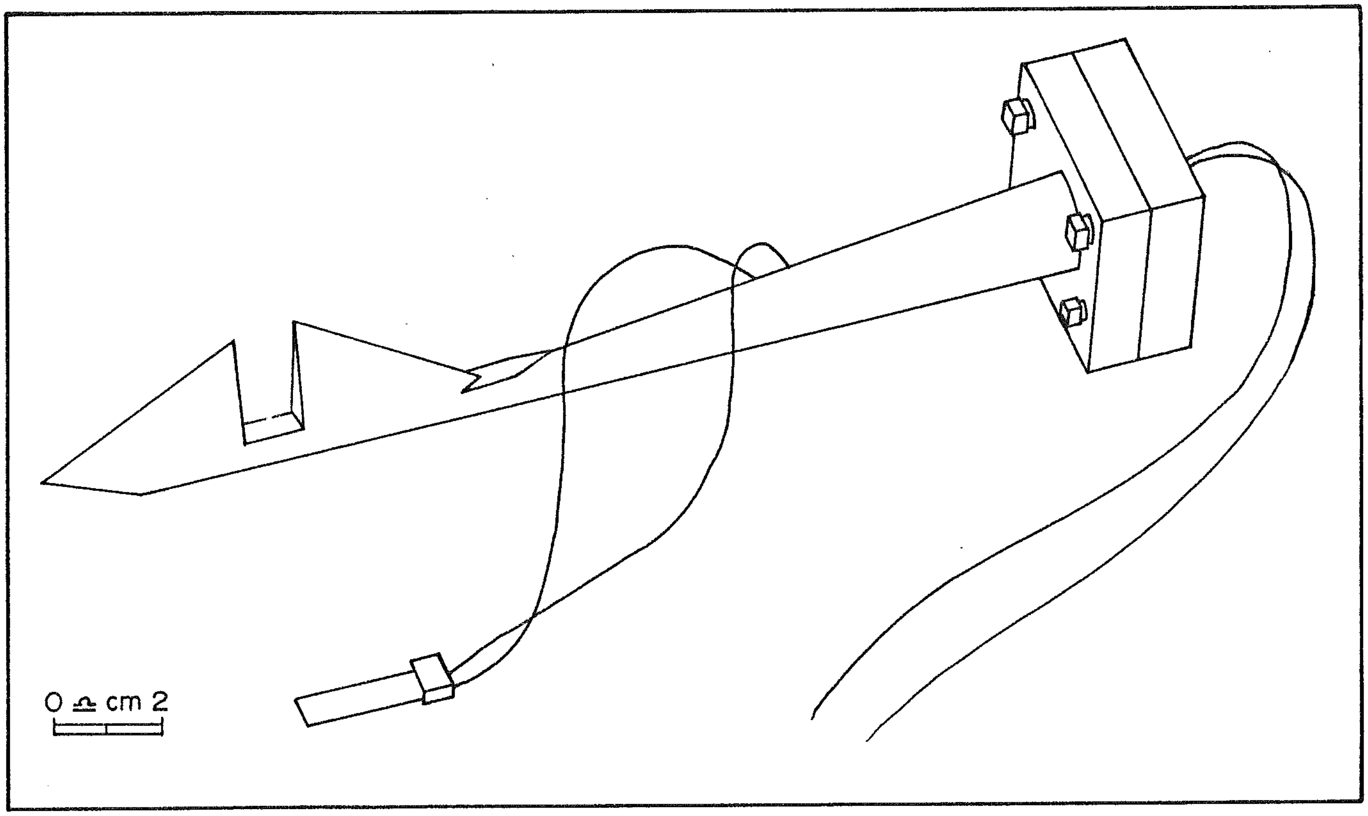

Figure 6 Diver operated shear wave probe

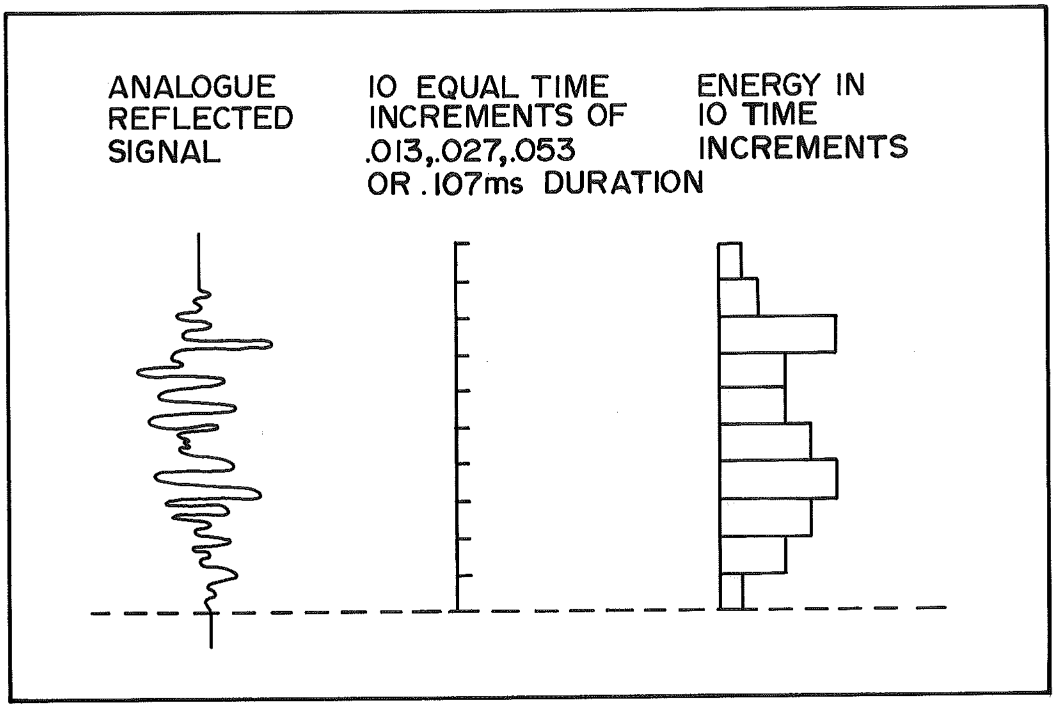

Figure 7 Method used in echo strength measurement

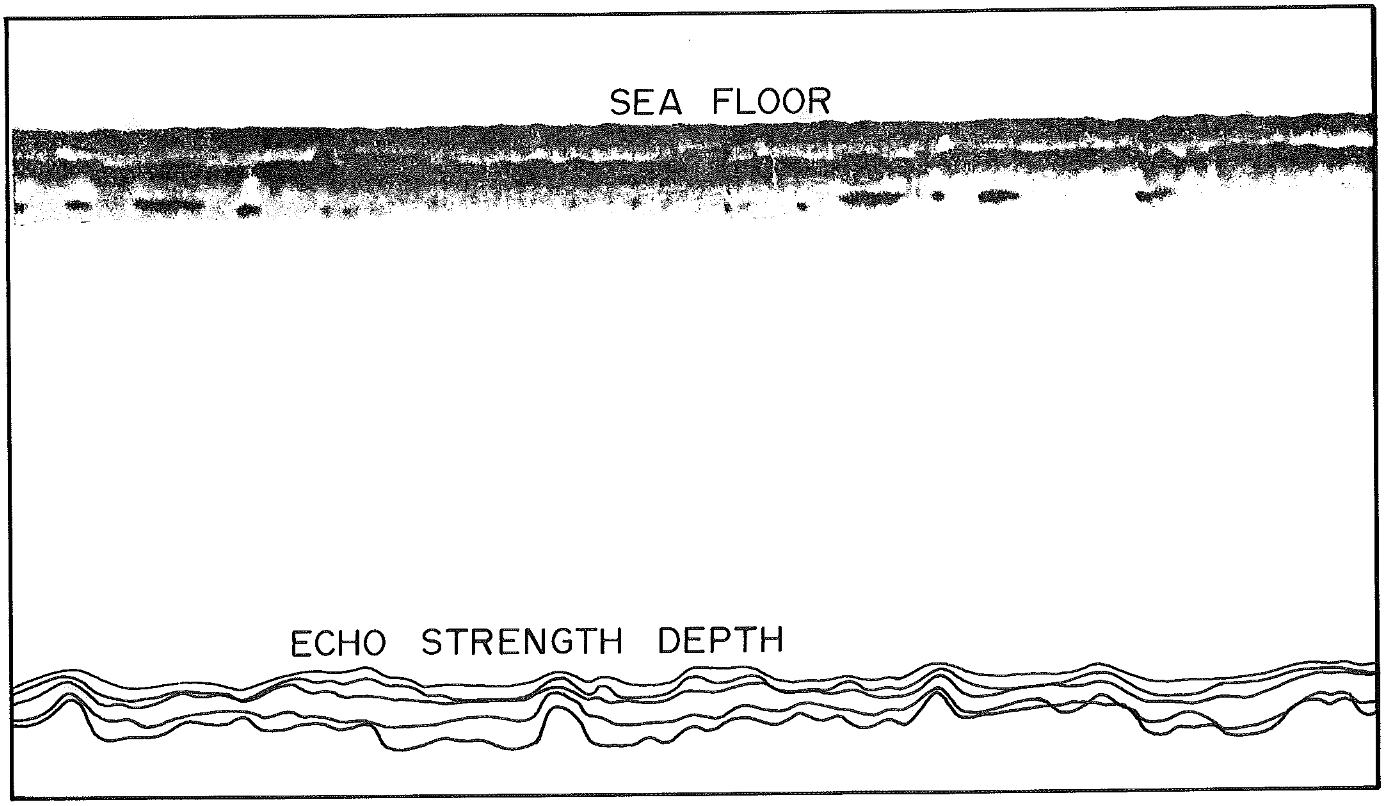

Figure 8 ~ Possible display for continuous reflectivity data

ACOUSTIC PROPAGATION IN SHALLOW WATER

Philip Staal
Defence Research Establishment Atlantic
Dartmouth, Nova Scotia

The Shallow Water Acoustic Group at DREA puts a lot of its effort into studying acoustic propagation in shallow water. This propagation is measured and modelled for ranges up to hundreds of kilometers. The frequency range in which we study is usually between 1 Hz and 10 kHz. We use a modular digital hydrophone array called HYDRA for making most of our measurements, although we have also used an ocean-bottom seismometer borrowed from the Bedford Institute of Oceanography. We normally use explosive acoustic sources and C.W. acoustic projectors during our experiments. This equipment is used to measure propagation loss, ambient noise, spatial homogeneity of the sound field, and dispersion in time, among other things. We also put a lot of effort into modelling propagation loss and dispersion, using a geo-acoustic model as input. Vertical reflection data obtained with a sub-bottom profiler are used to determine sediment types and thicknesses; large and small scale seismic refraction experiments are used to estimate sound speeds; and processed sub-bottom reflection data are used to estimate volume attenuation. Speeds of interface waves are used to estimate shear wave velocities. We have been very successful in modelling propagation over unconsolidated sea floor sediments, and have recently been focusing our attention on propagation over consolidated seafloor sediments such as chalk and granite.

INTRODUCTION

I work in the Shallow Water Acoustics Group at the Defense Research Establishment Atlantic (DREA) and in this presentation I will describe some of our measurements and explain the effects of the seabed on acoustic propagation over ranges of the order of 100 km. In collaboration with David Chapman and Dale Ellis of DREA, the topics of research include ambient noise, propagation loss, vertical noise direction, seismic propagation, spatial homogeneity and dispersion in the arrival times over long distances. The research equipment is a single array called the "HYDRA" array which is used for most of our measurements. We have also used an ocean bottom seismometer borrowed from the Bedford Institute of Oceanography. Figure 1 indicates the shallow water problem as we see it. However, in order to give a reasonable idea of the water depth compared to the distance involved, the scale must be expanded horizontally by a factor of about 1,000. We have always been concerned with water properties, sound speed and the roughness of the interfaces, but more recently we have been involved with sub-bottom properties.

TYPICAL EXPERIMENTAL PROCEDURES

The "HYDRA" array shown in Figure 2 consists of individual hydrophones, signal digitizers and extension cables which can be plugged together to make both horizontal and vertical arrays. Typically we use 10 to 20 hydrophones spaced several hundred metres apart with a sampling rate of a few kHz. The array can also be reconfigured under software control from the vessel. Usually one vessel is used for recording purposes and the second vessel used to drop explosive charges or to tow a CW source.

RESULTS

Typical long range propagation characteristics over a bottom sand covered by a softer layer are shown in Figure 3. The frequencies involved are 64 Hz (upper curves) to 1 kHz (lower curves). The fluid model used agrees with the experimental results within the accuracy of the measurements. Figure 4 shows a geological setting for propagation experiments carried our several years ago. Again the horizontal axis must be expanded by a factor of 1000 in order to obtain a realistic idea of scale. The propagation loss measured over this particular range over chalk (Figure 5) proved to be much greater at low frequency than that produced by use of fluid models. In order to explain this anomaly we had to introduce a shear wave conversion phenomenon into the model. Good agreement between the experimental and theoretical results was then obtained over the chalk. Unfortunately, reliable measurements of shear wave speed in the experimental area were not available. To overcome this problem, the Scholte or interface wave was used to infer the shear wave speed in the chalk.

A similar propagation experiment was carried out over a smoother granite zone in about 150 metres of water and over a 40 km range (Figure 6). Since in all propagation experiments water properties are important, sound speed profiles had to be obtained at certain positions along the range. Figure 7 indicates that over the shallow portion of the granite only a limited sound channel existed whereas in deeper water a sound channel definitely developed.

Thus over the granite cap we could expect good interaction between the water and the seafloor. Figure 8 shows the results of the propagation over the granite and we observe an interface wave travelling between 1 and 1.5 km/s. Since we are conditioned to seeing interface waves dying out after a kilometer or so, it was a surprise to see them extend up to 40 km. A group speed versus frequency graph from these shots (Figure 9) indicates that the interface wave is roughly 5 Hz. The symbols used refer to shot numbers. A simple model with compression speed of 5000 m/s in the granite, and a shear speed of 3300 m/s fitted the experimental data reasonably well. Since this was the only reliable estimate of shear speed available, a shear speed of 3300 m/s was used in the propagation model. The results are summarized in Figures 10 and 11. The experimental propagation loss at high frequency is much greater than the theory predicts and discrepancies of up to 60 dB exist between 20 to 30 Hz. The granite-west data is considered an intermediate case as propagation is in the direction of deeper water where sound channels would have trapped a portion of the sound, resulting in less bottom interaction. Our model is obviously missing something and the seabed roughness is a possible candidate. Also we are not too confident about the physical properties of the granite.

CONCLUSION

In conclusion, DREA is a user of detailed acoustic parameters, and speed and attenuation of compressional waves are very important to us. We also need estimates of bottom roughness particularly over granite. Selecting a heavily glaciated area is one possible way of ensuing a smooth surface. Finally, the shear speed and attenuation in the sub-bottom is very important and currently the only way we can infer these parameters is via the interface wave over the granite.

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Staal, P.R., "Acoustic Propagation Measurements with a Bottom Mounted Array", in Acoustics and the Sea-Bed (N.G. Pace, Ed.), Bath University Press, Bath, 1983, pp. 289-296.

Staal, P.R., Hughes, R.C. and Olsen, J.H., "Modular Digital Hydrophone Array", presented at IEEE Oceans '81 meeting in Boston, Mass. 1981, pp. 515-521.

Q. (from Taylor-Smith) Can I ask you a question about your data which shows the different materials, sand, granite 1, 2, etc. Where does the chalk come in all that?

A. The chalk and the granite look very similar. We actually have had measurements with quite similar results.

Q. (from floor) I am wondering when you talk about propagation loss what you are comparing it with. Are you simply saying that the amplitude is decreasing or are you saying that the amplitude is decreasing relative to some model for an interface wave?

A. We're saying this is the propagation loss in dB relative to 1 m so that is truly the propagation loss.

Q. But you may have energy which is propagating down as body wave energy and that you are really not losing it in the sense of attenuation. It may be simply propagating into the body and that is the nature of my question.

A. We consider that to be propagation loss. If it goes into the bottom and keeps on going and we don't see it, then we consider that to be propagation loss.

Q. I would be surprised if the attenuation is greater in granite than it is in sediments and you have to make that distinction?

A. Yes, that's true.

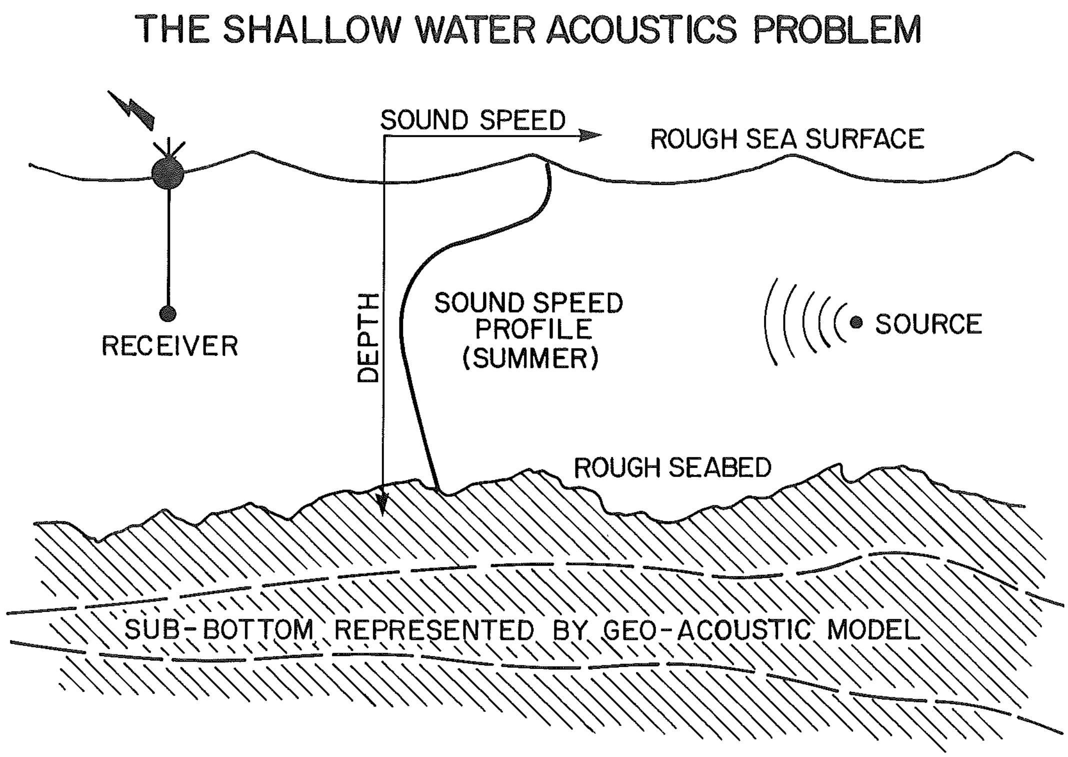


Figure 1. Our view of shallow water acoustic.

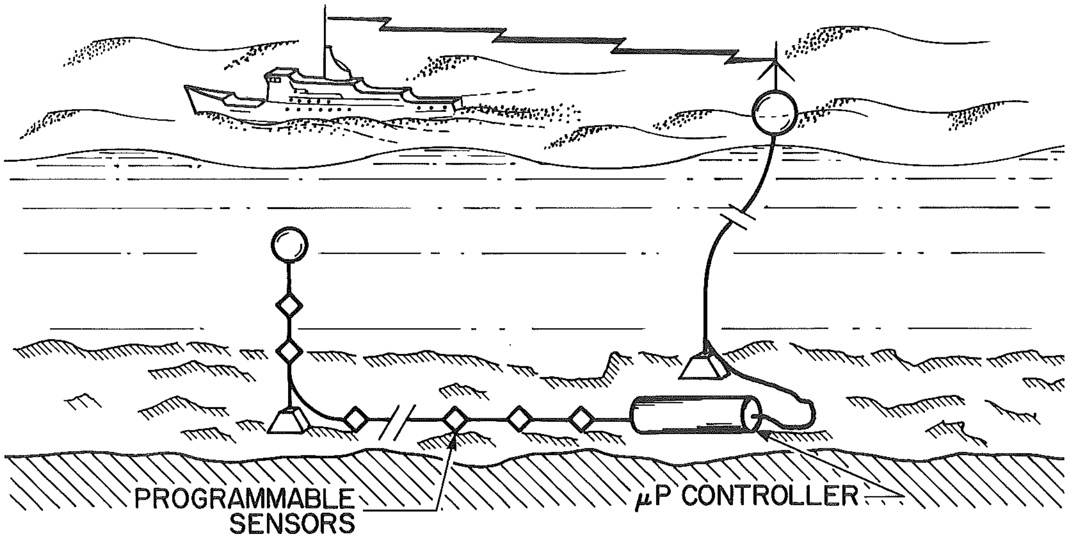


Figure 2. A typical deployment of the Hydra array.

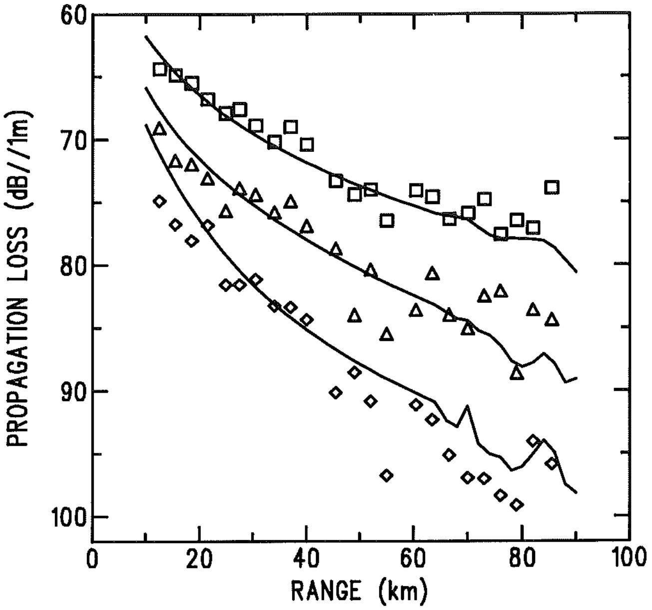


Figure 3.

Propagation loss versus range for a sand-covered bottom. The lines are theoretical results and the symbols experimental results. □ 64Hz, △ 256Hz and ◇ 1024Hz - 1/3 octave bands.

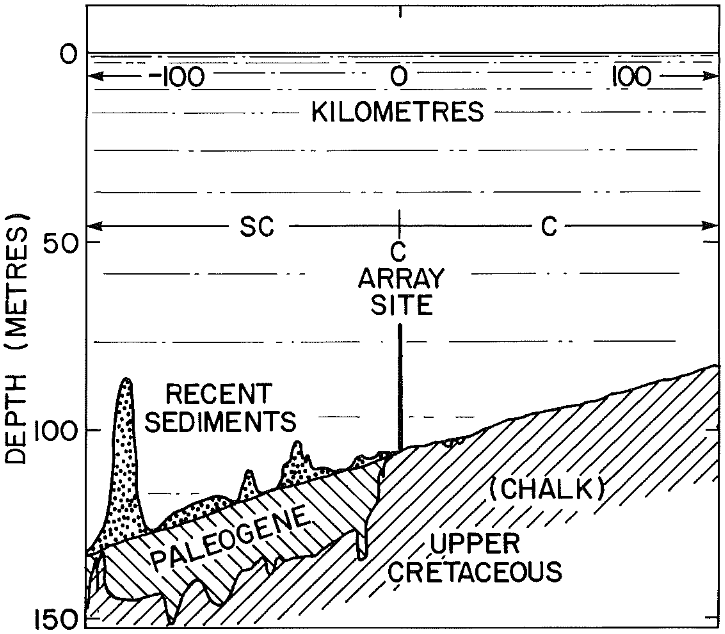


Figure 4.

A Hydra array deployment over chalk. The vertical bar at the array site shows the height of the upper hydrophone. The bottom properties are shown versus range for runs over the sediment and chalk.

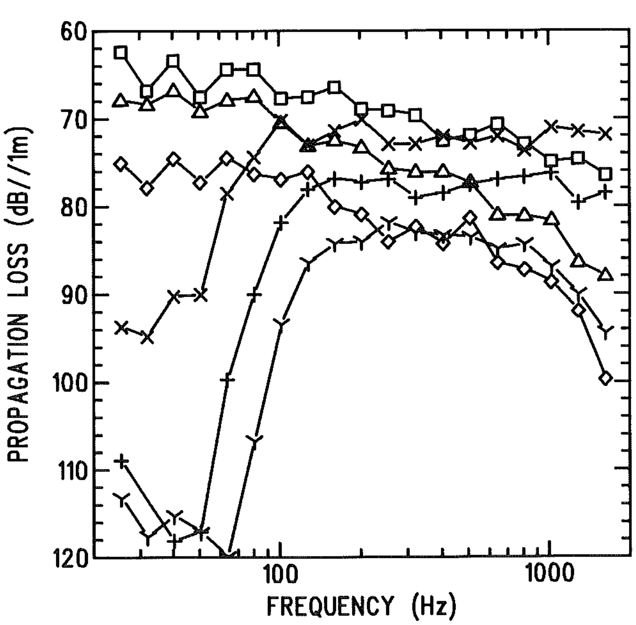


Figure 5.

Propagation loss versus frequency for a hydrophone 33m from the bottom over consolidated sediment: □ 12.5 km, △ 24.9 km, ◇ 49.0 km; and over chalk: × 14.1 km, + 25.0 km Y 47.0 km.

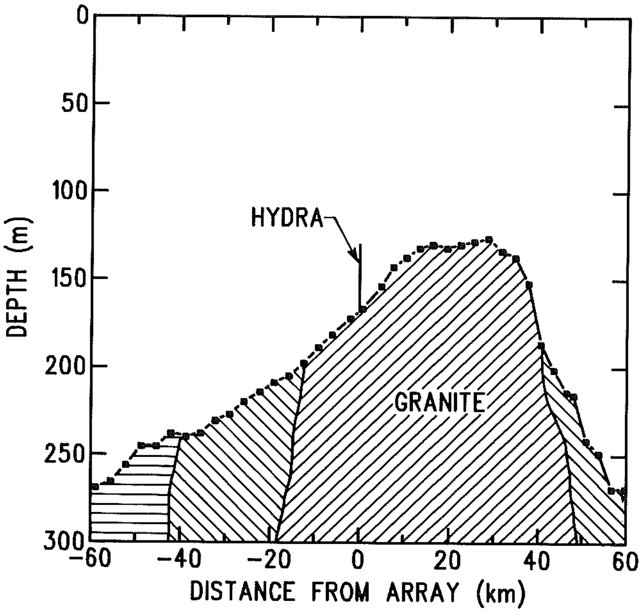


Figure 6.

A Hydra array deployment over granite. The vertical bar at the array site shows the height of the upper hydrophone. The bottom properties are shown versus range for acoustic-measurement runs.

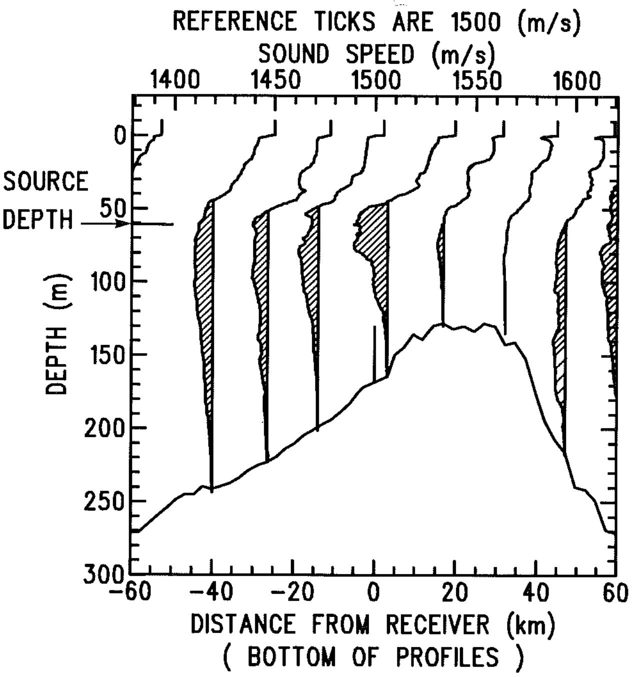


Figure 7.

A Hydra array deployment over granite. The vertical bar at the array site shows the height of the upper hydrophone. The sound speed properties of the water are shown for nine locations along the acoustic-measurement runs. A sound channel is shaded on the sound speed profiles.

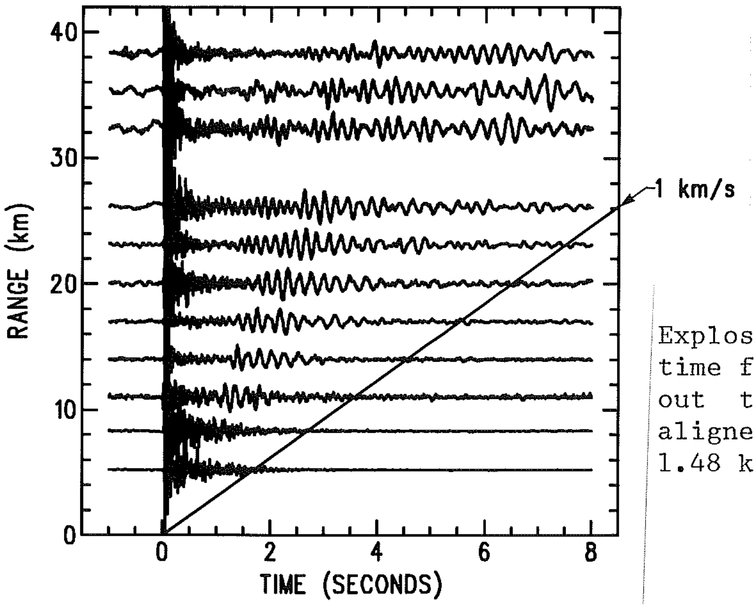


Figure 8.

Explosive-source pressure versus time for source to receiver ranges out to 38.5 km. The signals are aligned for a water sound speed of 1.48 km/s.

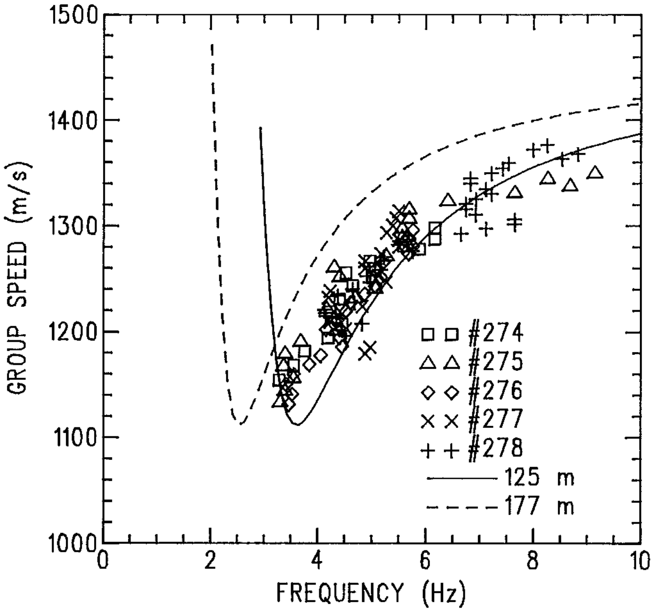


Figure 9.

Group speed versus frequency for five explosive sources and for two theoretical calculations with water depths corresponding to the shallowest and deepest places on the granite run. The theory assumed a water sound speed of 1.45 km/s and a granite compressional speed of 5.0 km/s, shear speed of 3.3 km/s and a density of 2.6 gm/cc.

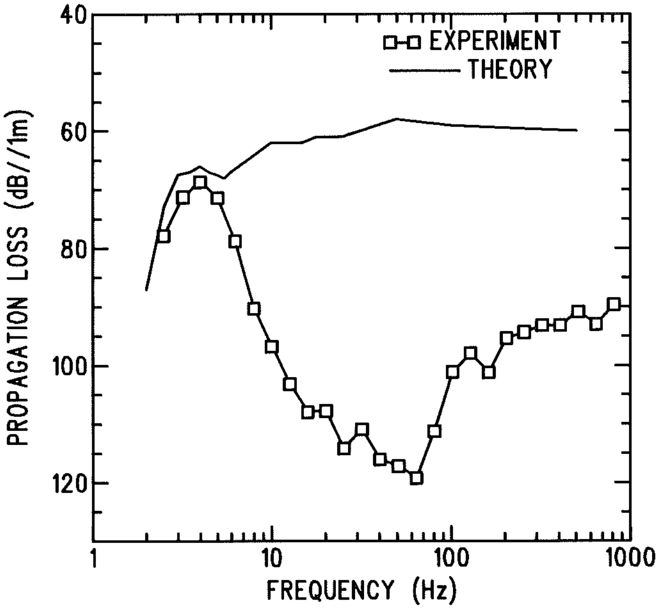


Figure 10.

Propagation loss versus frequency for a hydrophone on granite at a 20 km. range.

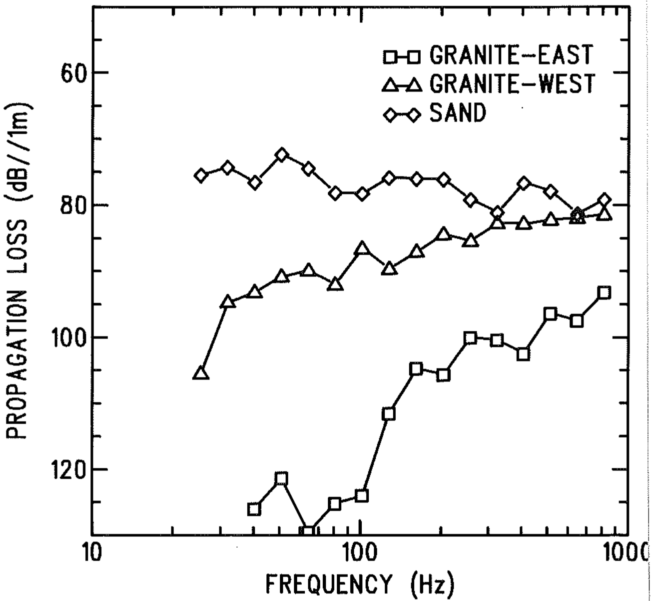


Figure 11.

Measured propagation loss versus frequency for a hydrophone on granite compared with propagation loss for a hydrophone on sand.

REVIEW OF BEAUFORT SEA PROGRAM

James Hunter
Geological Survey of Canada

INTRODUCTION

The Terrain Geophysics Section of the Geological Survey of Canada in Ottawa is basically land-based although occasionally we address specific marine orientated problems. One of the problems involves the identification of permafrost in the Beaufort Sea and in 1972 we made our first seismic reflection measurements of ice-bearing, or ice-bonded permafrost offshore. More recently, we were able to produce a generalized map of the main bodies of ice-bearing or ice-bonded permafrost using selected seismic sections provided by the major oil companies operating in the area.

GEOLOGICAL BACKGROUND

Within the confines of the Beaufort Sea there exist a considerable number of ice-bonded permafrost zones which can extend up to 600 m in thickness. As noted by Michael King earlier, there is an extreme dependence of sound velocity on temperature and except for inshore regions, with water depths less than 12 m, the upper portions of the sea shelf could be considered to have a temperature of -1°C. Permafrost zones are areas where there is a considerable slope on the sound velocity/temperature curves.

REVIEW OF RESEARCH

We are now able to comment with a little more confidence on the ice content in the immediate sub-bottom. The data base used in this aspect of the research were conventional low frequency seismic records. We cannot see the near surface detail as would be expected from a higher frequency system, but we can obtain an overview of the major thick layers of permafrost. A model of this situation, where permafrost is identified using a refraction phenomenon, could also be interpreted using the wide angle reflection principle. Velocity is usually computed as a function of depth. These estimates involve single ended (one way) reflection data and are therefore subject to error if the structures either slope or are irregular. However, with sufficient coverage of single ended data, sophisticated techniques are available that can reduce and maybe remove these effects. Since our data coverage is scattered this process is not worthwhile. Using the refraction information, we plot velocity and depth in the form of a section however more recently we have attempted an alternative technique that involves a common offset, variable area display to highlight irregular zones of permafrost (after Alan Bates, Gulf Oil). This technique involves picking the first arrivals from all available traces with time increasing down section. We call this the "iso offset" time section. It is a way of displaying irregular high velocity masses.

The occurrence of ice bearing materials close to the seafloor can also be detected. However, we can see through the shallow layers into the deeper main body of permafrost only in those cases where the refracted signals are attenuated. When the upper layer is thick, the lower layer cannot be detected.

The original generalized permafrost map mentioned earlier used a velocity threshold of 2400 m/sec^{-1} as a figure for the detection of ice-bonded permafrost. Because of more recent work by Michael King and others we feel that this figure should be revised. Velocities of 2400 m/s and above are now thought to belong to ice rich layers of permafrost which are probably coarse grained in texture. Layers with lower velocities in the range 1600 to 2400 m/s are also thought to contain some ice.

The apparent distribution of the permafrost that we have studied does not readily lend itself to being mapped but we have attempted to relate permafrost to other geological factors such as the change in sea level in the Beaufort Sea. In this program we produced a two-dimensional histogram of the depth of the top of the permafrost below the seafloor against axis of water depth and distance offshore. It appears that there exists a main body of permafrost near the shoreline which dips rapidly as deep water is approached. In the 22 m to 40 m water depth range there is a shallow, high ice content layer. Similarly, in water depths around 70 m. Although we have no definite explanation for this we feel that there is a main body of permafrost which, in water depths in excess of 10 m, is at a depth between 80 and 140 m and is probably very thick. The lack of shallow, high ice content lenses in the inshore region will be discussed later.

RECENT DEVELOPMENTS

The techniques described above are useful only in the study of thick permafrost lenses. In recent years we have been interested in mapping fine structures of the seafloor and have approached the problem by using short seismic arrays situated on the seafloor. However, to achieve greater efficiency we designed a towed 12 channel array with four closely spaced hydrophones per group and 7.5 m between groups. This array, which was built by the Nova Scotia Research Foundation, was to be towed within 5 m of the bottom and used to detect refraction events within 20 m of the seafloor. This program was initiated in 1981 and the problem of keeping the array stable and close to the seafloor was not solved until 1983. Over the last few seasons we have made 4,000 12 channel measurements of which 514 locations from flat lying areas have been selected for further studies. From this group a two-dimensional histogram showing the distribution of sound velocity against depth has been prepared.

Finally, I would like to explain the temperature phenomenon in the inshore region. Every spring for the last six years we have produced temperature profiles from nearshore to the edge of the shorefast ice by jet drilling cables into the seafloor and wherever possible making seismic measurements. The results indicate that a "warm bulb" (at -0.4°C) extends from the shoreline northwest of Pullin Island. This effect is attentuated at water depths in excess of 12 m. Results from the Itiyok Line east of Pullin Island indicate that inshore, the sea bottom temperatures at depth are above zero. Again, the same general trend exists with a warm bulb attenuating with depth and possibly resulting from the previous years outflow of warm water from the MacKenzie River. In this latter case core samples of the first 2 m of the seabed were recovered from most of the holes. The samples had low ice content. The most disconcerting aspect of this program was that the refraction measurements gave velocities no greater than 1600 m/s.

QUESTIONS

Q. If you have a seasonal change in temperature which is effectively travelling across the surface, would a downward travelling wave front exist?

A. Yes, but it is not quite as simple as that because the warm water progressively reaches greater depths at different times of the year. To model this situation requires a fairly complex computer program and we have just initiated such work with EBA Engineering Ltd. By cycling up to 50 years we are able to derive the main feature of this pulse. But we still have to change parameters to make the exact shape match the model. At least we can model it roughly but there are many unknowns to adjust and the result will probably vary laterally with the resonant time of the MacKenzie Water movement.

THE DEVELOPMENT OF THE ACOUSTIC CORE SYSTEM

David Caulfield
Caulfield Engineering
Sherwood Park, Alberta

The history of the "Acoustic Core" system is presented with particular emphasis on the application of E.L. Hamilton's absorption data to the development of a model for predicting the equivalent surficial acoustic impedance of the sub-bottom layers.

The importance of signal-to-noise is discussed as it affects system accuracy and the results of utilizing the system versus actual data is given.

The digital shallow seismic data allow for stacking, signal processing and improved presentation of data via colour plots. Typical results are given for each.

INTRODUCTION

The research described in this presentation is a summary of the last nine years' work in the development of an Acoustic "Coring" System using normal incidence reflection data. The usefulness of such a coring system is described by means of a case study in Vancouver Harbour undertaken in 1981. In this instance the site, Roberts Bank Pier, was of particular interest in that it had been dredged several years earlier and found to be very complex. Core samples taken at that time did not tie in with shallow seismic sections as presented on standard graphic recorders. Eventually it was discovered that what has been interpreted as a continuous sand horizon had in fact been sand lenses. Had quantitative information concerning the acoustic characteristics of the sediment been available on the original survey this sampling error may not have occurred.

THE ACOUSTIC CORING SYSTEM

The basic research for the Acoustic Core System was undertaken several years ago by Edwin Hamilton, Breslau and the author and resulted in a general classification of seafloor sediments by their acoustic impedence. Figure 1 shows the resulting classifications and as mentioned in earlier papers such a data set is regional in nature. This data set is from the continental terrace of California. Figure 2 shows acoustic impedence against bulk density for the same area.

In making use of such information with the acoustic core system, normal incidence reflection data must be recorded to enable the signal processing to be undertaken off line. Figure 3 shows the main steps of the computational procedure. With the various types of sources available (boomer, shallow sparker, fixed frequency profiler), it has been found necessary to record data on a tape recorder with up to 30 kHz bandwidth since useful energy up to 10 khz is often generated. This results in a digitization rate of 30 kHz prior to processing. It is necessary to make certain corrections such as the energy loss correction for absorption within the sediment and for the various beam patterns depending on the source used together with corrections for spherical spreading (Figure 4). The resulting quantitative estimates of reflection coefficients (Figure 5) can then be further manipulated to produce a relationship between acoustic impedence and elapsed time. The acoustic impedence values are normalized (to sea water) to make comparisons with other workers' results less complicated.

Figure 6 shows six seismic reflection signatures with a separation of about 6 metres between adjacent pairs. Although major layering exists, there is clearly evidence of historical ice scouring since detailed fine structure is absent. Considerable care has to be taken when actual core samples are compared with acoustic core logs. Local lateral variations suggest that some form of statistical averaging should be implemented, rather than instantaneous single estimates at one location. To date we have found that estimates of the energy incident on the seafloor are within 8% at their true value and with this information reflection coefficients and their acoustic impedence can be computed. Figure 7 shows a comparison between acoustic and actual cores taken on the Vancouver Harbour Survey. We have found that if we could assume that the acoustic impedence was increasing uniformly with depth, the model would give a constant impedence. However, using a simple signal to noise criteria does not allow the detection of a layer of low impedence below a higher impedence sediment. We now have the capability of detecting such layers. One method is to correlate a reference signal with the reflection signatures then providing the signal-to-noise criteria is satisfied a reflection coefficient profile could be generated. The resulting impedance model could then be used with the particular source function to produce a synthetic seismogram for comparison with the original field data. Using iterative techniques parameters such as absorption could then be varied to provide a best fit between the synthetic actual seismic signatures.

In comparing the acoustic and actual core log some differences existed, but in general the agreement was acceptable. Had this acoustic core method been available prior to dredging, the local areas of sand, silt, and clay may have been detected.

The signal-to-noise criterion mentioned above is based on techniques originally involved in determining the probability of false information transfer in the communication field. This subject is covered in detail in any good textbook on signal transmission and communications.

FURTHER WORK

Encouraged by the Vancouver Harbour Survey we felt it would be an interesting exercise to compare the acoustic coring technique in areas where cores had been collected by government and industry and shallow seismic data were available. From a suite of about 50 cores made available to us, agreement in terms of acoustic impedence was of the order of ±5% for 65% of linear footage and ±10% for 85% of linear footage (see Figure 8). This comparison used Hamilton values (Figure 1) for impedance estimates on the actual cores. Provided the acoustic/geotechnical relationships are well defined, or preferably regionally calibrated prediction of bulk density and grain size can be made. Figures 9 and 10 show some comparisons between actual and acoustic derived data from the Beaufort Sea.

Finally I would like to mention that we have attempted to improve the display of field data using colour as a means of identifying parameter amplitude rather than the usual grey scale technique used by most manufacturers of graphic recorders. Presently we have experimented with a colour display of the sub-bottom profile itself and the derived acoustic impedence section with encouraging results.

Q. (from Jacques Guigné) I was quite interested in your model but concerned that you mainly refer to very fine sediments. As geophysical interpreters we have no trouble at all in distinguishing silt and clay. Our problem is when we get into tills. Can you use your model on the East coast of Canada where we have got coarse gravels and tills? How would it perform?

A. I have been trying to find a source that could provide some cores and some data. I would be more than happy to try out acoustic techniques. I have been talking with Ed Hamilton and there seems to be no reason that we can't use the model. I have had no raw data whatsoever to experiment with. From a theoretical point of view, it should work on coarse material. I must emphasize that from what Hamilton has found we must have regional core data to place the curves on the proper location.

Q. (Jacques Guigné) You don't seem to take into consideration the pulse duration or the bandwidth into your model. It seems that no matter what system you use, you can utilize it. How can you then have the resolution with depth if you made the separations between your structures without any interactions or interference?

A. We have used data that has been available which have mainly been collected by boomers or ORE type systems. These are pulsed sources and we have deliberately limited the resolution to being equal to the pulse length. We would very much like to get into some other processing applications but are are limited at present by what is available to us.

Q. (Comment from Jacques) I think you would find that on the East Coast of Canada it's a totally different story to the Beaufort Sea and that you would definitely have to have a wide bandwidth sound source in order to be able to make any type of separations that would make sense.

A. I agree entirely. Could I just point out that the raw data from broadband systems used in the Beaufort is not very good from a signal to noise viewpoint. However, after processing much more information is displayed. In essence, the answer is yes; you must use the widest possible bandwidth signal you can.

Q. (from the panel) I take it you use regional density velocity information to come up with attenuation value, plug it into your model, then show predictions of densities, etc.?

A. I have a detailed paper about this but I skimmed over it in the presentation. The first thing we do is we take Hamilton's data for absorption vs. density and make a first estimate of what the solution should be. Then we calculate where the layer should be and what the predicted density and sound velocity is. The source signature derived from the first bottom reflection is then used to generate a synthetic seismic trace for comparison with the original. Initially it is going to be in error but we update the assumed parameters such as density or velocity and iterate until the errors reach a minimum. This results in our final absorption values and densities, etc.

COMMENT - There are a lot of variables.

A. That's right. That's the nice thing about computers. There's one other point though. It seems that by using the auto correlation function you can get an estimate of what the absorption is because in fact you can get differences in reflection coefficients directly from the first layer to the second layer.

Q. (from Roger Hutchins) How do you account for surface scattering anomalies in your reflection coefficient profile?

A. Scattering really shows up in the Beaufort Sea with all the ice scouring, etc. What we have done to date is to take two sources, a boomer for sub-bottom data, and an ORE profiler with a much narrower beam produced by six transducers. We look at the difference in surface scatter from the two sources and estimate the back scattering portion. We then subtract this energy from the sub-bottom profile.

Q. (from Bill Roggensack) I'm not a geophysicist but as I understand it you're compiling an acoustic profile you are calling an acoustic core. The principal unit that you are using to make the correlation between lithology and acoustic properties is the acoustic impedance...

A. ... and absorption

Q. (cont'd) ...and absorption. When you showed your agreement and indicated that something like 65% of the samples tested has an agreement within ±5% between the acoustic interpretation and the actual observed measurements, if we return to look at the table of impedances with lithology, which I presume is coming from Hamilton's original work, and place the ±5% error bars over them, what variation of lithology might you expect to get within your confidence limits?

A. We have to take a regional core at each location. Our acoustic core in no way replaced coring or other engineering tests. If we were to survey a new area we would take about 20 or 30 cores to ensure correlation and calibration with the acoustic system.

Q. (Jacques Guigne) If we are going to go back to "ground truthing" taking cores, why are we developing an acoustic core?

A. From what we have been seeing so far in the Beaufort Sea, two or three cores provide sufficient "ground truthing" to do the whole survey for the engineering application.

DESCRIPTION	ACOUSTIC IMPEDANCE $\frac{x\ 10^2\ g}{cm^2\ sec}$
Water	1450
Silty Clay	2016-2460
Clayey Silt	2460-2864
Silty Sand	2864-3052
Very Fine Sand	3052-3219
Fine Sand	3219-3281
Medium Sand	3281-3492
Coarse Sand	3492-3647
Gravelly Sand	3647-3880
Sandy Gravel	3880-3927

(After Hamilton and Bachman)

(Corrected for Temperature and Salinity)

Figure 1 Soil classification versus acoustic impedance.

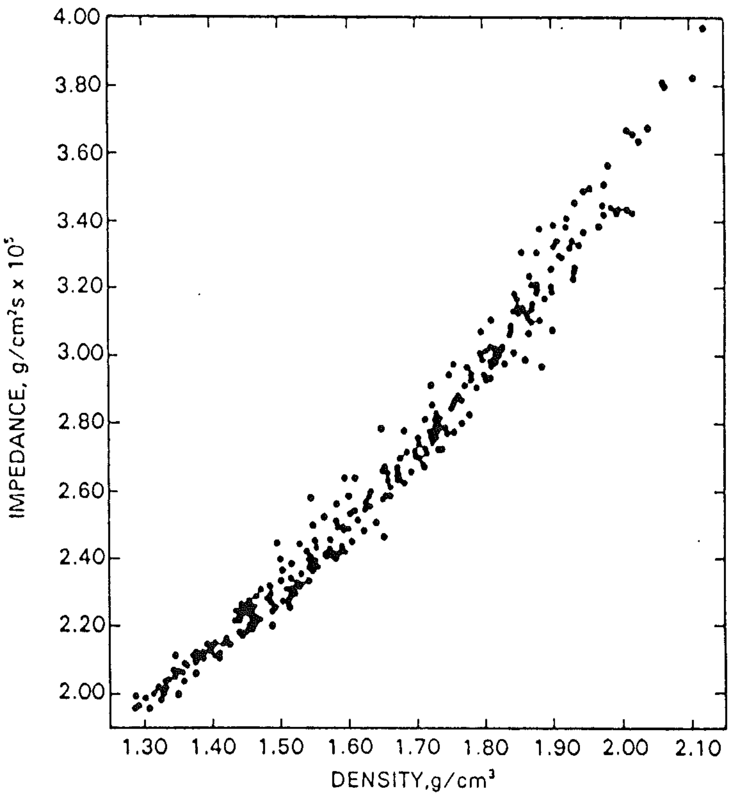


Figure 2 Saturated bulk density versus Impedance, Continental Terrace (Shelf and slope). (Hamilton and Bachman)

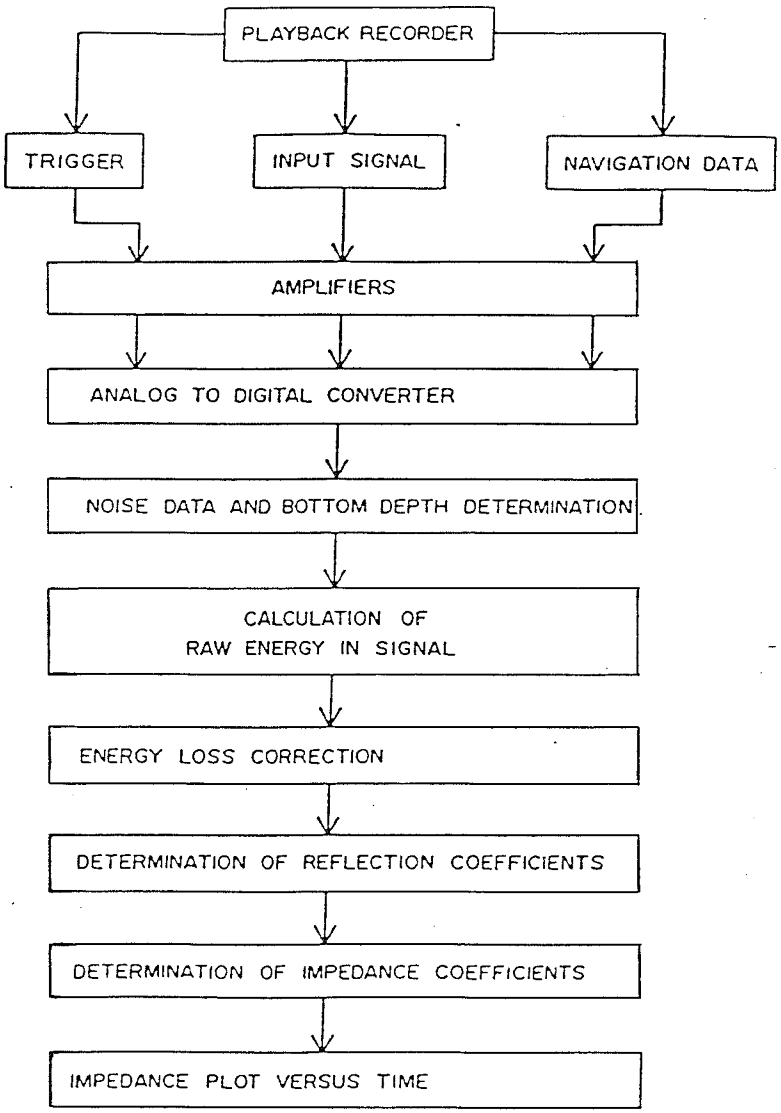
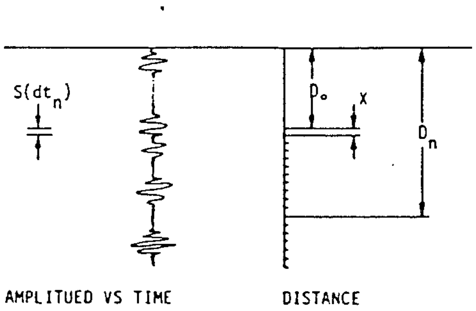


Figure 3 Computational procedure for the determination of acoustic impedance



A) ABSORPTIÖN LOSS: $T = T_o e^{-\Delta x}$

T_o = TRANSMISSIBILITY

B) SPHERICAL SPREADING LOSS: $N = f[\,20 \log \frac{Dn}{Do}\,]$

$D_n = D_o + n\Delta x$

$x = c \times dt$

C) BEAM PATTERN CORRECTION: $E_n = E_{n(observed)}[1-k_n(\frac{r}{R_n})\cos \rho_n]$

$r = d \tan \gamma$

$R_n = D\tan \rho_n ; \rho_n = \cos^{-1} \frac{D}{(D+\frac{n\,c\,\Delta t}{2})}$

$K_n = 0.75 + 0.25 \times \frac{\theta - \rho_1}{\theta}$

c = SOUND VELOCITY

Δt = SAMPLING PERIOD (TOTAL SAMPLES OBTAINED ARE SUBJECT TO FOURIER TRANSFORM)

θ = (BEAM ANGLE) / 2, THE ANGLE θ DEPENDS ON BEAM PATTERN AND DEPTH OF LAYER

; DEFINED MINIMUM ANGLE. WITHIN THE SOLID ANGLE

$\Delta\Omega = \frac{\cos\theta}{D^2}$ AT THE NORMAL REFLECTION WILL ARRIVE AT DETECTOR

Figure 4 Energy loss correction - calculations

$$R_n = \sqrt{E(\Delta T_n)/[E_{total} - \sum_{m=1}^{n-1} E(\Delta T_m)]}$$

Where

$$E_{total} = \sum_{n=1}^{N} E(\Delta T_n)$$

N = MAXIMUM NUMBER OF ENERGY SAMPLES, WHERE THE ENERGY IS GREATER THAN THE NOISE.

$$E(\Delta T_n) = \sum_{m=1}^{M} E(W_m, \Delta T_n)$$

M = TOTAL NUMBER OF FREQUENCY SAMPLES

Figure 5 Calculation of Reflection Coefficient

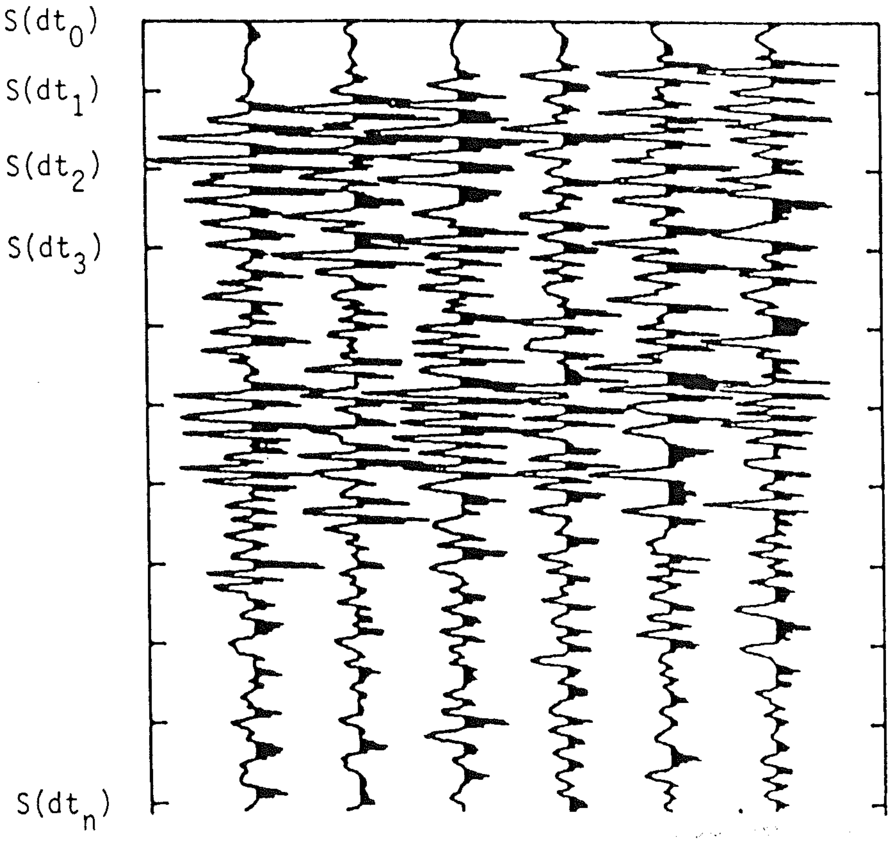


Figure 6 Typical Seismic Signals

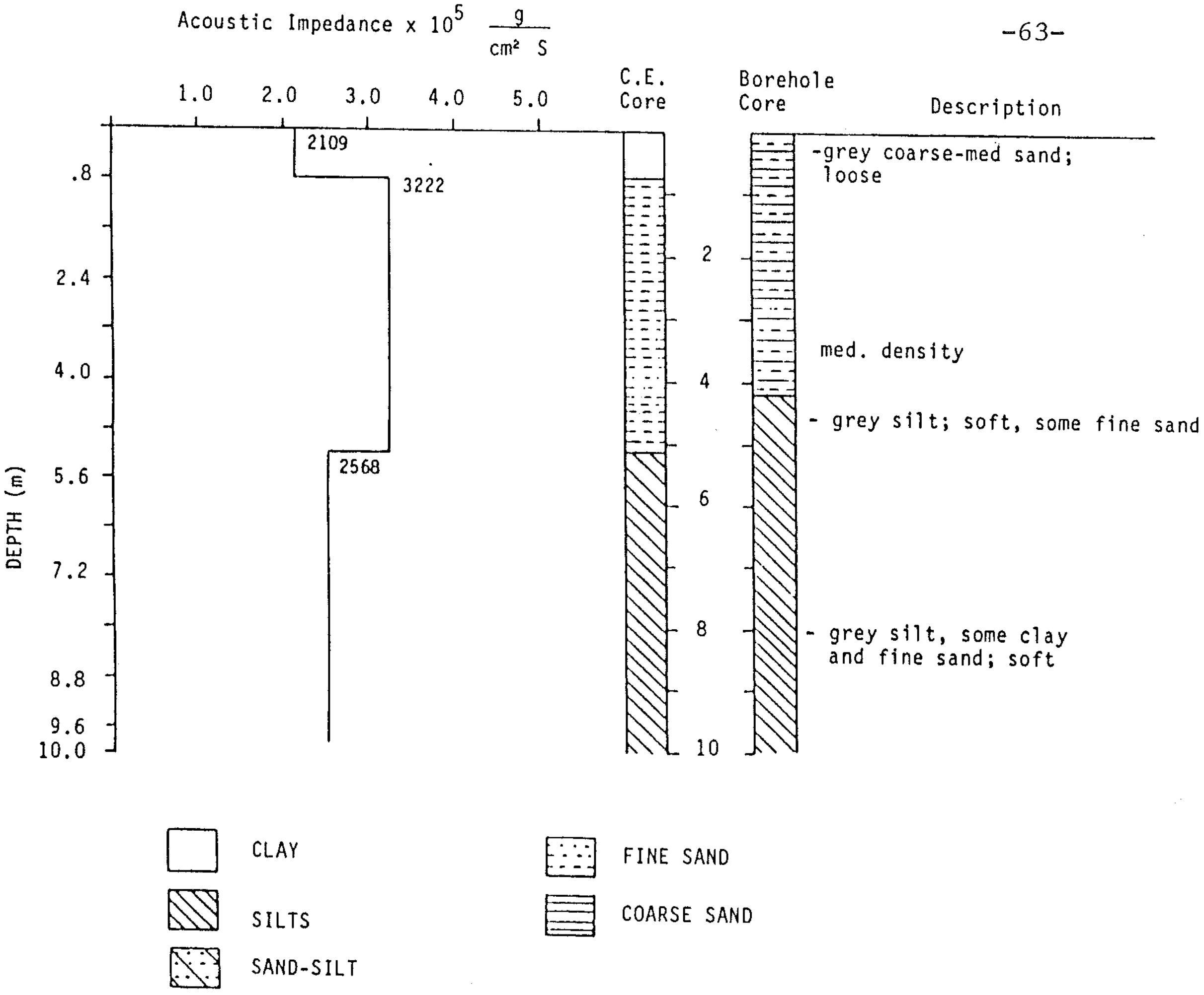


Figure 7 Comparison of acoustic and borehole cores (from Caulfield et al.)

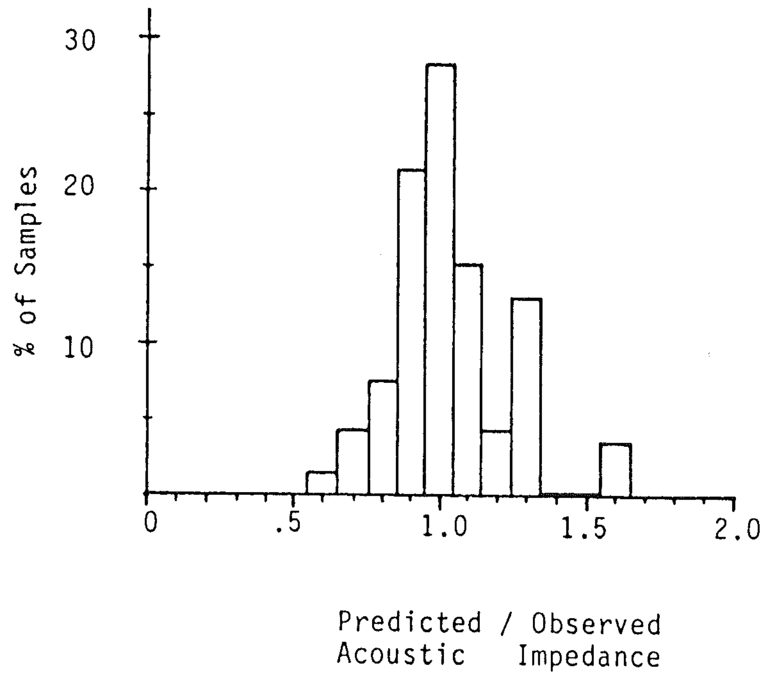


Figure 8 Statistical comparison of acoustic impedance

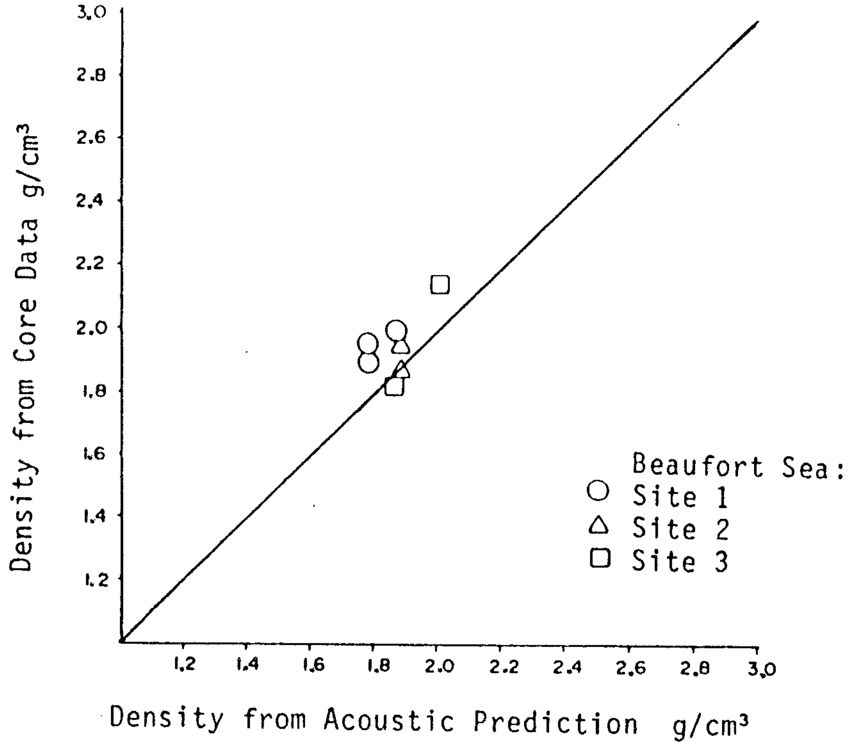


Figure 9 Predicted density versus core density

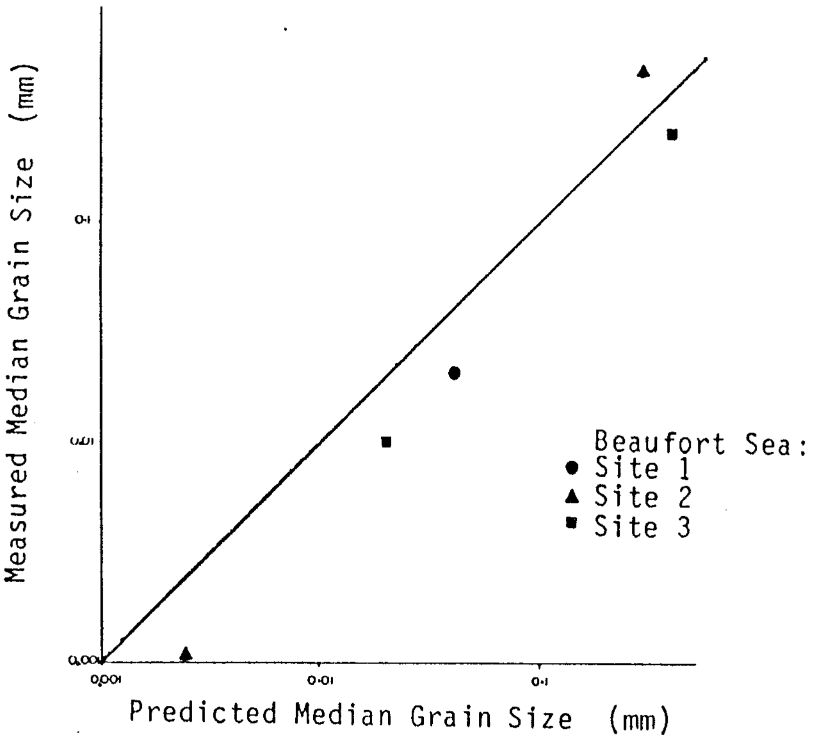


Figure 10 Predicted versus measured Median grain size (mm)

RESEARCH IN ACOUSTICS AT UNIVERSITY OF CALGARY

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We shall give a brief overview of some of the research underway at the University of Calgary including development of computer modelling, interactive processing and image analysis/interpretation systems, physical modelling, and a study of viscoelastic wave propagation.

We shall also discuss recent work in geotechnical vertical seismic profiling, wide aperture seismic studies and improved seismic processing. We shall emphasize connections where possible between physical properties of sediments and their acoustical expression.

INTRODUCTION

At the University of Calgary we are relatively new in the field of Geo-Acoustics. We have only been involved in the general area associated with Marine Acoustics for about one year. In this presentation, I will give a quick overview of some of our activities. First, however, I will mention some of the facilities that we have commissioned for laboratory studies and then continue with descriptions of our recent field programs.

REVIEW OF FACILITIES

One of the computer software systems under development is the Sierra Geophysics Modelling package. This is a three-dimensional modelling package which allows acoustic models to undergo sophisticated ray trace analysis. This model uses the elastic wave equation, however we have recently acquired a visco-elastic 3-D modelling package which is helping us to understand more sophisticated theoretical models for comparison with field data. We can generate a full, normal incidence, or image ray seismogram for various types of survey configurations and then we can gather the results into typical seismograms for further processing. The packages give us a complete seismic modelling system capable of both two- and three-dimensional processing with either an elastic or visco-elastic model.

We are also building a physical modelling tank that will enable us to simulate three-dimensional and other types of surveys. The tank is roughly 3 m X 4 m and several metres deep. We have two receivers located on one moveable arm and a source transducer located on another moveable arm with both arms controlled by a microcomputer. Models are constructed out of resins and various types of rubbers. All measurements are scaled so that data collected appears very similar to real seismic data. Presently, the modelling tank is in the final stage of commissioning. It is much larger than the one in a similar facility at the University of Houston and we hope that it will be more flexible in its use.

THEORETICAL METHODS

On the theoretical side, Dr. Ed Krebes is studying the visco-elastic wave equation and is seeking answers to important questions such as "What is the meaning of Reflection Coefficient in the visco-elastic case and how does it compare with the purely elastic case?". The important aspect of this work is that we arrive at the Helmholtz solution just as in the standard acoustic wave equation with the difference being that the wave propagation vector turns out to be complex. This, of course, means that attenuation effects, which are not normally accounted for in the elastic model are included in the analysis. The derivation of the reflection coefficient now becomes more complex because both an attenuation vector and a compressional wave vector are involved. These theoretical studies may help us understand terms like "reflection coefficient" and "acoustic impedence", etc. when applied to visco-elastic media.

The next obvious questions would be "To what extent does the visco-elastic wave equation apply to near surface phenomena in the marine case?". For example, if they do apply then perhaps we should consider a different approach in calculating reflection coefficients, acoustic impedence, etc. Examples of a synthetic seismogram generated using the elastic wave equation and a seismogram using the same model but with a visco-elastic wave equation clearly show the effects of attenuation using the visco-elastic model. We hope this type of modelling will help in the understanding of our particular type of field data.

VISUAL DISPLAY AND ANALYSIS

We are also involved in Image Analysis and have just acquired from Ottawa a Dipix Image Analysis System. We are presently adapting the system for seismic data and writing software to determine trace attributes such as instantaneous phase, frequency, amplitude, etc. With this system the possibility exists for pattern recognition by comparing selected attributes using scatter diagrams, for example. Although the system can only image in two dimensions at any one time, it can work with any number of dimensions, making possible classification using cluster analysis.

The scatter diagrams can aid in determining the distribution of selected attributes within a given portion of a seismic section. We can then look for methods of enhancing certain attributes. This leads to searching for producing zones in seismic sections by identifying areas with similar attributes. Our hopes for this technique in the near future are related to permafrost studies. We would like to establish a set of attributes which are indicative of permafrost zones, gas hydrates, etc.

Another aspect of our recent work was to use a commercial program for inverting seismic traces to obtain acoustic impedence curves. We show a comparison between a synthetic section generated from the impedence curves and the original seismic data. We were very pleased with the apparent accuracy of the method. We also have the capability of using well logs to create an even better fit to the actual geological situation. This technique almost results in a velocity analysis procedure. We are also able to generate synthetic seismograms from well logs.

FIELD PROGRAMS

In the past year we have conducted several VSP (Vertical Seismic Profiling) experiments at sea using a hole originally drilled for geotechnical purposes. A three component sonde was lowered into the hole, and using an air gun as a source, sets of seismic signatures were recorded and eventually processed. The shape of the first arrival is very indicative of the sound velocities of the section. One feature of the VSP method that we think is important is that <u>in situ</u> measurements of velocity are being made away from the borehole itself in undisturbed material. Some interesting differences between the observed geology and the VSP data have come to light. We also observe some very low velocities near the surface. Initially these data caused some consternation but further work had indicated that shallow gas-filled sediments are probably responsible. Similar results have been reported elsewhere[1]. We hope to be able to use the fact that bulk moduli and shear moduli are related to compressional and shear wave velocity. Such relationships could be useful in a geotechnical engineering context to infer these moduli from VSP data since the method is fast and coverage is good.

Another field program that we conducted last year was multi-ship refraction work in the Beaufort Sea. As a result we have just implemented an interactive refraction interpretation system including the generalised reciprocal method programs as well as automatic picking routines.

The next topic I wish to discuss involves one of our students[2] who discovered that some Beaufort Sea seismic data suffered loss of amplitude with offset on certain reflection events.

We show some stacked sections using near offset and far offset traces. Information appears to be lacking concerning the near surface material in the far offset traces and a significant difference exists between the near and far traces. Her studies indicated that because the critical angle is attained rather quickly in the near surface material, we simply do not obtain strong reflections at large angles. The deeper reflections, of course, are present. Her conclusion from this work suggests that long arrays may not be needed for high resolution work involving near surface material.

Finally I would like to mention that we have a student working on the design of a profiling system using an optimum "chirp" signal with correlation similar in some respects to the system discussed earlier by Larry Mayer. Together with some colleagues we hope to do some work with this system in the near future.

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[1] Reference in Geophysics, March, 1984

[2] Denise Poley

MARINE SEISMOLOGY IN SURFICIAL SEDIMENTS

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Previously, traditional travel-time methods of seismology have been applied to surficial sediment problems to give acoustic velocities (eg. Porter et al., 1974; Hunter et al., 1976), but the pre-occupation with normal-incidence profiling of many who are involved in mapping the seabed has dissipated effort which might better be directed towards making more widely available equipment suited to the observation of a more complete seismic response.

Since the late 1960's, seismologists have evolved modelling techniques which have greatly improved the understanding of lithosphere rheology. This approach has been applied to the interpretation of 12-channel acoustic data obtained on the Beaufort Shelf (data of the Geological Survey of Canada). The continuum-mechanical properties of the sediment materials were characterized by the parameters of a simple lossy elastic model (viz. p- and s- velocities and attenuations and bulk density). Seismogram modelling by the Fuchs-Mueller (1971) reflectivity method allowed estimates to be made of these parameters for a layered model and suggested a velocity profile which has neither been previously reported nor is recoverable from a travel-time analysis of the same data. Ambiguities of interpretation arise, but the method indicates that these might be resolved by towing acoustic source and receiver at an appropriate height above the seabed. There is no reason to suppose that an optimum height would, in all cases, coincide with the height which would be optimum for the observation of seabed scattering processes.

Many details concerning the application of seismogram modelling techniques to surficial sediments remain to be considered further, particularly the rheological basis of the model, but the need to pursue investigations in this general manner appears to have been established.

INTRODUCTION

Brekhovskikh (1960, p. 241) presented a formal treatment of the behaviour of a spherical wavefront at a plane interface and demonstrated convincingly that the processes occurring at that interface to produce the travel-time characteristics of the wave fields observed in exploration geophysics are a function of the geometrical disposition of source and receiver with respect to the interface and of the velocity contrast, but are quite independent of the mechanical characteristics of the media in question. All of the travel time methods start with this premise, and use various contrivances to invert the problem, that is, to derive the velocity structure of a layered space from the arrival time of acoustic signals.

The methods may be broadly classified as "travel- time" or "differential travel-time", according to whether measurement is made of an arrival time or of its gradient, a distinction which has more basis in practice than in theory. Field records whose time and distance origins are not well defined may still give useful results if receivers or shotpoints occur sufficiently densely to allow accurate measurement of travel-time gradients - the basis of the layer parameter method for dealing with wide angle reflexion profiles (Bryan, 1974). On the other hand, if observations are available at only a very few different separations between source and receiver, then careful attention to the zero points of time and distance will still allow results to be obtained. An illustration of this latter approach to what is more normally dealt with by means of the travel-time gradient method of a standard "refraction line" is given by McKay (1979) and discussed more fully by McKay and Mckay (1982) and McKay (1983).

Various methods of constructing synthetic seismograms on the basis of a mechanical model have been reviewed by Cerveny (1983). Of these, one which is commonly used by seismologists is the reflectivity method of Fuchs and Mueller (1971) wherein the plane-wave reflexion coefficient is first evaluated for a grid of incidence angle and frequency points and then integrated for each receiver position to yield a seismogram by multiplication with the source spectrum and inverse Fourier transformation.

The reflectivity method of Fuchs and Mueller has been applied to modelling seismograms obtained in the Beaufort Sea.

APPLICATION TO BEAUFORT SEA DATA

These seismograms were drawn from the data set which the Terrain Geophysics section of the Geological Survey of Canada gathered with a 10 cu. in. air gun and a 100 m long, 12 channel seismic streamer made at the N.S. Research Foundation. A kinematic analysis of these data is presented elsewhere in this volume by Hunter et al., and the first attempts at modelling the dynamic characteristics of these seismograms was based on the layered structure and p-wave velocities suggested by that analysis. Variation of density, s-velocity and p-and s-attenuations were produced. The model shown in Figure 1, and the parameters shown in Figure 2 are for a field seismogram from the Nerlerk area. Several hundred synthetic seismograms were constructed in this modelling process. Some of the values obtained (Figure 2) appear unusual, but are not impossible for the expected layering, viz. layer 1 - surficial holocene mud; layer 2 - partially ice-bonded sand; layer 3 - fully ice-bonded sand. One of the biggest problems is with the high value for the p-wave velocity in layer 3. Field measurements of p-velocity in permafrost (eg., Hunter, 1974) suggest that this seldom takes a value above 3.5 km/s, although Antsyferov et al. (1964) observed a velocity of 4.65 km/s in a laboratory specimen of permafrost-like material.

Experience with the modelling of a seismogram from the Ukalerk area helps shed light on this high value for the layer 3 velocity. It proved impossible to produce a theoretical model for the field seismogram of Figure 3 by making reasonable (or even unreasonable) variations in density, s-velocity and attenuation (Figure 4). It was necessary to depart radically from the simple layered model implicit in the conventional kinematic analysis and to postulate a model with appreciable velocity gradients before any approximation to the field record could be reached (Figure 5). In the light of this finding, a re-interpretation of the seismogram of Figure 1 with models which allowed velocity gradients similar to those of Figure 5 showed that the velocity profiles given in Figure 6 appear to be alternatives, and that the seismic data from the Nerkerk area is intrinsically ambiguous in this respect, although the velocity profile of Figure 6b is to be preferred in view of the anticipated velocities within the zone of fully ice-bonded permafrost (Neave et al., 1979). Further modelling investigation has shown that a suitable towing depth for the seismic equipment would remove this ambiguity.

CONCLUSIONS AND DISCUSSION

The work described in this paper and in earlier papers (McKay and McKay 1982; McKay, 1983) was pursued in two ways; firstly by making minor modifications and additions to existing profiling equipment to allow the collection of acoustic velocity measurements and secondly by constructing and operating new equipment to allow the gathering of multichannel data suitable for analytical treatment by methods established in the allied field of seismology. The results from the former method are as important as from the latter approach in that they are immediately applicable to the improvement of current survey practice (which has been described as "desultory" by Cratchley et al., 1982). The latter approach required the considerable re-orientation of accepted field operations and data-reduction methods before its use could become widespread, but it is clearly necessary if erroneous conclusions about velocity structure deduced from simpler methods are to be avoided. Much recent research work on sedimentation has been based on deep-tow vertical-incidence reflexion profiling. The results presented in this work reinforce the opinion of McKay and McKay (1982), that such a technique is a superficial way of analysing the acoustic response of seabed materials. The results also show that a deep tow deployment would be essential for the realization of a geometrical disposition of source and receivers for the gathering of multichannel data optimal for analysis by the synthetic seismogram method.

Keen (Clark, 1984) has noted that "in marine seismology in the last five years, the computer has come to be looked on as a resource as valuable as research ships. There's no point in even going to sea and collecting data if you can't process it. It would be better to tie the ships up and put the money into more computers." It seems both appropriate and necessary to re-iterate this statement in the context of surficial sediment studies where single-channel, normal-incidence profiles (Figure 7) have become recognized as the end product of a "geophysical" survey whether analogue or digital acquisition methods are used. Since the required observational techniques do not increase ship time beyond what is needed by the conventional approach, it may be hoped that attention to the considerations outlined in this paper will significantly improve current practice in seabed investigations, whether they are carried out to satisfy the aims of the sedimentologist, the civil engineer or the underwater acoustician.

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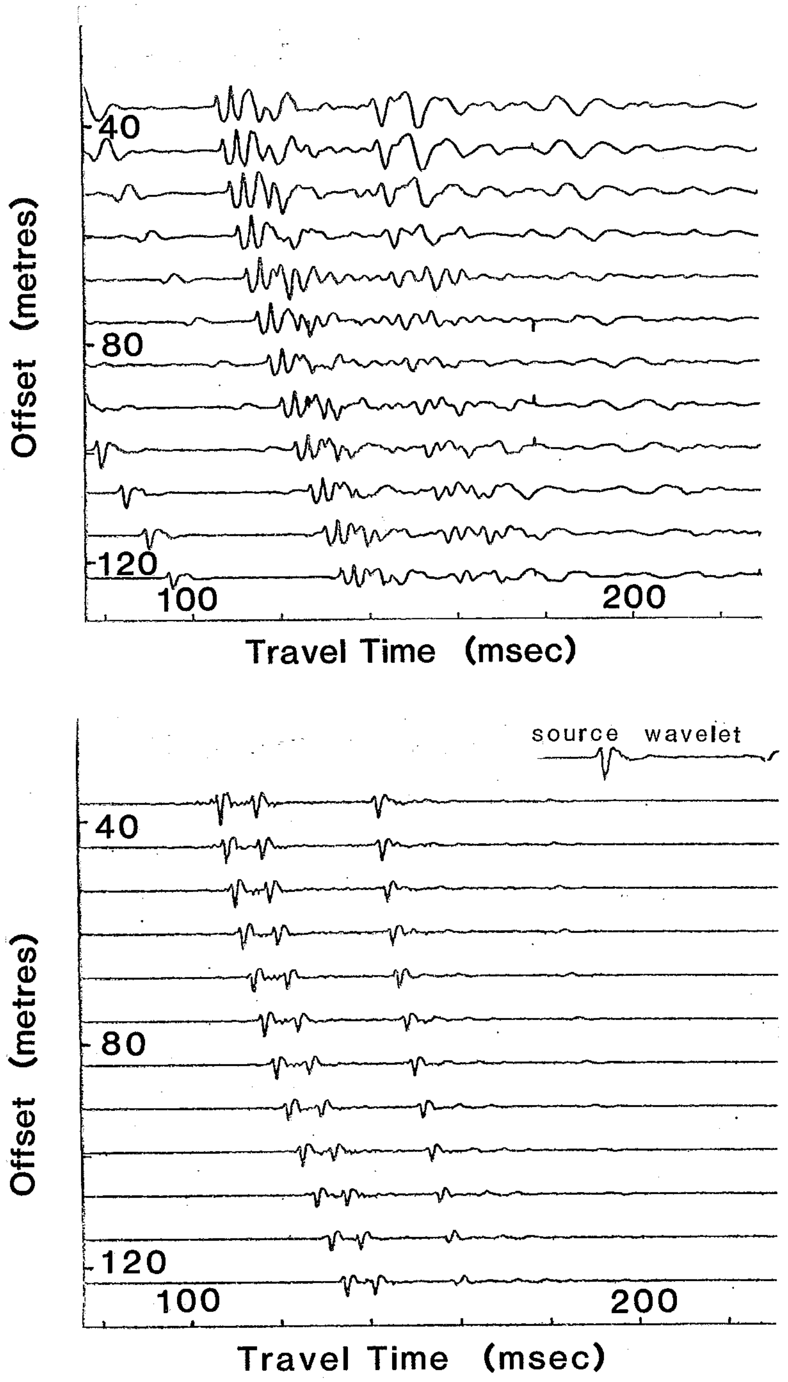

fig. 1. Field seismogram (top) from the Nerlerk area of the Canadian Beaufort Sea. The synthetic seismogram (below) is constructed on the basis of a simple 3-layer model using the parameters given in fig. 2.

	p-velo. (km/s.)	s-velo. (km/s.)	density (gm/ml)	1/Qp	1/Qs
Layer 1	1.46-1.55 (1.48)	0.0-0.2 (0.01)	1.60-1.70 (1.65)	<0.02 (0.02)	not found
Layer 2	1.95-2.05 (2.00)	0.5-0.9 (0.55)	1.95-2.05 (2.00)	<0.002 (0.001)	>0.02 (0.03)
Layer 3	4.2-4.9 (4.7)	2.5-2.8 (2.55)	1.95-2.05 (1.98)	>0.01 (0.01)	not found

fig. 2. Parameters which are suggested by the modelling technique as applied to a simple layered structure for the field seismogram of fig. 1.

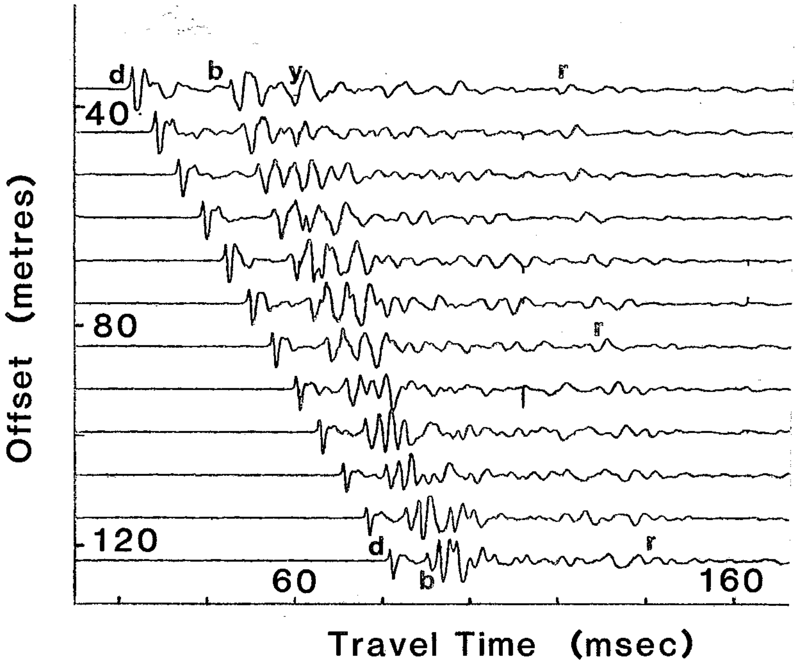

fig. 3. Field seismogram from the Ukalerk area of the Canadian Beaufort Sea.
Note that the arrival "d" - the direct water-wave is not modelled in the synthetic seismograms.

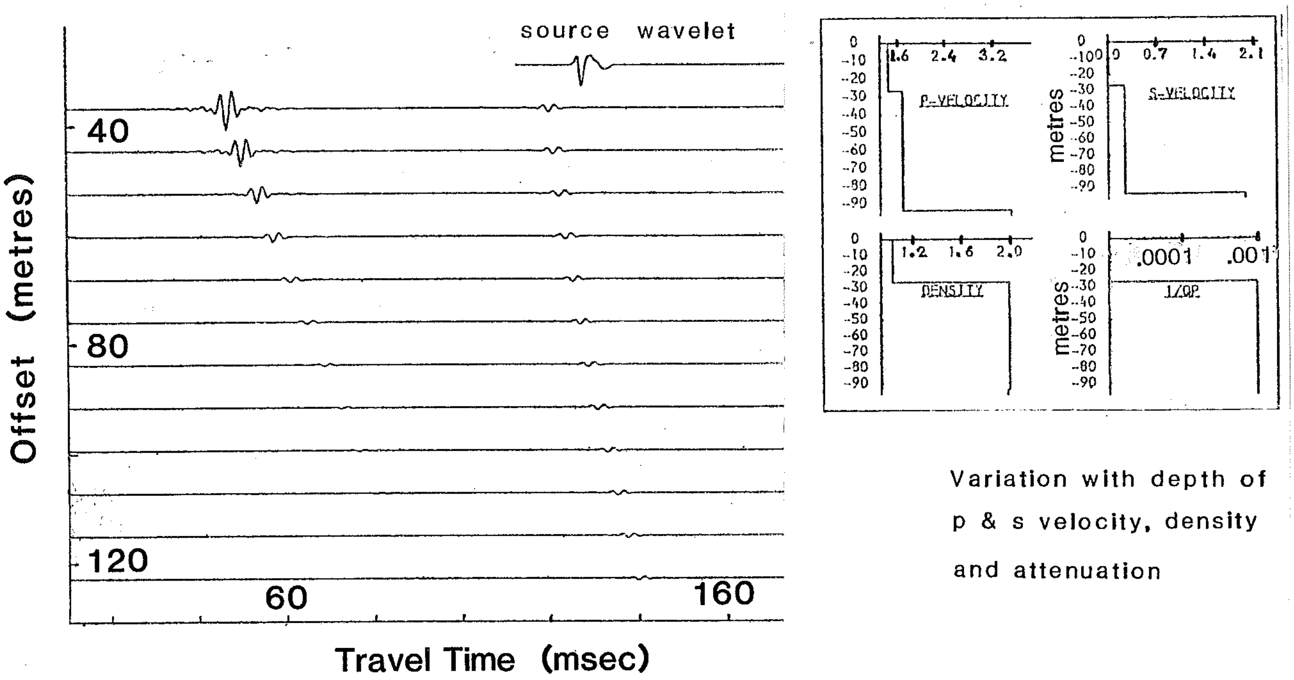

fig. 4. An unsuccessful attempt to fit a simple layered model to the field seismogram of fig. 3.

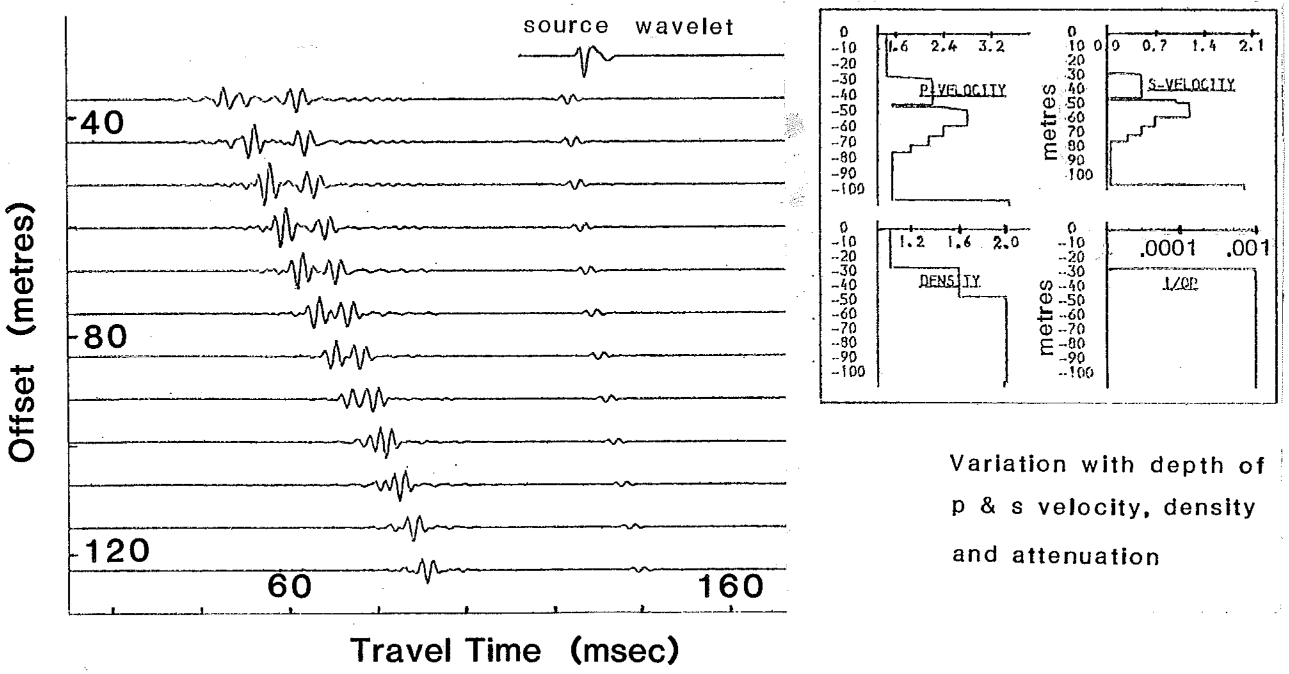

fig. 5. Some approach to the field record (fig. 3) is obtained by removing the constraint of simple layering and allowing a more continuous variation in p- and s-velocity.

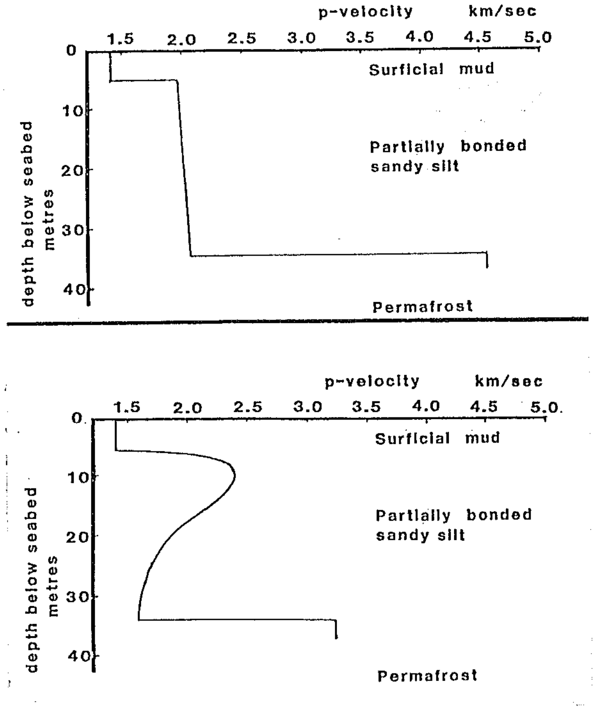

fig. 6. The variation of p-velocity with depth which arises from a dynamic analysis of the field data which :

a. Is restricted to near-uniform layers. (above)
b. Allows much greater variation in velocity gradient. (below)

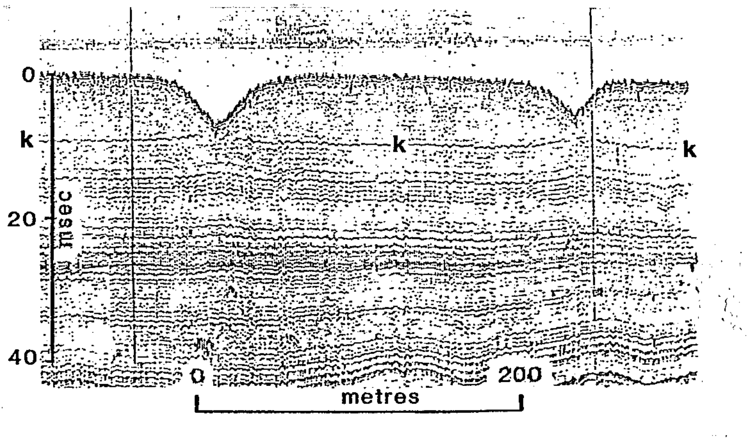

fig. 7. A conventional single-channel, normal-incidence reflection profile over pockmarks in the Emerald Basin, Scotian Shelf. Even in locations such as this, where variation in acoustic velocity may be expected as a result of sediment gasification, a profile of this kind is regularly used as the basis for mapping sedimentary units and structures, although obvious questions remain unanswered about the flexure of the event "k" beneath pockmarks (McKay, 1980) and about the nature of the parallel reflectors (Mayer, 1979).

CHARACTERIZATION OF SEAFLOOR SEDIMENTS BY GEO-ACOUSTIC SCATTERING MODELS USING HIGH RESOLUTION SEISMIC DATA

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This paper describes current research in interpretational modelling using high resolution marine seismic data acquired with a sound source having a frequency bandwidth extending from 0.5 kHz to over 10 kHz. The data must be corrected for disturbances caused by motion of the sound source and hydrophones and for variation in the sound source output. Inversion of the corrected data yields estimates of R.M.S. surface roughness, bottom topography and correlation distances in the range of 0.1 m to 1 m, and acoustic absorption constant, volume backscattering constant and acoustic impedance contrast as the parameters of geo-acoustic surface and volume scattering models. Presentation of the data in the form of sonograms, a contoured map of normalized signal power in the time-frequency plane, provide a basis for the qualitative assessment of textural features of the material.

INTRODUCTION

For several years I have been associated with a project known as the "Seabed" project and today I shall be presenting a summary of several aspects of the work that relate to seafloor properties. I shall concentrate on the problems and importance of making a reproduceable measurement because, as with all scientific endeavours, without such a measurement good science cannot exist. The presentation is a conceptual overview of the principles of what we refer to as quantitative seismic profiling. These methods are now in routine use for regional geophysical mapping of the Canadian continental shelf and since 1976 in excess of 75,000 line kilometers of data have been collected. The "Seabed" project was supported by the Department of Energy, Mines and Resources, Department of National Defence, The National Research Council and Fisheries and Oceans. In addition, data was supplied to several University groups for use in research projects supported by the National Science and Engineering Research Council.

The goal of the program was to develop and improve the method of making geological maps with particular reference to surficial sediments.

DATA COLLECTION AND SIGNAL PROCESSING

Figures I and 2 shows the method of collection and on-line processing of the raw seismic data. Briefly a "fish" comprising a sound source and receiver is towed behind a survey vessel. The sound source, in this case a Boomer, transmits a short 120 microsecond pulse of sound energy into the water. Reflections from the sea floor and deeper horizons are received either by a towed hydrophone array or fixed single element hydrophone and transmitted to the ship for display, recording, and invariably processing.

The processing system produces three different types of outputs that we term "feature metrics". One output is termed sonogram parameters which are the parameters that characterize surface and volume scattering geoacoustic models of the seafloor, together with attentuation estimates of the first layer. These are computed off-line using tape recorded data. The second group, reflectivity metrics, are computed in real time and are measurements of the signal (echo) parameters that are related to seafloor roughness, variability and hardness. The third group, coherency metrics, describe a scattering model with estimates of rms roughness and correlation distances. This third group are computed off-line. The three outputs are summarized in Figure 3 which also indicates that fish depth and image enhanced graphic recordings are also produced.

DISCUSSION

If a body, such as a fish, could be towed at a well defined and controlled depth then time registration between sequential echoes would be subject only to the effects of the target geology. However in real life this ideal situation is hardly, if ever, realized. The tow fish is subject to many kinds of disturbances mainly due to heave and other forces acting on the tow cable. Since we are employing sound sources with frequency bandwidths in the order of 10 kHz (pulse lengths of 120 microseconds) resolvable distances are of the order of 15 cm and detectable changes much less. Ideally, if "clean" data are required displacement corrections to within 2 cm must be applied to the raw data to compensate for the dynamic disturbance of the tow fish. For survey mapping, the positions of the fish in the vertical as well as in the X and Y geographic planes must be known. The accuracy required of the fish positioning system reflect the accuracy of the survey. In detailed surveys, positional accuracies of metres in water depths of 1000 metres and beyond are not unusual. These specifications mean that the three position and three velocity vectors of the towed body must be known with "missile" grade precision.

ACOUSTIC DETAILS

As far as the acoustic arrangment is concerned, a calibrated and highly repeatable pressure pulse has to be generated in the water and the echoes detected by towed or fixed hydrophone arrays. The Huntec system meets these requirements by using a "boomer" sound source with a calibrating hydrophone in the near field. Two receiving systems comprise the echo detection process. One short hydrophone array is towed behind the fish and has directional characteristics combined with low self noise. However, some geometric control is lost because of the decoupling that is inherent in the arrangement. This weakness is overcome by an internal hydrophone mounted beneath the boomer plate. Here geometrical stability is assured but the receiving characteristics are modified by the plate resulting in decreased resolution capabilities. Detection of the bottom arrival together with the positional information enables bathymetry data to be recorded.

The output characteristics of the source concentrates the higher frequency components of the beam along the main beam axis and so high pass filtering of the seismic echo can control beamwidth to some degree. Sufficient energy exists to reduce the beamwidth to the angular resolution of an echo sounder (10°). The seismic echoes from which the feature metrics are derived are processed through a "whitening filter" prior to computation. Calibration information and spreading loss corrections are then applied before graphic presentation on a gray scale recorder.

The heart of the Huntec system is the source itself. It is an electrodynamic plane, piston generator with a 50 cm aperture. Up to 1000 joules of electrical energy can be stored in the fish and can be discharged on command. With the pre-whitening filter mentioned above useful energy in the range 500 Hz - 10 kHz is projected into the water.

With impulsive, broadband sound sources such as the boomer, the definition of source level is inconvenient; more relevant is a figure of peak acoustic intensity and pulse duration (length). The boomer at full power and under ideal conditions can penetrate up to 60 metres of hard sediments and return useful data. The beam width at 2.5 kHz is about 60° and consequently the illuminated area is approximately equal to the height of the fish above the bottom. Figure 4 shows the on-axis pressure pulse. As the angle increases, the peak intensity falls and the pulse broadens. The principal energy is concentrated between 4 kHz and 6 kHz and the -5 dB frequency band extends from 2 kHz to 8 kHz and over a ±30° total angle. At angles greater than 30° the lower frequencies extend over a broader range.

SONOGRAM DISPLAY

It is these spectral characteristics that are useful in generating the sonogram display mentioned earlier. The sonogram is basically a contoured plot of the energy spectrum of an echo against elapsed time. The spectral characteristics of the echo are generated by a Fourier Transform process acting on windowed segments of the echo. The resulting spectra are then assembled as shown in Figure 5 in the form of an amplified contour map with frequency plotted against elapsed time. The shaded area of Figure 5 represents those contours where the energy in the echo is substantially above the ambient noise level.

The overall shape of the contoured surface is used in a means of displaying the acoustic reflectivity characteristics of the seafloor. Figure 6 shows a stacked sonogram for a smooth sand bottom overlying a sediment which contains many internal scatterers. Figure 7 shows a stacked sonogram which is interpreted as having been generated by a sea floor with strong "surface scattering". This technique lends itself to a method of extracting acoustic properties from sediment using a modelling process. Figures 8 and 9 are examples of synthetic sonograms that have been modelled to fit the actual stacked sonograms shown in Figures 6 and 7 respectively. These models include the velocity and attenuation characteristics of the sediment, surface roughness characteristics and volume scattering terms.

CONCLUSIONS

In conclusion, this nonintrusive method of measuring the acoustic properties of sediments is seen as powerful addition to the more usual graphic sections. Apart from the extraction of acoustic properties, the method provides a qualitative display which is used in sediment identification.

QUESTION

Q. How do you make the near field/far field conversion using the near field hydrophone?

A. If the transducer is on the main axis and close to the plate, its response represents the velocity history of the plate. In the far field the response represents the acceleration. The relationship between the two can be computed in the form of a transfer response.

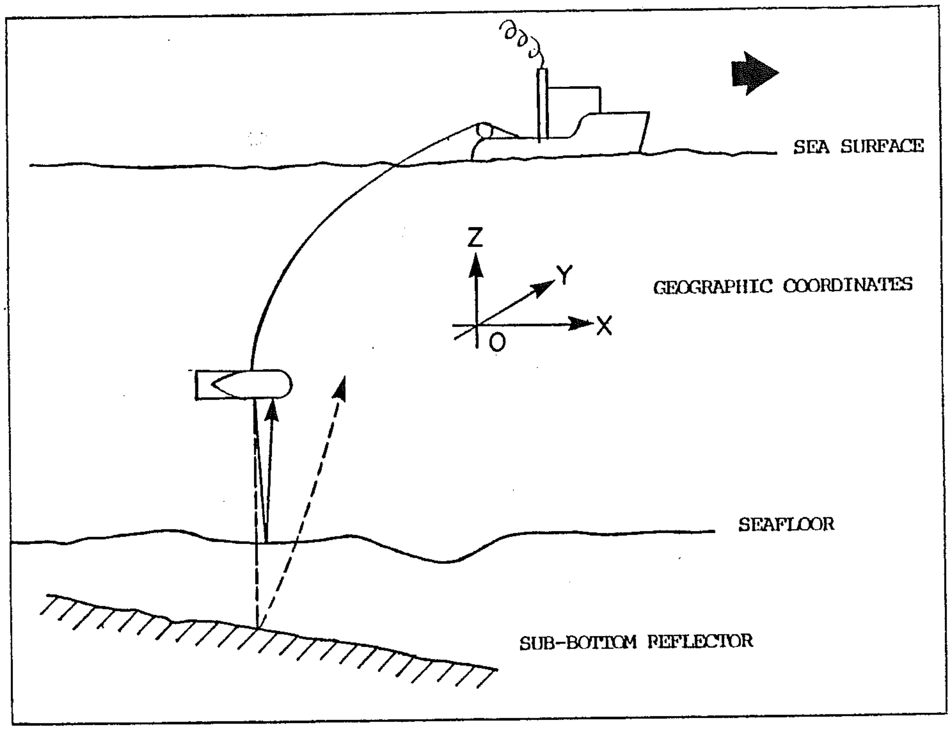

Figure 1 Data collection arrangement

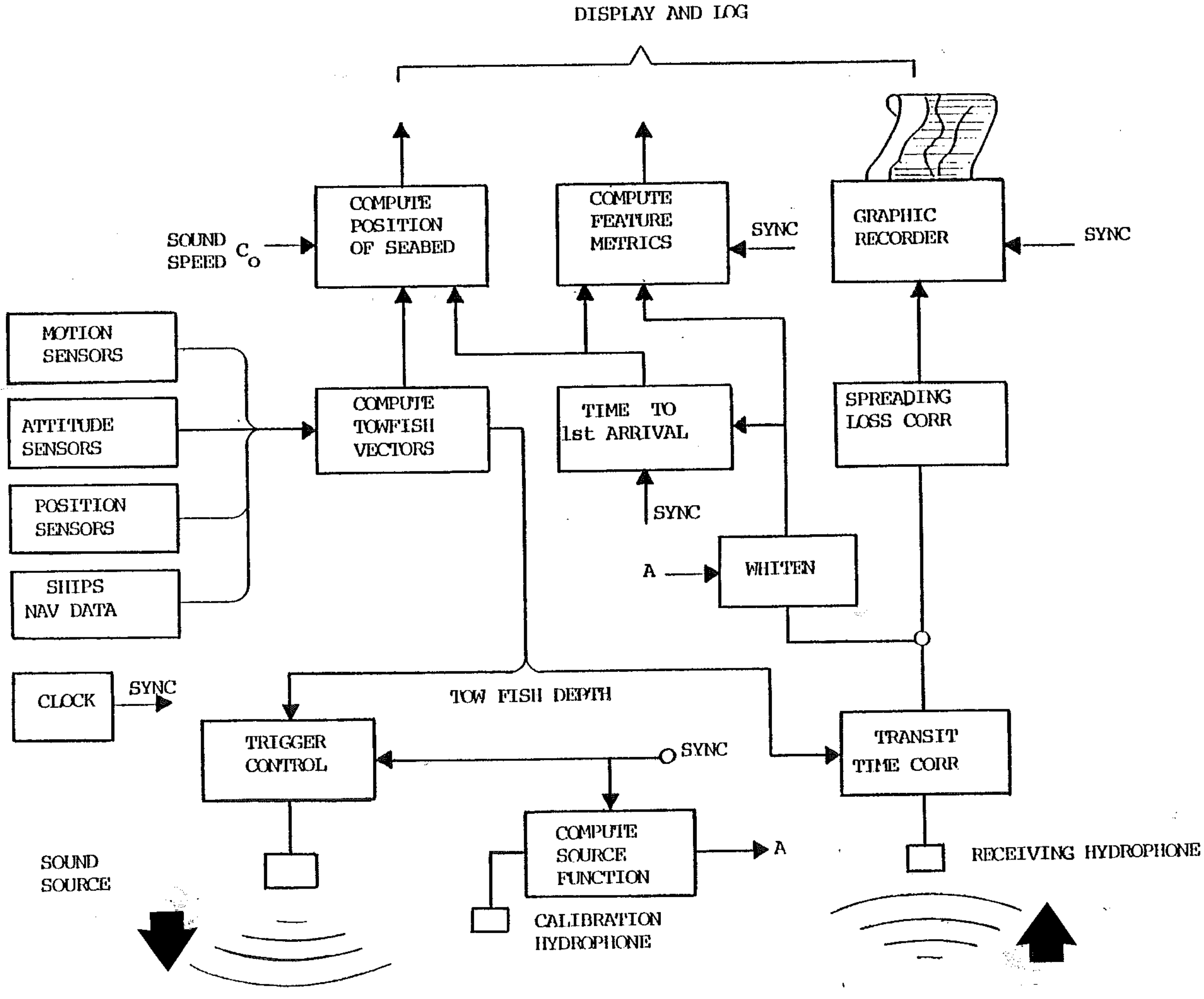

Figure 2 Data processing technique

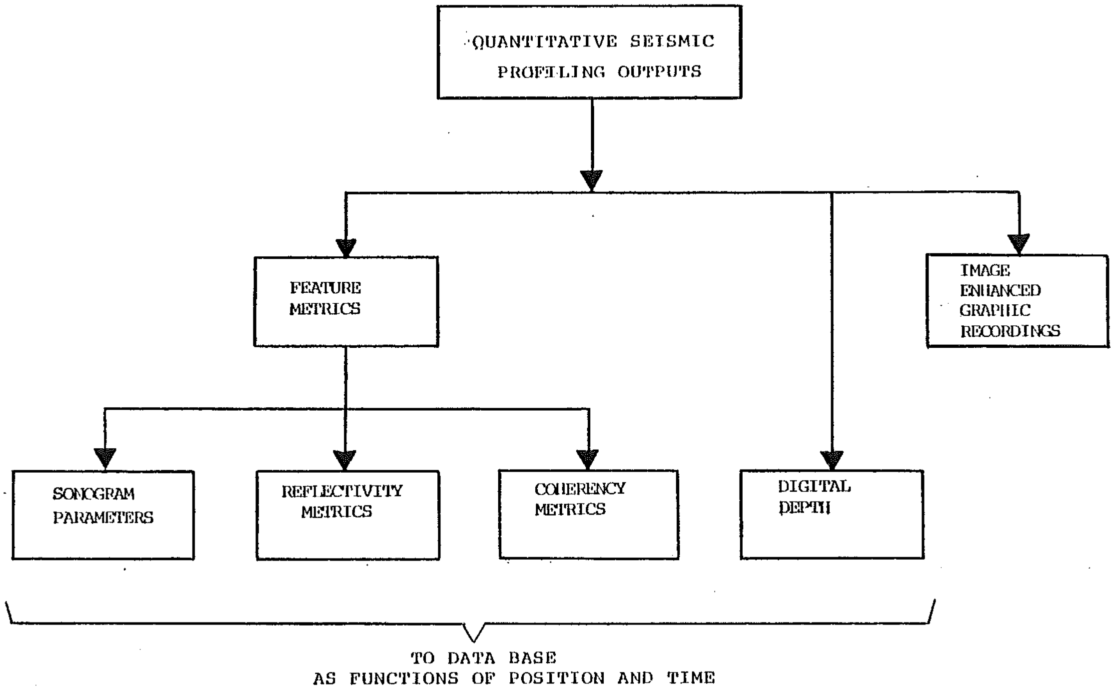

Figure 3 Data processing technique - off line

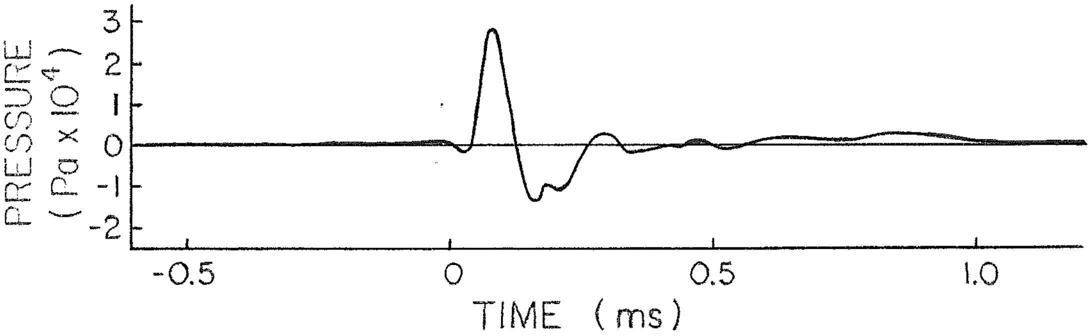

Figure 4 Huntec '70 on-axis boomer pressure pulse

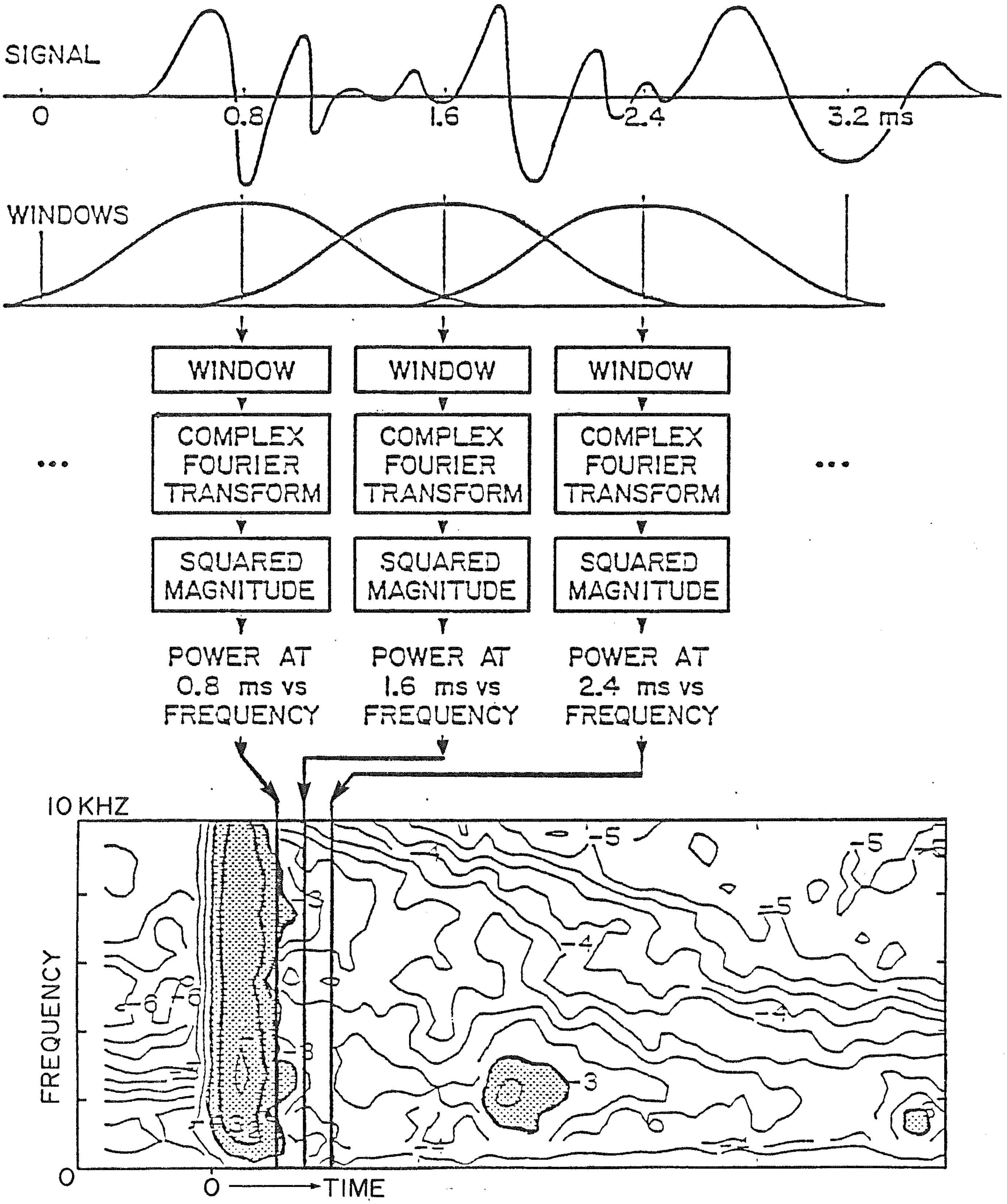

Figure 5 Calculation of a sonogram. In practice the calculation is performed at intervals of 0.2 ms in the time direction.

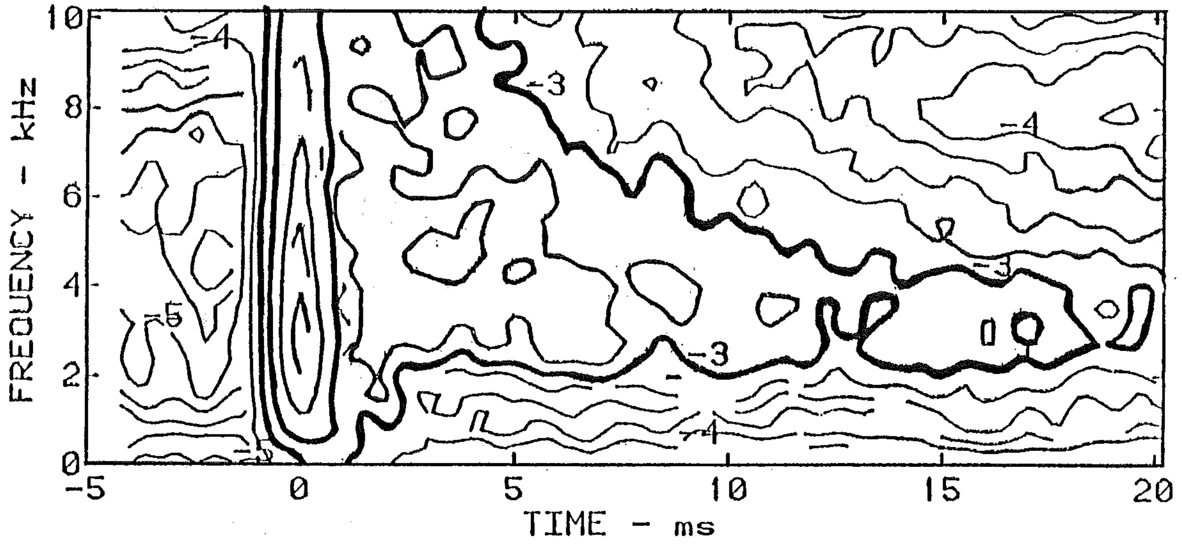

Figure 6 Stacked sonogram from a smooth surfaced bottom (Sambro Sand) overlying a sediment (Scotian Shelf Drift) containing many internal scatterers. The first a-rival is clearly outlined by the -2 Neper contour, and is of a duration comparable to the time resolution of the sonogram. The energy which arrives after the first arrival is interpreted to be caused by volume scattering from the till material.

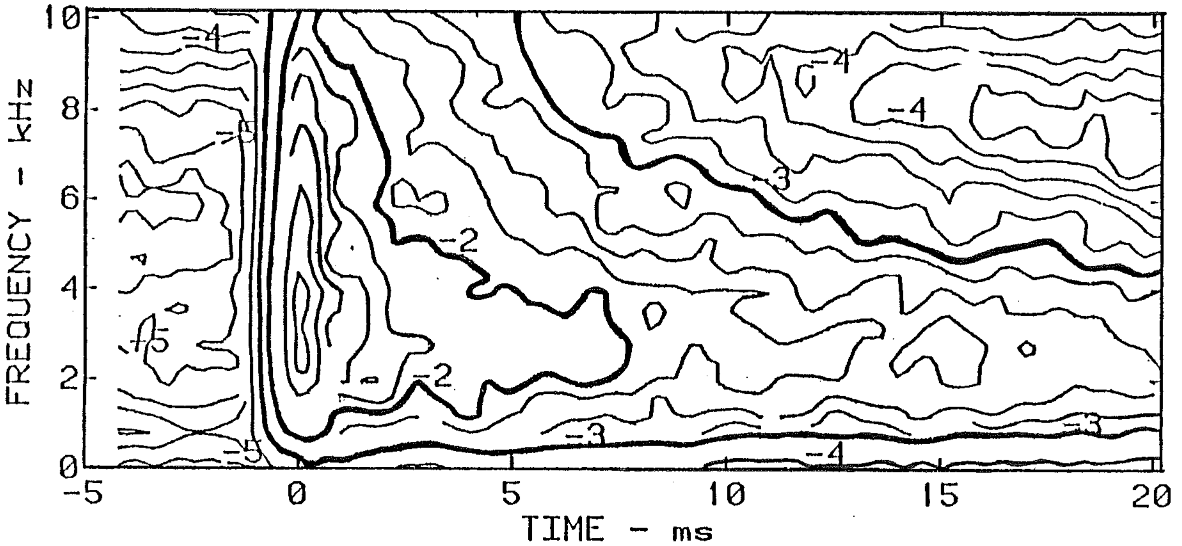

Figure 7 Stacked sonogram from a rough(Scotian Shelf drift and bedrock) bottom. There is no clear distinction between the first arrival and the energy which arrives later. The high frequency energy is reduced due to the source function. This is interpreted to be the result of strong surface scattering.

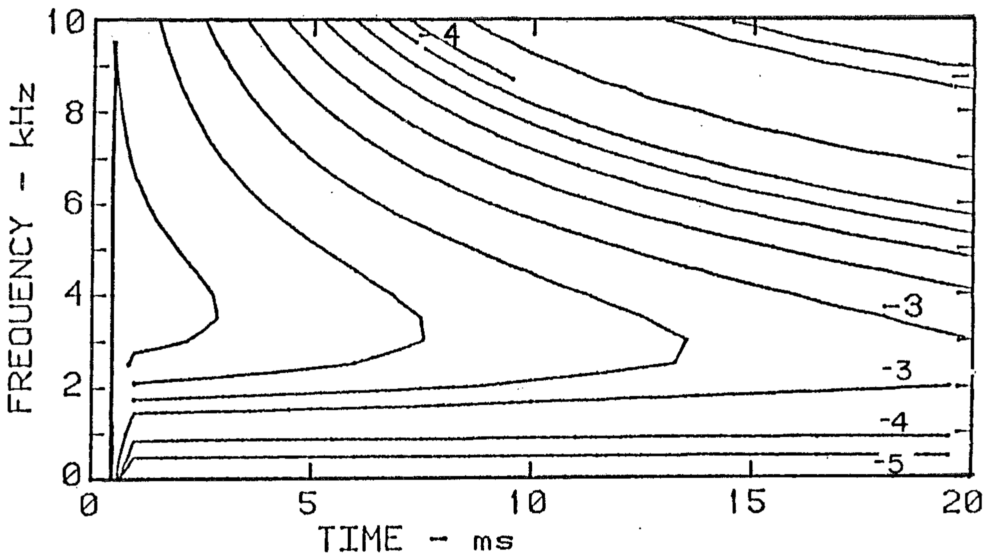

Figure 8 Synthetic sonogram reulting from an attempt to fit a surface scattering model to the volume scattering actual sonogram of Fig. 6. Parameter values H= 0.06m, L=0.225m Reflectivity 0.06.

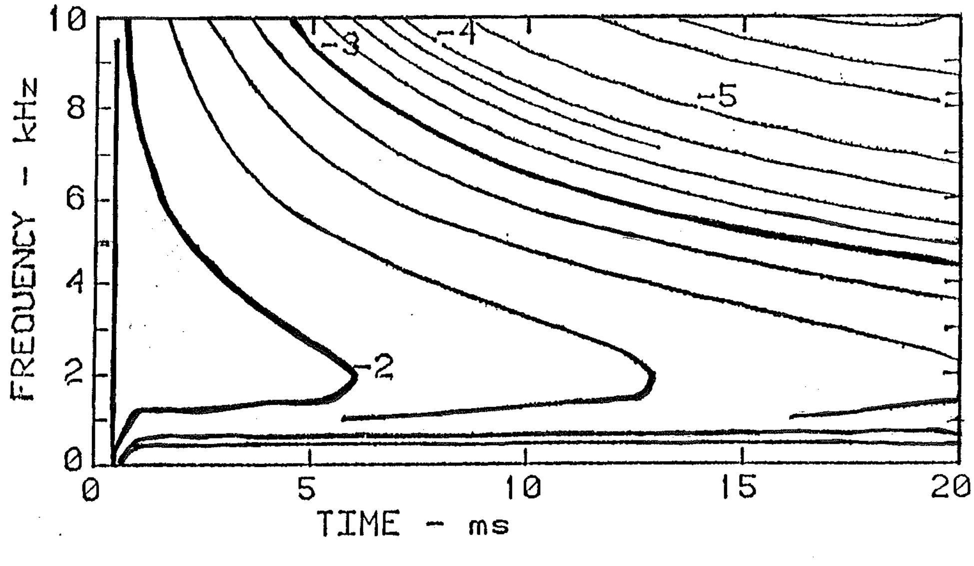

Figure 9 Synthetic sonogram for surface scattering model fitted to actual sonogram of Fig. 7. Model parameters are H=0.13m,L=0.50m and bottom reflectivity is 0.80.

SONAR ESTIMATES OF SEAFLOOR ROUGHNESS

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We present an analysis of the effects of micro-roughness of the ocean bottom on a sonar signal. The results best apply to features where the roughness amplitude is less than one-quarter of an acoustic wavelength such as with ripples, beds of rocks, and nodules. The shape of the probability density function (PDF) of the echo envelope is explained in terms of the RMS roughness and a new parameter, the correlation area of the bottom. The area is equal to the product of the x and y correlation distances along the floor. The PDF is shown to be extremely sensitive to small changes in the roughness. Furthermore by determining the RMS roughness from standard coherent reflection measurements, the correlation area may be extracted directly from the PDF. Thus both vertical as well as lateral information is obtainable from sonar data. The technique can be used to discriminate between different types of bottoms that may have the same roughness but have different correlation areas, for example, a floor with ripples versus one with rocks or nodules. This research is described in detail in Stanton, T.K., J. Acoust. Soc. Am. 75, 1983, pp. 809-818. The analysis combined 1) a general statistical model employing the Rice PDF (S.O. Rice, in Selected Papers on Noise and Stochastic Processes, N. Wax, Ed., New York, Dover 133-294 (1954) and 2) a theory originated by Eckart (C. Eckart, J. Acoust. Soc. Am. 25, 566-570 (1953). The analysis is applied to sonar data collected from the continental shelf near Cape Hatteras, North Carolina. The results are consistent with the known characteristics of the area.

INTRODUCTION

The object of this research work is to obtain micro-roughness properties of the seafloor using a downward looking sonar. The features of the seafloor that are being studied are not resolvable as individual features. The effects of a rough surface on an impinging pressure wave is to cause variations in amplitude and phase of the returned echo (Figure 1) and the degree of this variation or scattering is dictated in a complex manner by the roughness characteristics of the surface. To date the most generally accepted theory of surface scattering involves the Eckart (1) theory in which an RMS surface roughness can be determined by using a stacking process on an ensemble of echoes from a downward looking sonar. The question addressed in this talk is "Can we do better than this one-dimensional approach"?. The suggestion made in this presentation is that a three-dimensional approach can be used that will provide additional information that relates to factors known as the correlation area.

DISCUSSION

Figure 2 highlights the method which involves an additional computational procedure using echo envelope statistics as well as the Eckart scattering formulation. The result is an estimate of the correlation area $l_x + l_y$ which is a product of the individual X and Y correlation distances (of the seafloor). In qualitative terms a signal reflected from a perfectly smooth seafloor would itself be a perfect replica of the incident signal with changes only in amplitude due to the reflection properties of the surface alone. If a signal is reflected or scattered off a rough surface its amplitude will fluctuate and it will have a lengthened "tail" (see Figure 1). By using the Eckart scattering process on repetitive signals the coherent part of the echo can be determined with the incoherent or scattered component averaged to zero. The probability density function or the amplitude frequency distribution function of the coherent component is a delta function implying the signal is consistent through all measurements (Figure 3). However the PDF of the raw echo produces a "Rice" function.

Correlation distance is usually defined in terms of a single dimension. This is acceptable in the special case when roughness features are long crested. Usually seafloor roughness has an alignment caused by bottom currents (Figure 4). The importance of this is that the two-dimensional correlation functions have a base width that is determined by the wavelength of the ripples in one direction and the variation in the crest in the perpendicular direction. Since no distinction can be made between the two coordinates only the product can be derived. Figure 5 shows the echo amplitude PDF of a smooth and rough seafloor and Figure 6 the Eckart/Rice formulation. This method has been tested against ground truth date taken in the same general area and published data taken from the North Atlantic Continental Shelf using a broadband source. The results are summarized in Figure 7.

SUMMARY

To summarize, this method combines the Rice Statistics and the Eckart scattering theory to get a product of the RMS roughness and the correlation area. The Eckart scattering analysis allows the roughness to be determined alone. By combining the two analyses the correlation area can be determined. This method overcomes weaknesses of the Eckart theory alone in that roughness caused by nodules or pepples are not distinguishable from roughness caused by sand ripples.

POSTSCRIPT

If you are not concerned with what the roughness is, but just what the sediment properties are, be careful. Reflectivity measurements can be severely degraded by the roughness. Taking an average of values may suffice in some cases but may produce absolutely meaningless results in others. To be safe, operate at acoustic frequencies that are low enough such that:

$$e^{-2k^2\sigma^2} \doteqdot 1$$

where $K = \frac{2\pi}{\lambda} = \frac{2\pi f}{C}$ wave number (f = frequency)

σ = rms roughness

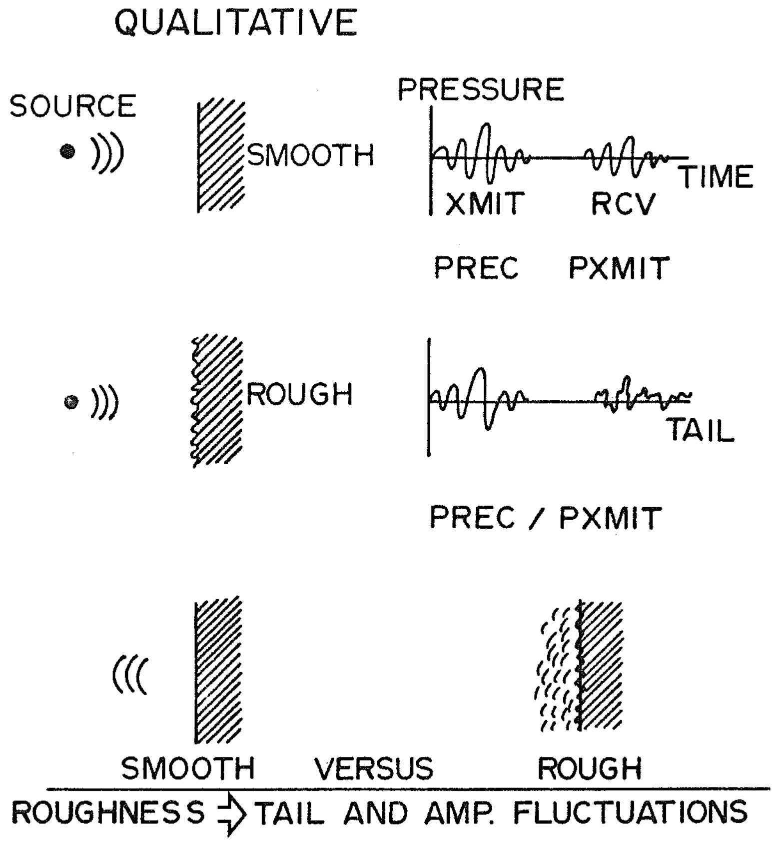


Figure 1 Variations in amplitude and phase due to scattering processes

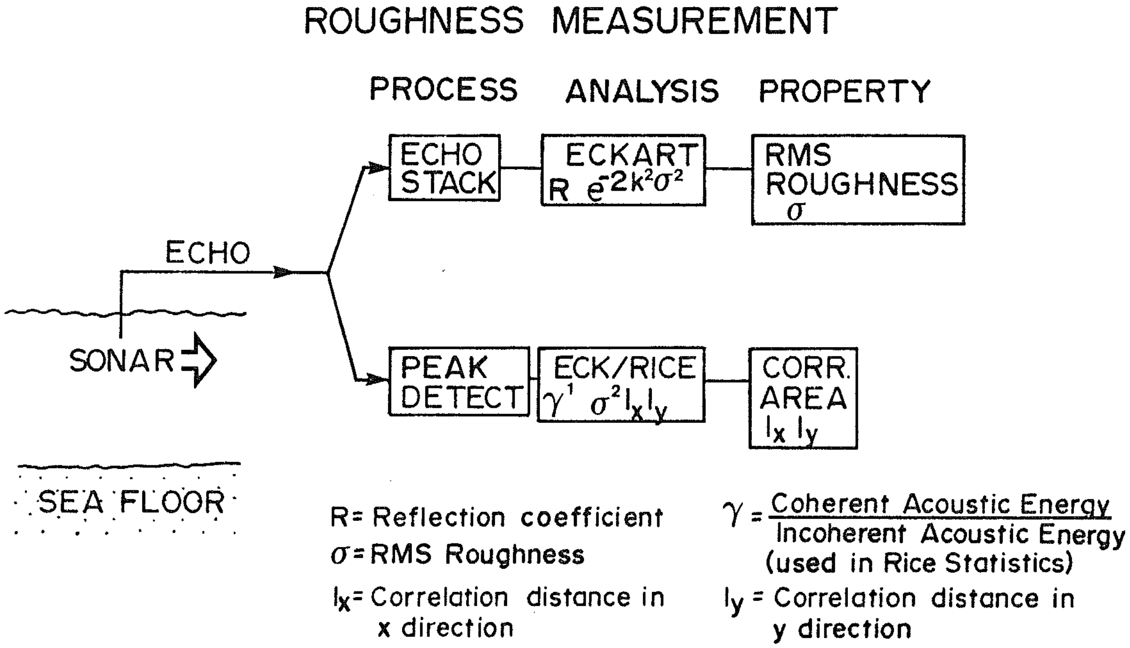


Figure 2 Details of roughness measurement using sonar energy

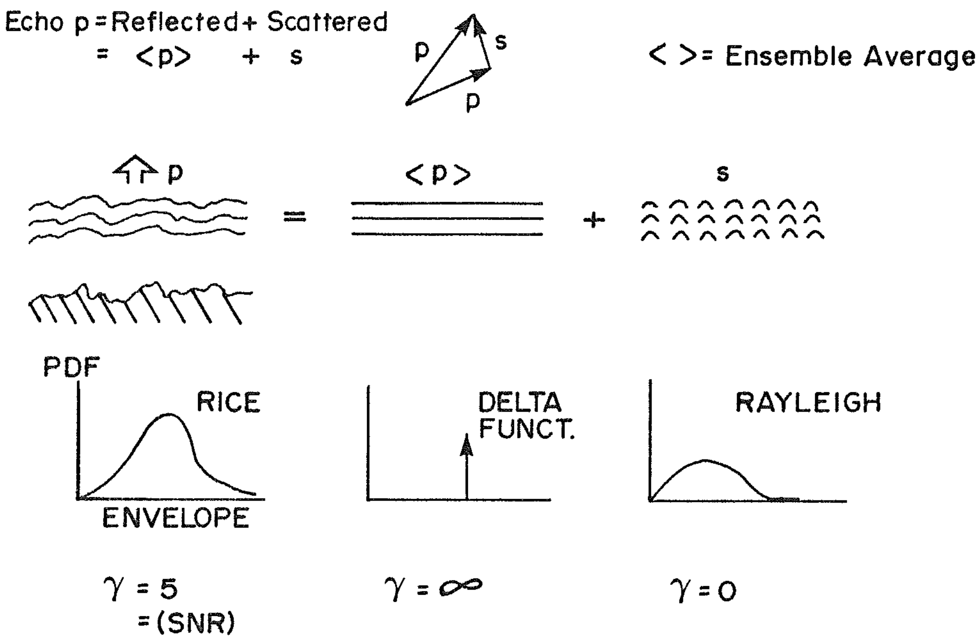


Figure 3 Relationship between the statistical parameters of scattered energy.

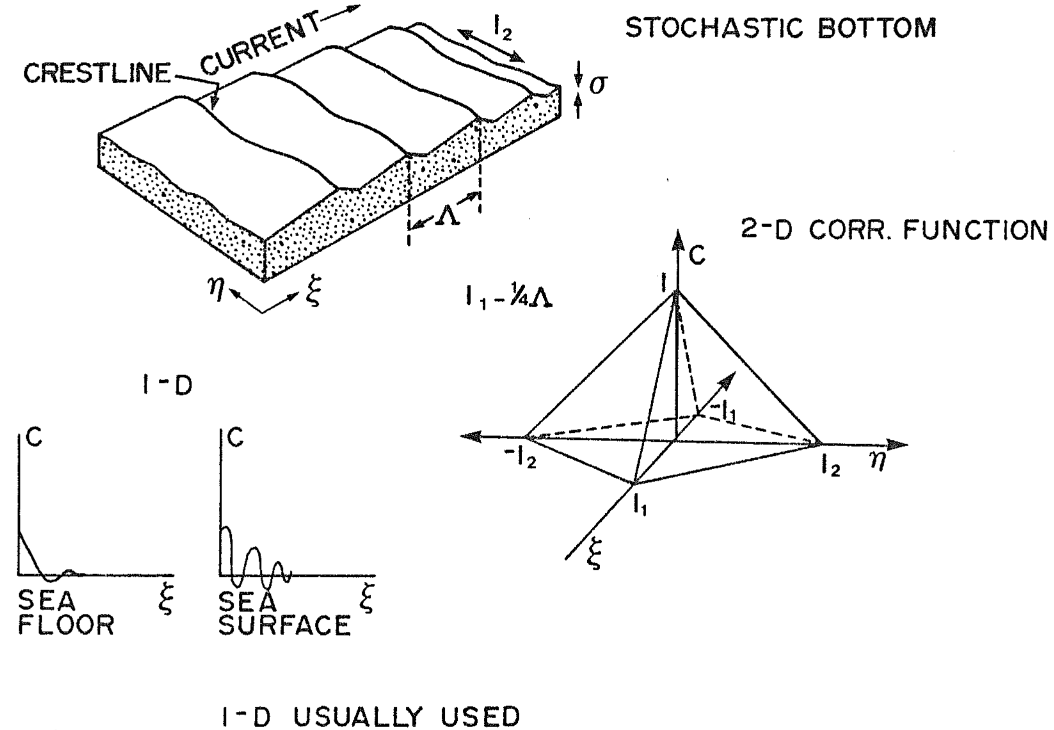
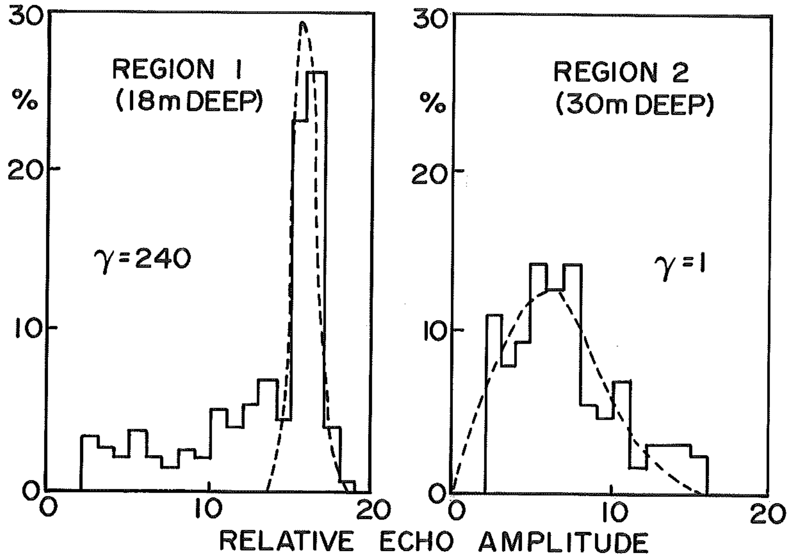


Figure 4 Correlation functions for various types of sea floor



smooth
surface

$\sigma = 1\text{cm}$

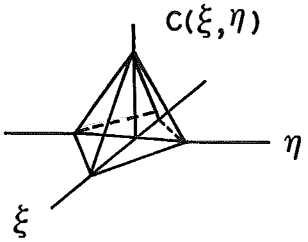
$l_x l_y = 100 - 700\ \text{cm}^2$

rough
surface

$\sigma \simeq 3\ \text{cm}$

$l_1 l_2 = 2700 - 14000\ \text{cm}^2$

Figure 5 Echo amplitude probability density function for a smooth and rough surface



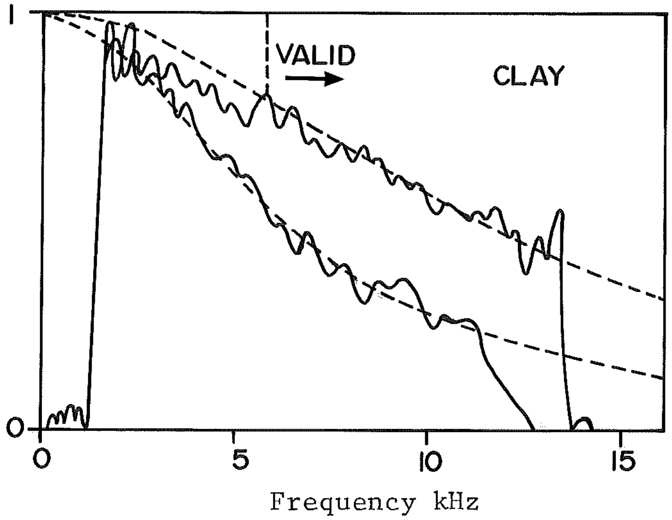
$$\gamma^{-1} = \frac{\text{Reflected E.}}{\text{Scattered E.}}^{-1} = 4\ k^2\sigma^2\ \frac{k^2\chi^2}{8\pi}\quad C(\xi,\eta)\ e^{-a(\xi^2+\eta^2)} d\xi\ d\eta$$

$$\simeq 4\ k^2\sigma^2\ \frac{k^2\chi^2}{8\pi}\quad C(\xi,\eta)\ d\xi\ d\eta$$

where χ = beamwidth and $C(\xi,\eta)$ = correlation function

Final Results $\gamma^{-1} = \frac{1}{3\pi}\chi^2 k^4\sigma^2\ l_x l_y$

Figure 6 The Eckart/Rice formulation



Coherence
Function
$\frac{\langle p \rangle^2}{\langle p^2 \rangle}$

Ground Truth
1 photograph
of seashells
$\sigma \simeq 1\text{cm}$
$l_x \simeq 20\text{cm}$
$l_x l_y \simeq 200\text{-}800\ \text{cm}^2$

Prediction from $\frac{1}{1+\gamma^{-1}}$ fit to data gives $l_x l_y \simeq 900 - 3000\ \text{cm}^2$

Figure 7 Summary of results from North Atlantic continental shelf

SOUND SPEED, POROSITY AND DENSITY OBSERVATIONS ON SAND SAMPLES

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In order to estimate the range of sound speeds that a particular sediment can exhibit, an experiment was devised that would allow continuous measurement of sound speed as packing of a sample was varied from a minimum to a maximum condition. The results indicate that for non-cohesive sediments, a sediment can exhibit a range of sound speeds in excess of 100 m/sec. The inference from these data is that a three- rather than a two-dimensional display is necessary in displaying any relationship involving a descriptive parameter such mean grain size and physical properties such as sound speed. The third parameter must describe the state, or condition of a sample and porosity, void ratio or wet density can be used for sands. Realization of this phenomenon helps in understanding the rather nebulous relationships between sound speed and mean grain size that are commonly found in the literature.

This work was undertaken at the University College of North Wales in 1975.

INTRODUCTION

This presentation discusses acoustic and geotechnical measurements made on samples of saturated sand under controlled laboratory conditions. The main reason for this work was to obtain calibration or state curves of sound speed against porosity for sand samples that had been collected at specific sites where in situ sound speed values had been obtained. A second objective was to provide an insight into the way porosity of a sample directly affects a physical property. In this discussion sound speed only is addressed but electrical resistivity data (Jackson, et al., 1978) were obtained concurrently with the sound speed measurements.

LABORATORY MEASUREMENTS

The basic idea behind the laboratory technique was to deposit a sand sample in a measuring cell with maximum porosity and then to make measurements of sound speed as the sample's state was allowed to change to its minimum porosity condition.

The actual measuring cell is shown in Figure 1. It consists of a plexiglass cube with a volume of approximately 1 litre. A graduated measuring cylinder is mounted vertically above the cell and the total volume of the cylinder is such that for non-cohesive sediments the entire range of volumes corresponding to maximum and minimum porosity can be accommodated. The acoustic measurements were made across two faces of the cube using a travel time method involving two transducers. Compressional wave sound speed could be determined to an estimated accuracy of 3 m/sec.

Since measurements were to be made over a range of porosity values it was necessary to develop a method of attaining the loose packed condition. After a number of experiments a suspension method was selected where wet sand was allowed to settle slowly in the water filled cell to remove any extraneous air. The sensitive nature of a sand in this condition meant that prior to a measurement cycle, great care had to be taken to minimize disturbance.

Packing of the sediment was carried out in stages and two methods were necessary. At the start of a cycle, short, sharp taps on the cell's base were sufficient to cause settlement of the sand and to record a measureable volume/level change on the calibrated column. In the final stages of packing more vibration was necessary. This was achieved by the use of the sediment sieve shaker on which the measuring cell was mounted. Shaking periods ranging from seconds in the early stages, to tens of minutes where necessary in order to achieve the maximum packing condition. At each stage a volume/level measurement from the column and a transit time measurement from the transducers were recorded. A water bypass tube ensured that no liquid loss occurred during the measurements.

Repeated runs were made by re-suspending the sediments by several inversions of the cell and allowing the suspension to settle back to an initial loose packed condition. The volume/level observation, in conjunction with the total weight of the suspension, and the known total volume of the cell enabled the porosity at each stage of the experiments to be calculated. With knowledge of either the total dry weight of the solid material or the specific gravity of the grains, the corresponding values of wet density could be computed. The measuring system was capable of giving a porosity estimate within 2%.

RESULTS

Table 1 summarizes the geotechnical data, measured parameters and derived properties of the four sand samples selected for these experiments. Figure 2 shows typical acoustic waveforms through water and sand at both minimum and maximum packing states. (The resistivity measurements were made using the perpendicular axis but encompassing the same volume of sediment). Figure 3 shows the velocity/porosity "state" curves for four separate runs on sample 3. This sample exhibited good repeatability between runs with porosity values ranging from 0.48 in a loose condition to 0.38 when tightly packed. Corresponding sound speed values for these limiting states were 1672 m/s and 1780 m/s respectively.

For comparison, Figure 4 shows the results of four runs on sample 4; a sediment with a much higher $CaCO_3$ content in the form of shell fragments. Note that the four curves are less repeatable than those of sample 3, although they take a similar form. Also, in comparing sound speed at a particular porosity value, the sound speed curves on average are about 50 m/s lower than for the sample shown in Figure 3. Figure 5 summarizes the averaged data for the four sand samples. In this set it appears that the $CaCO_3$ content plays a major role in positioning the curves on the graph. In a similar manner, the sound speed against wet density curves (Figure 6) suggest an equivalent relationship with $CaCO_3$ content.

One further interesting feature observed during the original experiments was the effect of packing on the amplitude of the received signals. Figure 7 shows a typical profile which indicates that perhaps two energy loss mechanisms exist and that their effectiveness depends on the packing density of the sediments. Although the measuring technique is not ideal for sound attenuation estimates (i.e. not a true insertion loss measurement), pulse amplitude does decrease as packing increases and the rate of decrease appears to change when porosity is 0.4 or less.

Since these experiments were conducted, similar data sets have been obtained from both synthetic and actual sediments. Shear wave propagation measurements have also been made.

CONCLUSION

Several interesting conclusions can be made about these initial observations. Published data usually shows a single sound speed estimate for a sediment whereas in fact such a point is one of many on a characteristic or state curve. It is felt that more emphasis should be given to the fact that when a physical property, such as sound speed, is related to a geotechnical property, such as mean grain size, a third dimension, that of the state of packing (i.e. void ratio or relative density) should always be included. This applies to both actual and synthetic relationships derived from mathematical models. Although this presents obvious graphical problems, failure to acknowledge this fact can lead to a misinterpretation of published data sets. This three-dimensional approach implies that in reality a second independant measurement has to be taken in order to identify and relate a field-measured physical parameter with a geotechnical property. Other inferences from this work are listed below:

1. Sound speed/porosity relationships are <u>more</u> realistic than sound speed versus grain size.
2. Within a sediment type classification sound speed alone is a <u>poor</u> estimator of sediment properties.
3. For <u>non cohesive</u> sediments, acoustic impedence can change up to 16% over the possible range of packing conditions.
4. Any data set which relates a physical property against mean grain size should <u>either</u> be qualified with a state/packing parameter or given 16% uncertainty limit.

REFERENCE

Jackson, P.D., Taylor-Smith, D., Stanford, P.N., "Resistivity-Porosity - Particle Shape Relationships for Marine Sands", Geophysics,. Vol. 43, No. 6, October 1978.

Table 1

GEOTECHNICAL DATA

Sample Number	Mean Diam. ϕ	$\sigma\phi$	o/o $CaCO_3$
1	2.86	0.286	11.0
2	2.03	0.287	6.5
3	1.98	0.283	5.2
4	1.29	0.72	23.0

MEASURED PARAMETERS (Averaged limiting Values)

Sample Number	Porosity		Density kgm^{-3}		Sound Speed $msec^{-1}$	
	Loose	Dense	Loose	Dense	Loose	Dense
1	0.48	0.38	1900	2060	1690	1770
2	0.48	0.39	1870	2010	1690	1770
3	0.48	0.38	1880	2040	1670	1780
4	0.50	0.38	1870	2050	1630	1735

DERIVED PROPERTIES

Sample Number	Acoustic Imped. $Rx10^6$		Reflection Coeff.		Impedance Ratio	
	Loose	Dense	Loose	Dense	Loose	Dense
1	3.12	3.65	0.35	0.41	2.08	2.37
2	3.16	3.56	0.35	0.40	2.06	2.31
3	3.14	3.63	0.34	0.41	2.04	2.36
4	3.05	3.56	0.33	0.40	1.98	2.32

ΔZ 15-16%

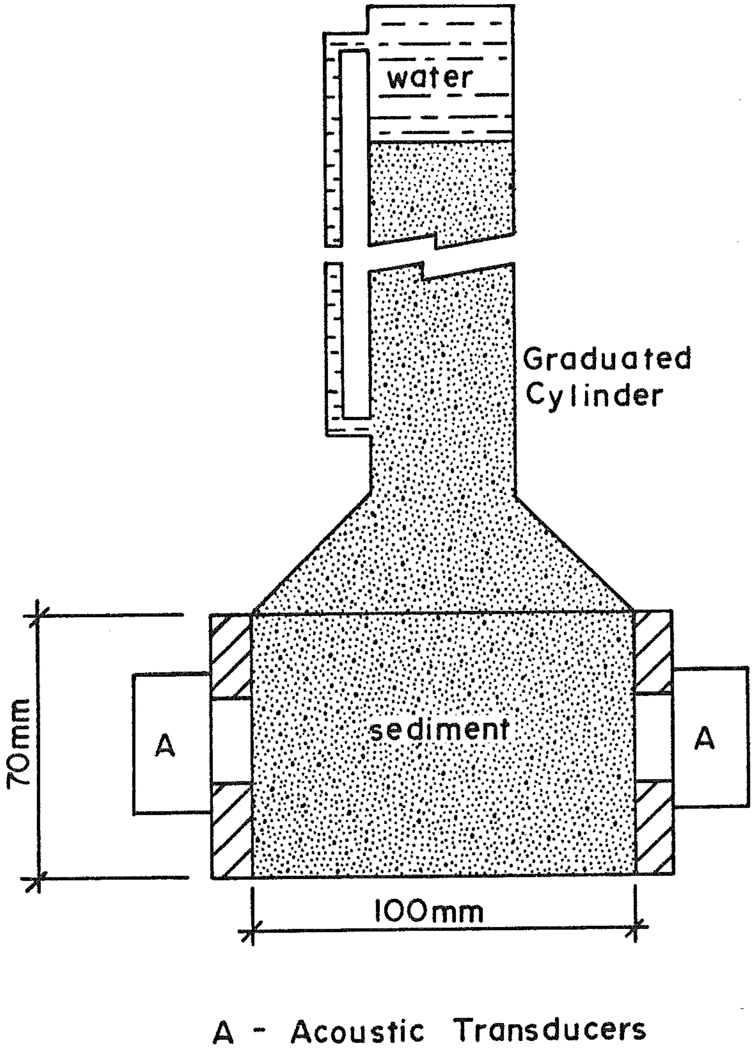
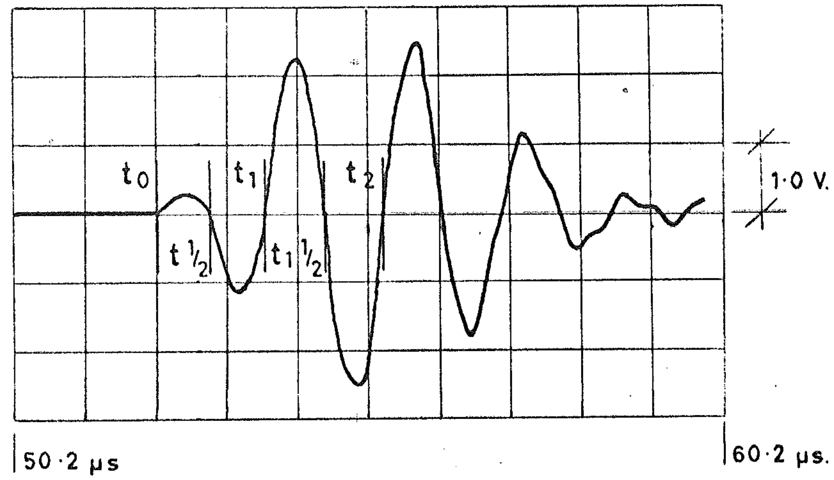
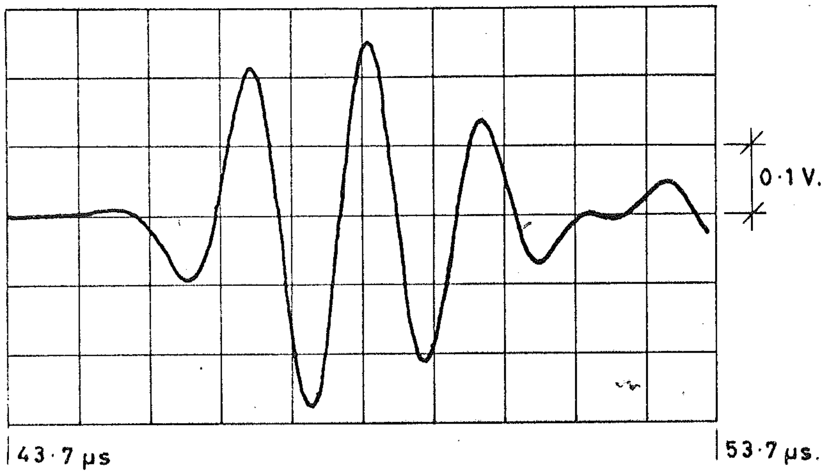


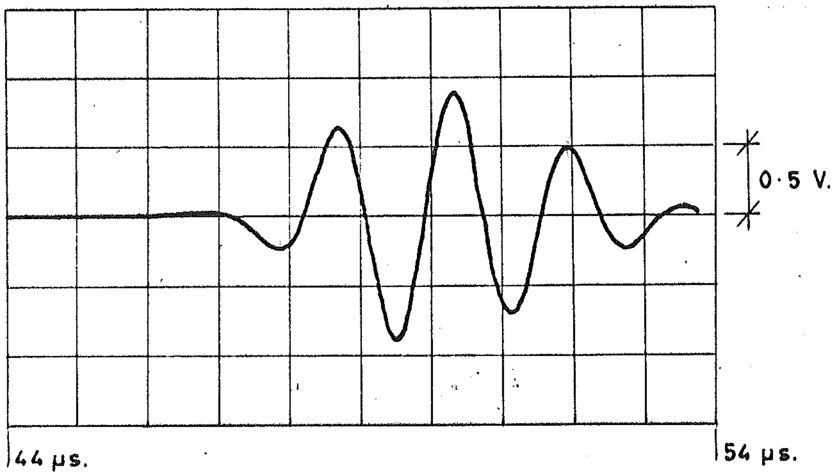
Figure 1 The acoustic/resistivity test cell.



(a) through sea water.



(b) through fine sand at min. porosity.



(c) through fine sand at max. porosity.

Figure 2 Typical Compressional Wave Signatures received through Water and through Sediment.

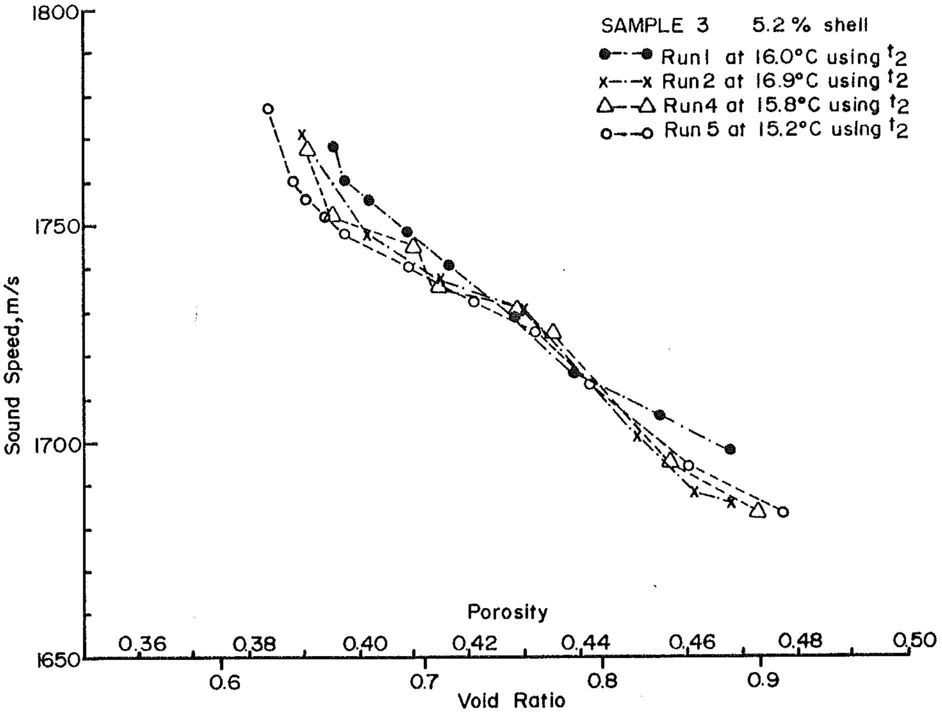


Figure 3. Sound speed against porosity for a saturated sand with low shell content.

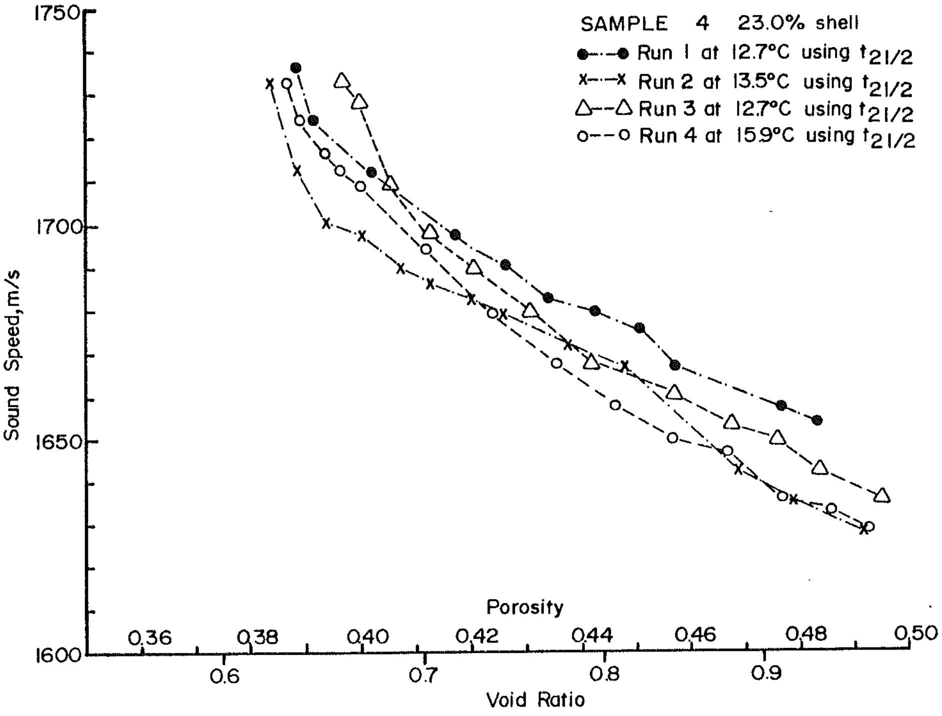


Figure 4. Sound speed against porosity for a saturated sand with high shell content.

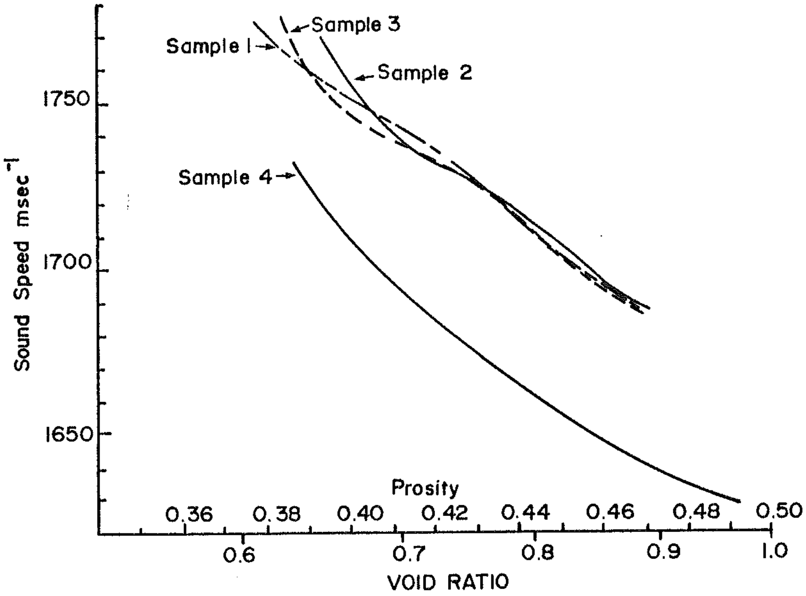


Figure 5. Sound speed against porosity for four different sands

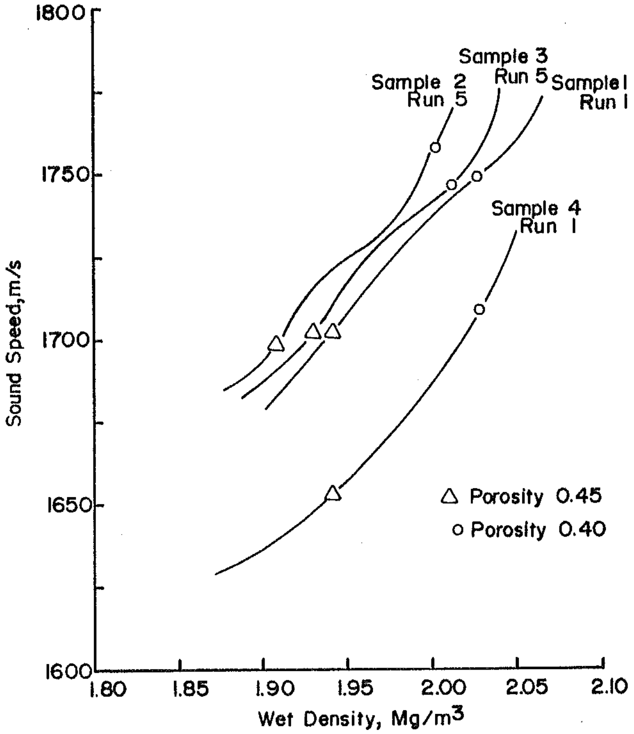


Figure 6. Sound speed against bulk density for four different saturated sands.

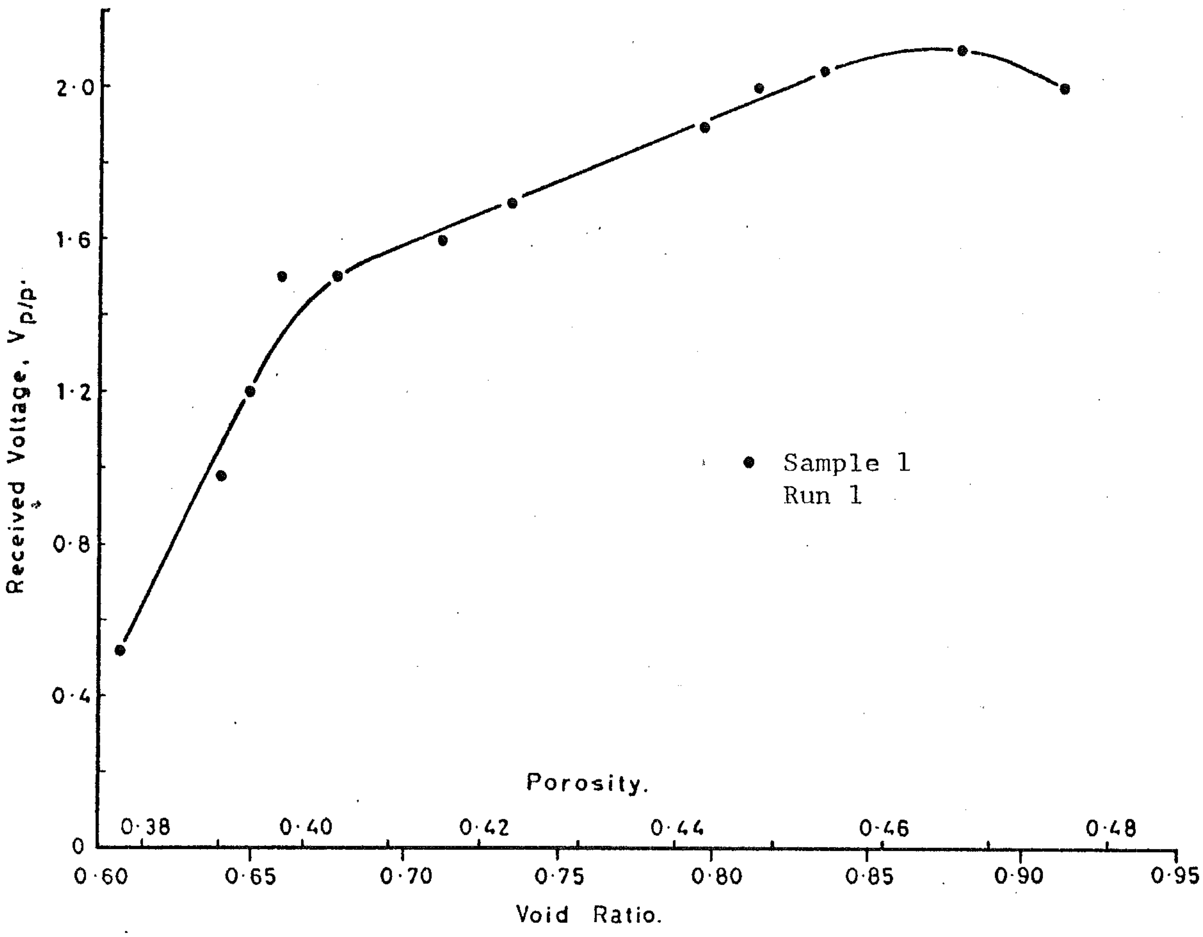


Figure 7 Received signal amplitude against porosity for a saturated sand

DESIGN AND EXPERIMENTAL DEVELOPMENT OF AN "UNDERWATER ACOUSTIC DRILL"

Jacques Yves Guigné
NORDCO
St. John's, Newfoundland

This study experimentally develops a high resolution deep penetrating acoustic spot profiler or interrogator called an "Underwater Acoustic Drill". The objective is to design a new ground truthing tool capable of vertically mapping in detail, variations found within sedimentary sequences especially within complex sediment mixtures typical of glacial drift deposits and of permafrost structures. To verify the acoustic concepts, a comprehensive laboratory investigation is initiated, simulating the behaviour of the Acoustic Drill over a variety of complex sedimentary structures. The outcome of these experiments will direct the engineering framework needed to proceed to a full scale prototype.

The conceptual Acoustic Drill will involve the application of non-linear acoustics. A curved array held stationary at a fixed height over the seabed will incorporate a comprehensive set of transmitters. A wide band of frequencies can be formed parametrically in each of the transducers along with a short clean transmit pulse. The analysis to accompany the probe will involve the use of convolution and filtering methods, Fourier integrals, auto correlation and cross correlation. Through the use of a two channel FFT recorder, the impulse response will be studied in real time. The activation of a particular source element or array configuration can then be executed upon examination of the ongoing analysis. The final display of the results would appear as a vertical "Acoustic Core" supported by graphic plots of the analysis.

INTRODUCTION

The "Underwater Acoustic Drill" project forms part of a three year study initiated in 1982 by NORDCO Limited in parallel with Ph.D. studies presently being carried out in St. John's, Newfoundland [1] by the author under the direction of Bath University, U.K. [2] This research project came into being because of a pressing industrial requirement for more detailed and reliable interpretations of shallow high resolution profile data. Offshore high resolution seismic reconnaissance has as its primary objective, to define the lithology of the seabed more clearly for possible hazards and structural anomalies. The identification of these hazards are important in exploratory drilling in order to install the initial casing efficiently and to establish safe drilling procedures in the early phases of the program. The presence of boulders, hydrate and gas accumulation, permafrost, faulting, major scarps and softer sediments such as ooze are all potential drilling hazards especially if these are not expected at the time of their encounter. They also become hazards to the safety of the platform if not adequately identified at the time of siting of the production facility.

Seismic profilers are able to provide predictions on the general occurrence of such hazards. By seismically mapping the reflections from interfaces between formations in a continuous manner, their physical properties can be inferred. It is thus possible to produce structural maps of any geological horizon which yields reflections. However, the horizons themselves cannot be identified without independant geological information such as might be obtained from borehole studies (Dobrin 1976). Sufficient information can be gathered in areas where the seabed is largely composed of acoustically transparent sediments such as silts, and/or clays. However, in a seismically hard environment such as is seen off the coast of Newfoundland and Labrador where the emitted energy is redistributed in the seabed by various forms of attenuation and of scatter, seismic reflection surveys tend to yield low penetration and little continuity.

In certain cases it is important to be able to identify the exact nature of a particularly strong discontinuous sub-bottom anomaly and to be able to interpret beyond its primary reflector with confidence. An example of this is presented in Figure 1.0. The prominent reflector seen on this seismic section, which was collected during a reconnaissance survey in the Davis Strait in 1982, was interpreted to be one of the following: (Guigne 1984)

1. gas in the sediment
2. a rough portion of the Ordovician Limestone beds which are believed to be the dominant bedrock type near the seabed surface.
3. a Precambrian bedrock inlier exposure.

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[1] Ocean Engineering, Memorial University of Newfoundland
[2] School of Physics, Bath University, England

Since all three possibilities represent significantly differing explanations, this particular site could pose a problem if drilled.

PROGRAM OVERVIEW

The subject of this project is specifically designed to introduce to the geophysical/geological community a new concept in ground truth control which complements and enhances existing geophysical mapping. The study experimentally develops a high resolution deep penetrating acoustic spot profiler/interrogator called an "Underwater Acoustic Drill". Through its use, detailed vertical mapping and interpretation of variations found within sedimentary sequences, especially within complex sediment mixtures typical of glacial drift deposits and of permafrost structures, would be possible. Of special interest to the project is the modelling of sediment structures found in the Canadian Arctic waters, particularly, the ability of the "Underwater Acoustic Drill" to define lenses of cobbles or boulders within a column of sediment and to detect the nature or presence of sub-bottom permafrost.

In addition, the analytical modelling techniques developed for the evaluation of the concepts can be applied to other remote mapping seabed methods. This aspect is of special importance to offshore engineers who require realistic appraisals of the performance of profiling systems under specific conditions.

The application of a Parametric Source was carefully studied and theoretically found to be a potentially effective source for the Acoustic Drill. This approach appears to have favourable sub-bottom profiling attributes which could prove advantageous over a morainic bottom. The limitations of the technique's very low power efficiency and requirements for stability can be met by the fixed mode of profiling envisioned for the drill. The integration of several returns would raise the level of signal to noise sufficiently to obtain clear records. High resolution capabilities and potential for deep penetration are also possible through the wide bandwidth inherent in the source.

SYSTEM MODELLING

A computation format was developed to model mathematically the behaviour of a propagating sound signal as it encounters a water/sediment interface and then as it enters into the sediment. The internal complexity of seafloor sediments was studied to establish mechanical properties for the sediment model. This was followed by a performance evaluation and a comparison of an optimized Conventional Monostatic Transducer to an optimized Parametric Array truncated at its nearfield/farfield transition. This termination was calculated for the condition where the carrier frequency wave associated with the Parametric Array is discontinuously attenuated on passing through a water/sand interface. The source height above the seabed was therefore set such that the termination occurred within the nearfield of the transducer. Such parameters as power, carrier frequency and transducer diameter were then optimized with respect to ℓ (refer to Figure 2.0).

Since the analytical appraisal of the Acoustic Drill concept depends on realistically evaluating various transmission loss factors, a stratigraphic sediment modelling approach was selected. Our understanding of the geomorphological processes which have taken place along the Eastern Canadian Shelf has been very limited by the scarcity of the data collected and the difficulty in interpretation. However, by inferring from processes which have occurred in other glaciated environments, as well as from the generally accepted knowledge of the character of till composition and distribution, a useful stratigraphic model was made which incorporated till. The exact reproduction of an actual site was not necessary. However, the model specifically designed for this project does take into account the conditions of a seismically hard seabed through the emplacement of till sheets (ground moraine) within a series of finer sediment layers. This model is similar to a drift section in Midlothian Scotland as described by Kirby (1969). The Pleistocene stratigraphic sequence expressed in it provides for a realistic representation of sedimentary sequences of varying particulate size beds. The actual model structure enlarges on the section by increasing the thicknesses of each sequence and including a surface layer of acoustically transparent material as a cap. In addition, a strong base reflector does terminate the model. The model structure is illustrated in Figure 3.0. Its composition consists of a 40 m deposit over a Tertiary Coastal Plain Sediment Base. An experimental approach is presently underway to prove the feasibility of the analytical study. This involves the use of a deep water tank[3], a versatile positioning system and a parametric source with supporting instrumentation. Figure 4.0 shows the layout of the system. The action of the transducers simulates scaled conditions. Figure 5.0 provides a detailed breakdown or synopsis of the soils used in the experimental model which Figure 6.0 illustrates in a qualitative manner the signal's propagation geometry.

In the initial stages of the experiments, non-linear signals were successfully generated in the water tank. The resultant signals are in accordance with the theoretical signatures computed in the model analysis (see Figure 7.0). Instead of beating two high frequencies, a carrier wave modulated by a Guassian envelope was sent to the transducer. As this Guassian modulated acoustic pulse travels through the water it self-demodulates. This effectively produces the low frequency pulse required.

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[3] The tank selected for this acoustic study makes use of a deep water tank belonging to the Hydraulic Laboratory facilities of Memorial University of Newfoundland. The dimensions 4 m deep, 4 m wide and 4 m long provide an exceptionally good free field condition in relation to the high frequencies used.

PROPOSED HARDWARE

The proposed source would be positioned 8.5 m above the seabed so that the non-linear "mixing" zone can exist in the water column immediately above the bottom. In operation the Acoustic Drill would sit stationary on the seafloor. No horizontal translation is initially anticipated because signal averaging is necessary due to low efficiency of the non-linear process involved. For operational reasons a collapsible frame has been proposed with ballast in the bottom parts and floatation up above. On lifting and lowering in air the drill would remain on the sea surface with the legs extending to their full amount. Then the whole extended unit would be lowered to the seafloor. Recovery would be a reverse of the lowering process. At present, the detailed design has yet to be done. It is hoped that a prototype unit will be under construction in late 1985. Ultimately, this unit could be deployed from a submerged vehicle which could hover above the bottom with the necessary stability characteristics.

Figure 8.0 shows a conceptual drawing of the "Underwater Acoustic Drill". The proposed three sets of transducers have several transmitters. These will allow the sound energy to be directed independently in several directions. The reflection data from each transducer would be received by the hydrophone array and transmitted to the support vehicle for digital analysis and display. When processed, the detected echoes should allow several acoustic sections to be assessed. The question that will then arise is "which reflections are real, and which are not?". The answers to these questions will be derived by using the data from all the transducers, by stacking, and using moveout correction techniques similar to those used in other branches of geophysics. By processing in the frequency domain, parameters such as attenuation, scatter and reflecting characteristics could be studied. This should allow a model of the sediment column to be developed.

By studying, in real time, the impulse response, the Acoustic Drill array can then be energized accordingly. In other words, the activation of a particular source element or array configuration can be executed upon examination of the earlier responses. The use of a Hilbert transform would allow an envelope of all time domain functions to be displayed. Noise sources could be identified by the use of a coherent and non-coherent output spectra. In a frequency spectrum, the Cepstrum analysis could provide detection of periodicities.

The results compiled from each set of transmitters would be statistically compared. The horizontal detection of reflectors could thus be investigated within the confines of the three sets of the transmitter positions. The final display of the results would appear as a vertical "Acoustic Core" supported by graphic plots of the analysis.

ACKNOWLEDGEMENT

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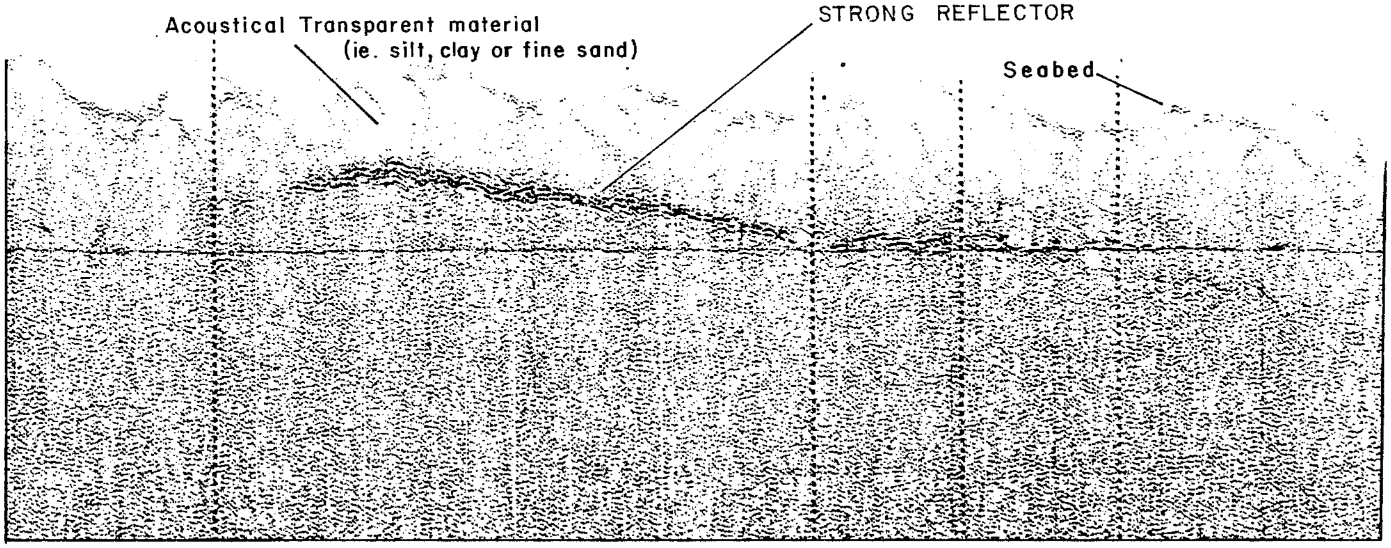


Guigné 1984

Possible Interpretation :

i) Gas in the sediment.

ii) A rough portion of the Ordovincian limestone beds which are believed to be the dominant bedrock type near the seabed surface.

iii) A Precambrian bedrock inlier exposure.

FIGURE 1.0 Particularly strong subbottom reflector.

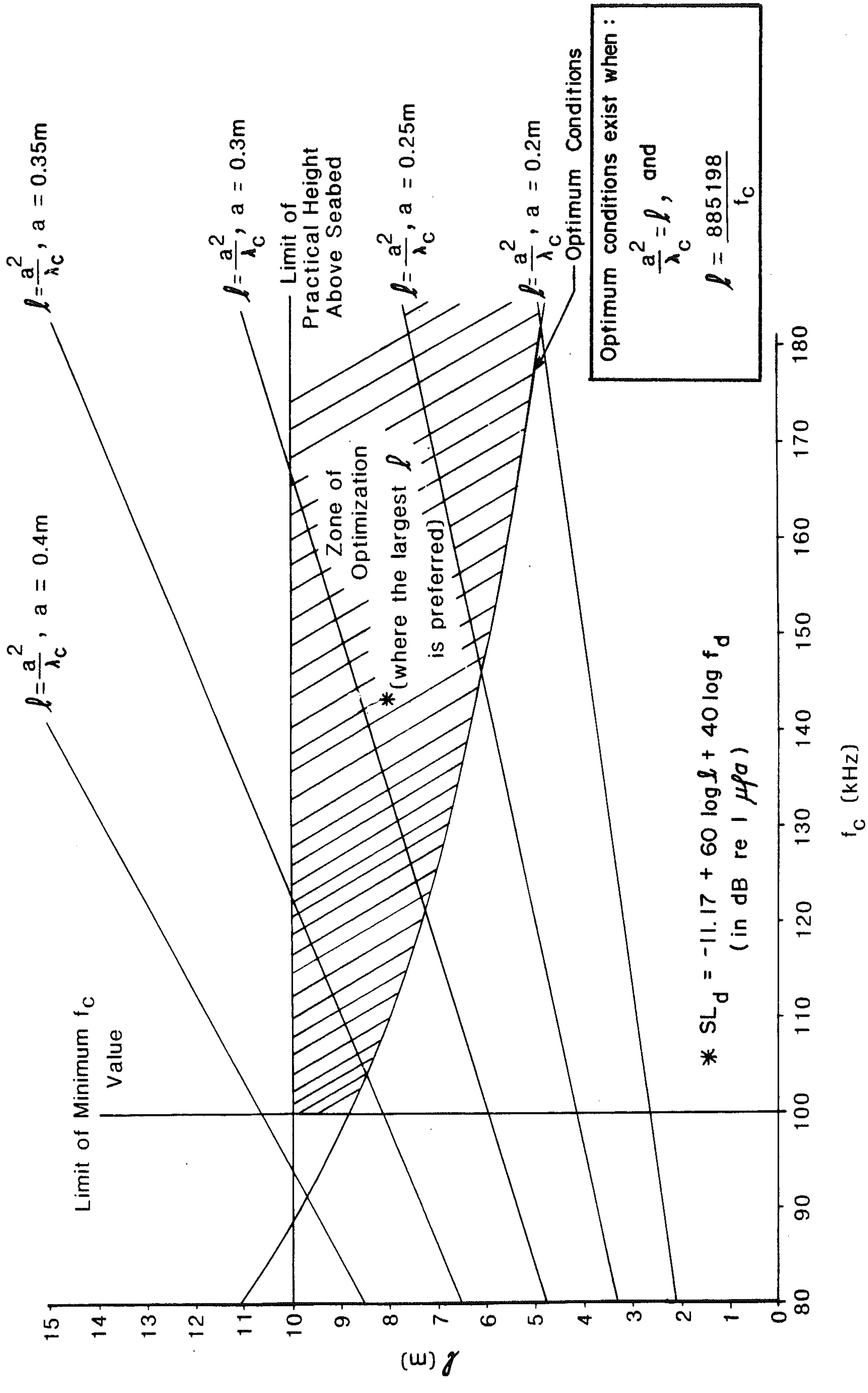
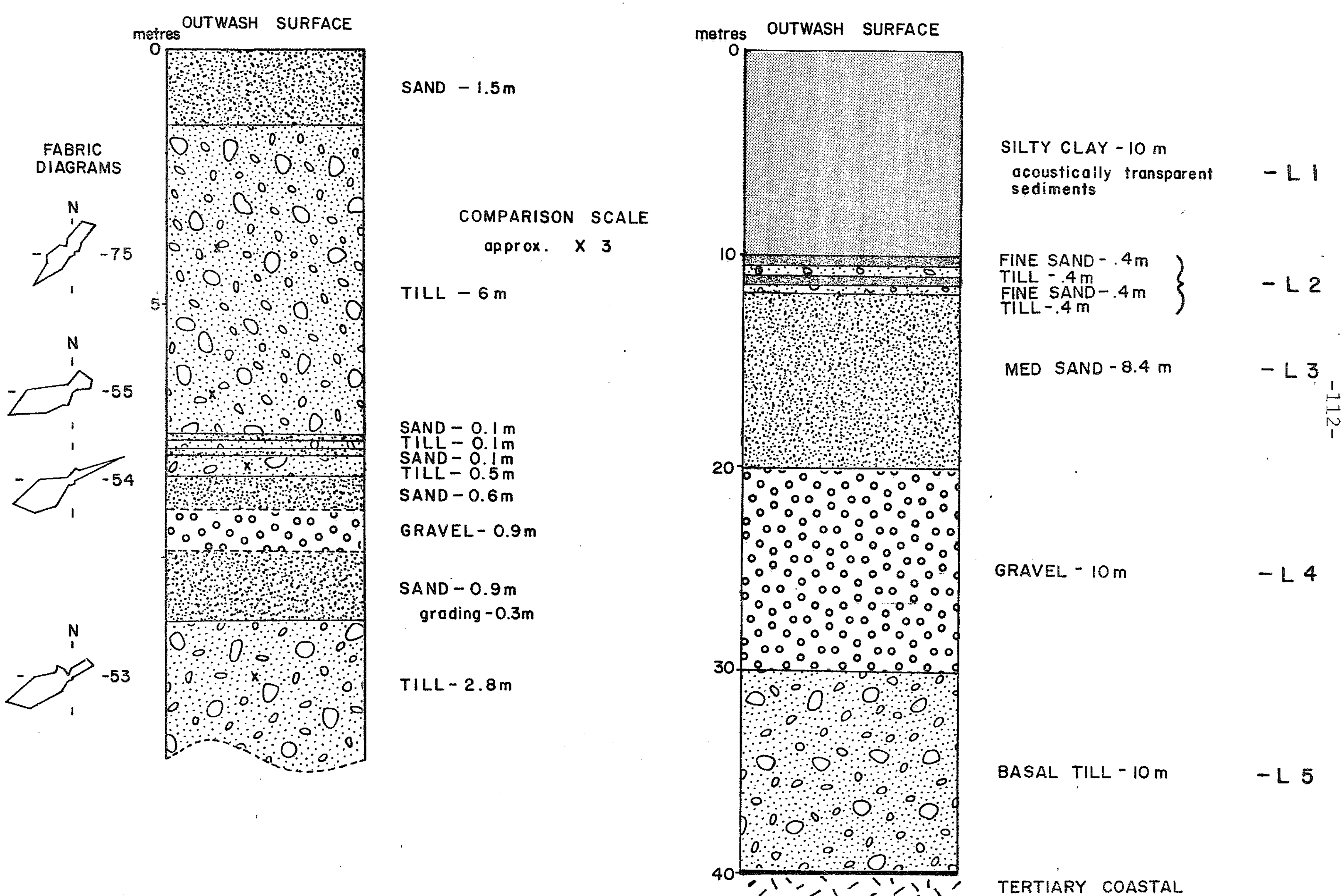
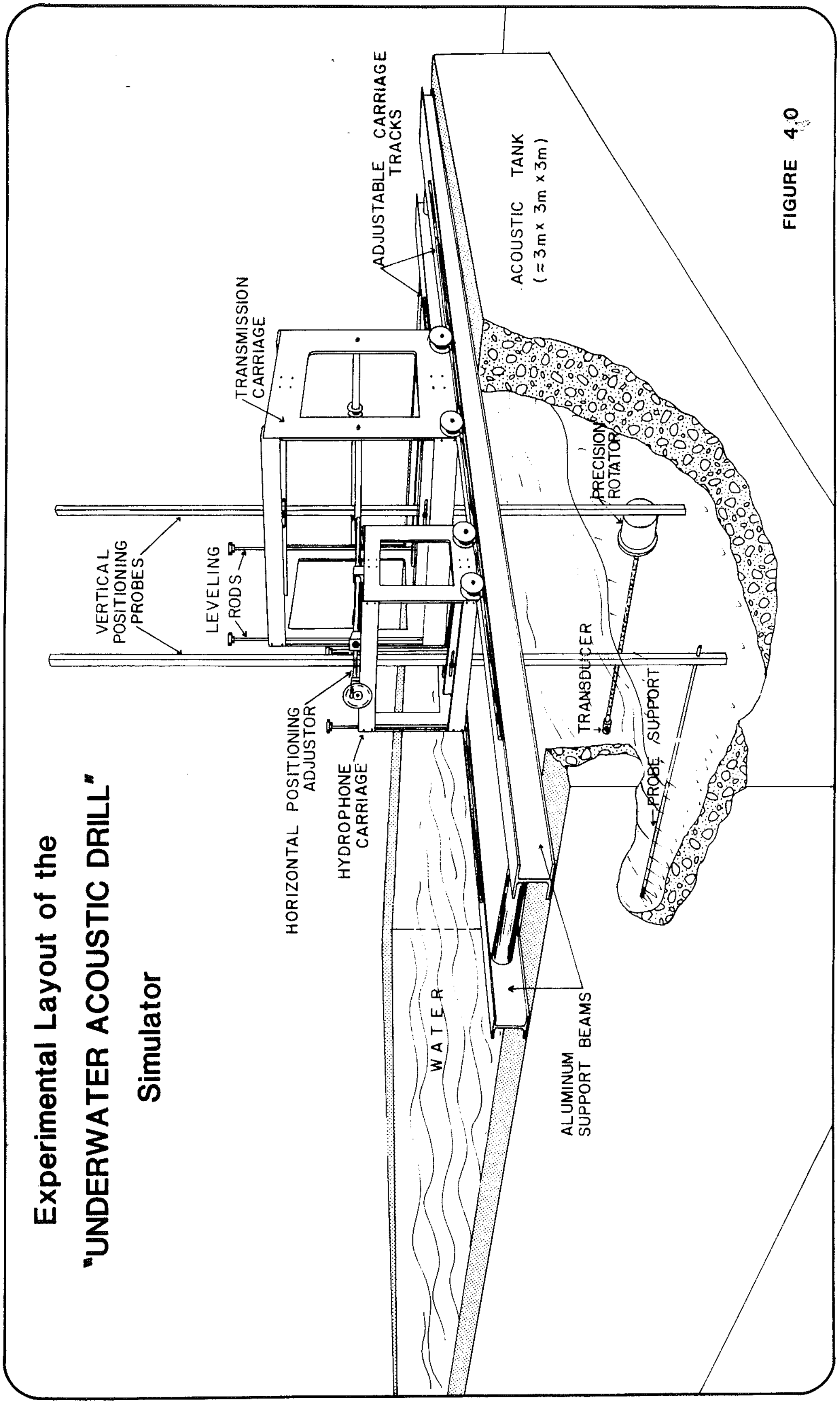


FIGURE 2.0 Optimization of a Terminated Parametric Array.


Section at Park Burn, Midlothian Scotland showing the alternation of Till and Fluvioglacial deposits. (after Kirby, 1969)

Project's Stratigraphic Model

FIGURE 3.0 Depositional Chronology for the Project's Statigraphic Sediment Model



Experimental Layout of the "UNDERWATER ACOUSTIC DRILL" Simulator

FIGURE 4.0

A. Soil Type (Let the scaling factor k = 17.5)

FULL SCALE SOIL TYPE	PARTICLE SIZE LIMITS (mm)				LABORATORY SCALE SOIL TYPE	CORRESPONDING SIEVE SIZES FOR LABORATORY MODEL SOIL
	FULL SCALE		MODEL SCALE			
	from	to	from	to		
Fine Sand	0.08	0.40	0.005	0.02	MEDIUM SILT	Asphalt Plant Dust and/or Rock Crusher Dust
Medium Sand	0.40	2.00	0.02	0.11	COARSE SILT TO FINE SAND	PASSING #140 SIEVE TO 0.02 mm
Gravel	5.00	80.00	0.29	4.60	MEDIUM AND COARSE SAND	PASSING #4 RETAINED #50 (5 mm to 0.3 mm)
Boulders	250.00	500.00	14.3	28.6	MEDIUM GRAVEL	PASSING 1 1/4" (32 mm) RETAINED 5/8" (16 mm)

B. Model Type (Let the scaling factor k = 17.5)

FULL SCALE MODEL	THICKNESS (Metre)	LABORATORY SCALED MODEL	THICKNESS (Metre)	LAYER
Silty Clay	10.0 mm	Terminating/Reflecting plate and water - (1/2 thickness of Full Scale Model Layer)	0.29	1
Fine Sand Till Fine Sand Till	0.4 0.4 0.4 0.4	Asphalt Plant Dust Rock Crusher Dust Asphalt Plant Dust Rock Crusher Dust	0.02 0.02 0.02 0.02	2
Med. Sand	8.4	Asphalt Plant Dust with Grade 0 Blasting Sand	0.48	3
Gravel	10.0	Grade 0, 1 and 2 Blasting Sand	0.57	4
Basal Till	10.0	Beach gravel and Montmorillonite	0.57	5
Tertiary Coastal Plain Sediments	Basement Reflector	Styrofoam S 100	5 cm	Base

FIGURE 5.0 Synopsis of the Experimental Soils.

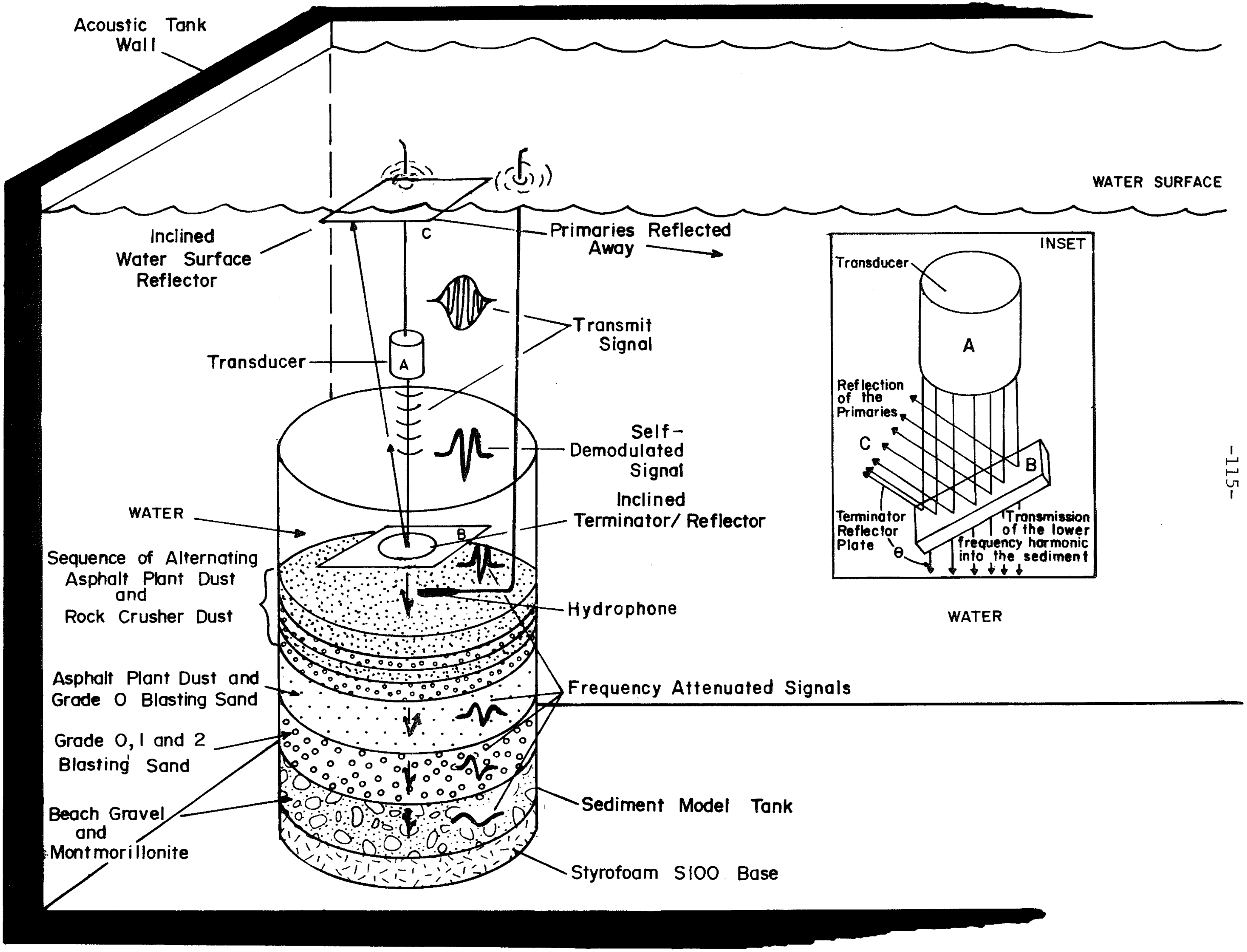
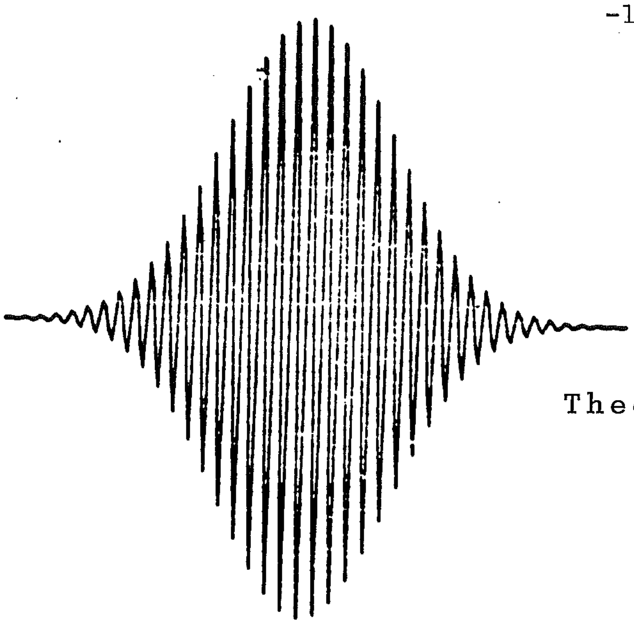
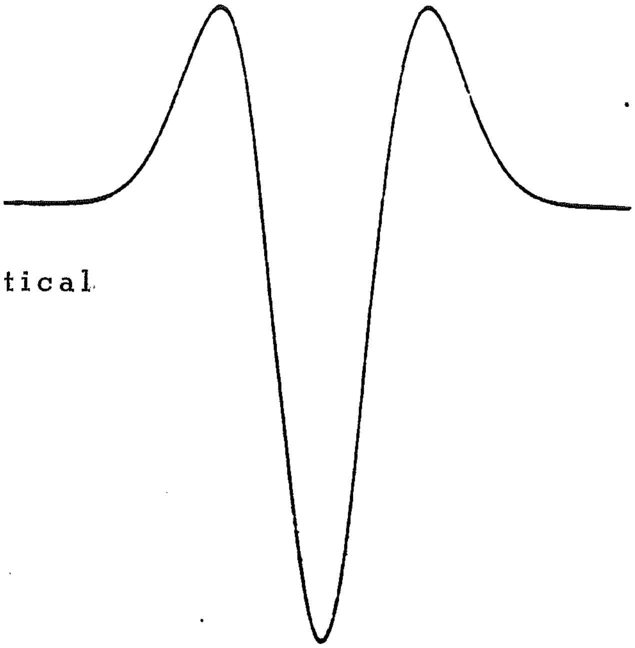


FIGURE 60 Qualitative Examination of the Propagation Geometry



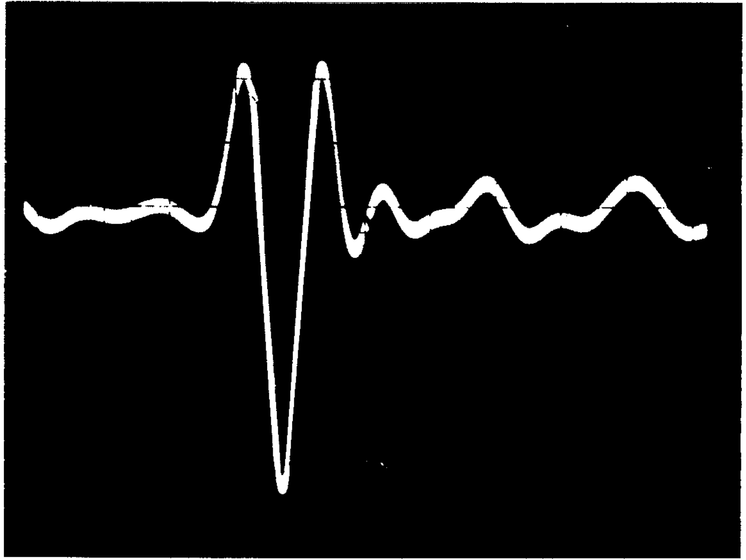
Transmit Signal

Theoretical



Self-Demodulated Signal

EXPERIMENTAL TANK TEST



April 2, 1984 Vertical 50mV/Div Horizontal 10usec/Div

SELF-DEMODULATED SIGNAL

FIGURE 7.0 Self-Demodulated Signal

Conceptual Drawing of the "UNDERWATER ACOUSTIC DRILL"

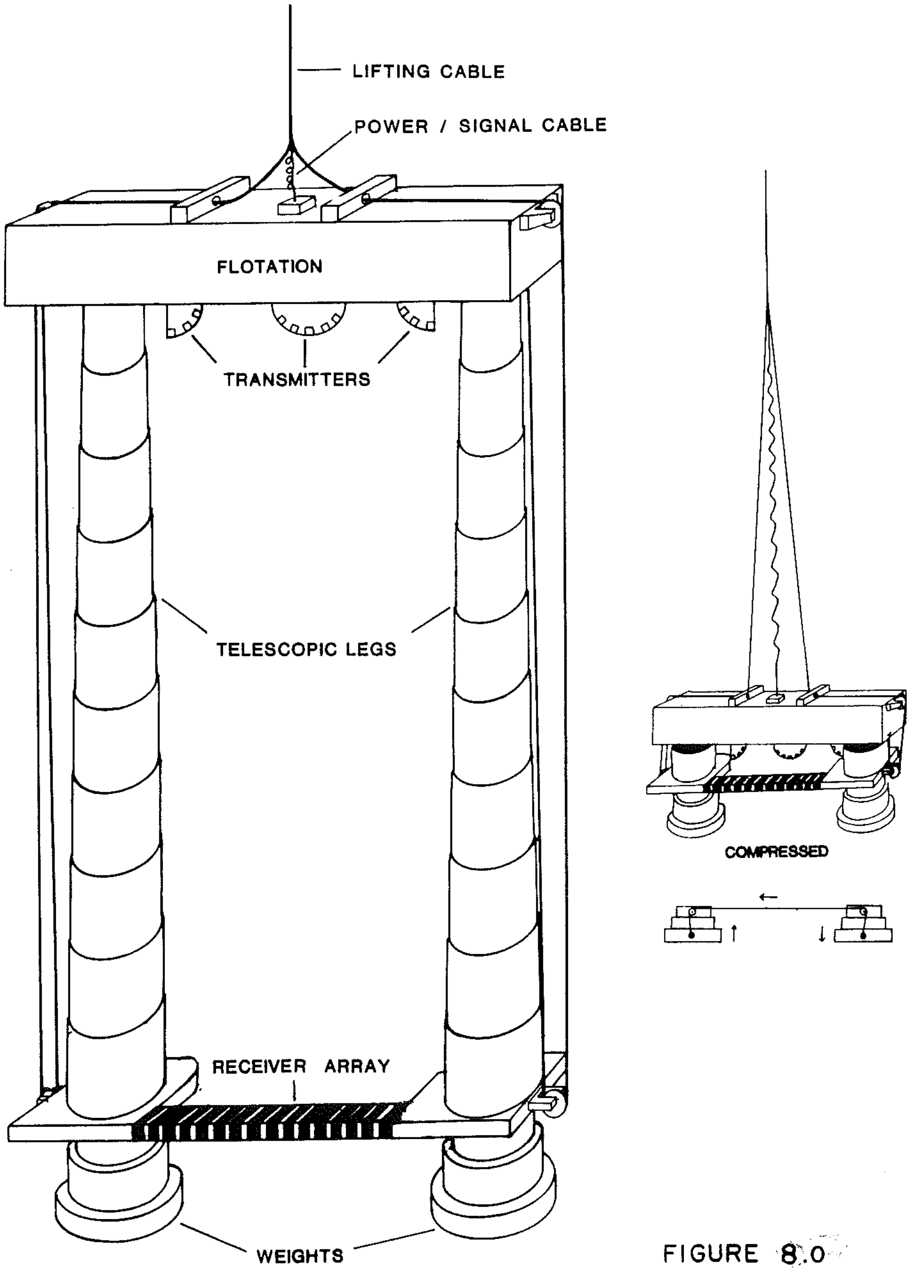


FIGURE 8.0

RECENT RESEARCH ON THE ACOUSTIC RESPONSE OF THE SEAFLOOR

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Applied Research Laboratories, The University of Texas at Austin (ARL:UT), has an active research program aimed at understanding the acoustic properties of the seafloor. This article reviews recent theoretical and experimental research on aspects of the Biot theory, high resolution subbottom profiling, and the simulation of signal interacting with a layered seafloor.

INTRODUCTION

This paper describes recent research on the acoustic response of the seafloor carried out at Applied Research Laboratories, The University of Texas at Austin (ARL:UT). The first topic discussed is the theoretical and experimental research of A. Bedford and M. Stern on applying the Biot theory to describe wave propagation in marine sediments. Next, the work of T. Muir on using parametric arrays for high resolution subbottom profiling will be presented. Finally, recent research of P. Vidmar aimed at the accurate simulation of bottom interacting signals will be discussed.

RESEARCH ON THE BIOT THEORY

The Biot[1-2] theory of wave propagation in sediments has recently been applied to marine sediments[3-7]. The Biot approach has the advantage of being based on a much more detailed view of the physics of the problem than is the viscoelastic theory. It is, however, much more difficult to use since it contains a large number of parameters which are not specified or derived by the theory itself. While some of these parameters can be obtained from measurements made on samples (when they are available), other parameters are determined through empirical relationships whose use in a particular case may be questioned. Any progress that can be made to reduce the number of empirical parameters is significant. When the point is reached that all parameters can be measured, or determined from well founded theoretical relationships, then the Biot theory will have reached it's potential.

Drs. A. Bedford and M. Stern at ARL:UT have examined several aspects of the Biot theory. Their recent work[8] has resulted in a relationship between two of the parameters in the Biot theory - the drag coefficient, which is a function of the relative velocity of the pore fluid and the frame material, and the virtual mass coefficient, which is related to the relative accelerations of the two materials. The analysis considers a solid material with an externally imposed time harmonic oscillation. If this harmonic motion has a very long wavelength, i.e., the entire frame is oscillating in phase, then the gradient terms in the Biot equations can be neglected. The remaining terms produce a complex relationship between the drag and virtual mass coefficients. The real and imaginary parts of this relationship yield expressions for the drag and virtual mass coefficients that depend on the response of the fluid to the harmonic motion of the frame. The virtual mass and drag coefficients, calculated for cylindrical pores at several orientations, were used in the Biot equations to evaluate the compressional velocity and attentuation. Figure 1 shows the calculated compressional velocity as a function of frequency for several pore orientations. Note that there is a significant dependence on pore orientation. The value of 54.74° corresponds to randomly oriented cylinders. Future extensions of this research will treat realistic grain structures found in sedimentary material by using a finite element method for numerical calculation of the fluid velocity.

In other recent research[9], a three-component Biot model has been applied to the problem of wave propagation through a sediment with gas bubbles. While the theoretical work is complete, there are no measurements available for comparison with predicted compressional velocities and attenuations. There are, however, measurements of propagation through water with bubbles[10]. Figure 2 shows that the theory gives excellent agreement with these data (now a two-component system).

The Biot theory has also been used at ARL:UT to study the acoustic reflectivity of a depth dependent seafloor[11]. This research shows that there is little difference in reflectivity between Biot and viscoelastic treatments of high porosity sediments such as clays, but that there is a difference for low porosity sediments such as sands.

A recent laboratory experiment at ARL:UT has tested the Biot theory's predictions of compressional wave velocity and attenuation as a function of the viscosity of the pore fluid[12]. This is an important test of the theory. Since the viscosity appears as a explicit parameter in the theory, any changes in velocity or attenuation should be predicted. Figure 3 shows the schematic of the experiment. Compressional waves are propagated through the sediment while the viscosity of the pore water is changed by adding glycerin. The experimental results shown in Figure 4 demonstrate that the Biot theory accurately predicts the dependence of compressional wave velocity and attenuation on viscosity.

Other experimental research at ARL:UT has resulted in the development of shear wave transducers[13] for use in laboratory and _in situ_ measurements and the design of an experiment to measure the acoustical properties of hydrated marine sediments[14]. The _in situ_ measurement of shear and compressional velocities is made by recording the travel time and amplitude of waves propagated across the head of a core barrel as it penetrates into the sediment[15].

PARAMETRIC ARRAYS FOR HIGH RESOLUTION PROFILING

Another aspect of the experimental work at ARL:UT is the development and use of parametric sources. Figure 5 shows vertical profiling data obtained in shallow water off the coast of San Diego[16]. The parametric source[17] was approximately 2 m in diameter, had a bandwidth from 500 Hz to 5 kHz, and a beamwidth of about 4°. The returns marked A are due to reflection from the sediment surface and sea surface. The returns beginning at B are from layering at depths of more than 5 m into the sediment. Extremely fine scale lateral and vertical resolution are possible using this approach to acoustic profiling.

SIMULATION OF BOTTOM INTERACTING SIGNALS

The interaction of sound with the seafloor is another strong research area at ARL:UT. Efforts over the past few years to simplify the level of detail needed to describe the seafloor have been fairly successful. The effects of density gradients[18] and scattering from the water-sediment interface[19] were found to be negligible at low frequencies for typical deep sea sediment types (clays and silts). The low shear wave velocity of marine sediments results in little energy being converted into shear waves at the water-sediment interface[20]. However, coupling to shear waves can take place where velocity gradients are large[21] or at deeper boundaries where the shear velocity of the sediment is higher[20].

When these effects are combined, a reasonably simple model[22-23] of the interaction of low frequency sound with the seafloor emerges. The seafloor can be treated as a fluid with ray paths determined by the gradient in compressional velocity. The effects of attenuation along the path through the seafloor and reflection and transmission at interfaces must be included in the model. Conversion to shear waves occurs at interfaces and is included through the calculation of the reflection and transmission coefficients. The relatively low shear wave velocity and high shear wave attenuations typical of marine sediments[24] effectively eliminate reconversion of shear energy back into compressional energy.

This view of the interaction with the seafloor has been implemented for numerical calculation of the time series of signals interacting with the seafloor. Figure 6 illustrates the excellent agreement that can be obtained when simulated time series and data are compared[22]. The source was an explosive charge. In this case, the seafloor consisted of a single sediment layer about 200 m thick. The geometry was chosen so that there was no interaction with the basalt beneath the sediment. Figure 7 illustrates an attempt to simulate the qualitative features of a time series generated by an explosive charge in an area suspected of having small-scale layering in the upper part of the sediment[23]. The sediment has an overall thickness of about 775 m and was modeled as a clay layer with about 35 silt and sand layers in the top 335 m. The range was chosen so that energy penetrated through the layers. The effects of partial reflection at each of the small layer interfaces produce a time spread and exponential decay in the simulated time series that is similar to that seen in the data.

SUMMARY

ARL:UT has an active research program addressing theoretical and experimental aspects of the interaction of sound with the seafloor. Research on applying the Biot theory to marine sediments has resulted in (1) development of methods for calculating the drag and virtual mass coefficients, (2) a three-component theory for propagation through sediments containing gas bubbles, (3) calculation of the acoustic reflectivity of a depth dependent Biot material, and (4) experimental verification that the Biot theory correctly predicts the dependence of compressional velocity and attenuation on viscosity. Work on using parametric arrays for subbottom profiling has shown that the bandwidth is wide enough and the beamwidth narrow enough for high resolution subbottom profiling. Research to identify and understand the major acoustical processes occurring in the seafloor has resulted in computational models that can simulate the major features of signals reflected from the seafloor.

ACKNOWLEDGEMENT

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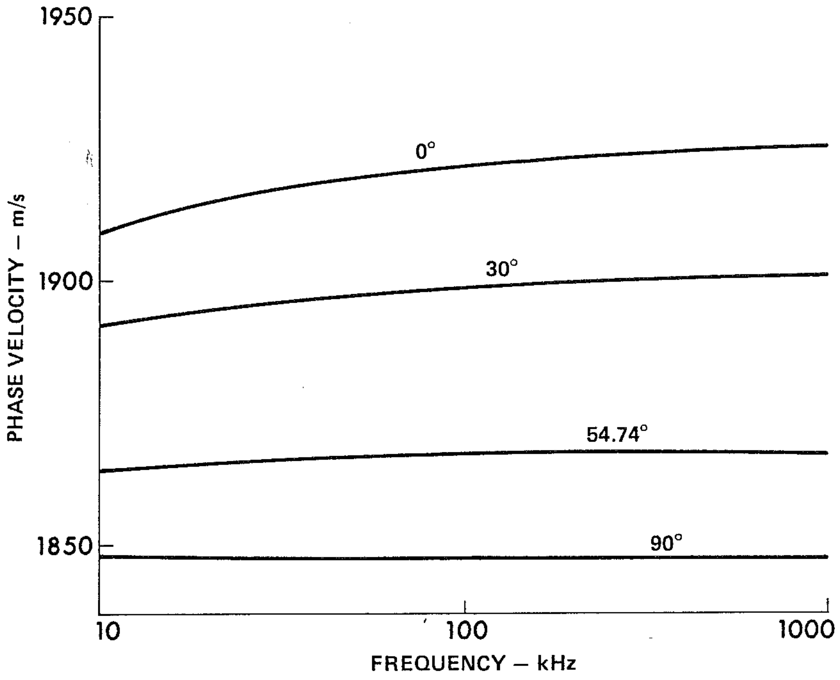


Fig.1 Compressional velocity as a function of frequency with orientation as a parameter. 54.74° corresponds to a random orientation.

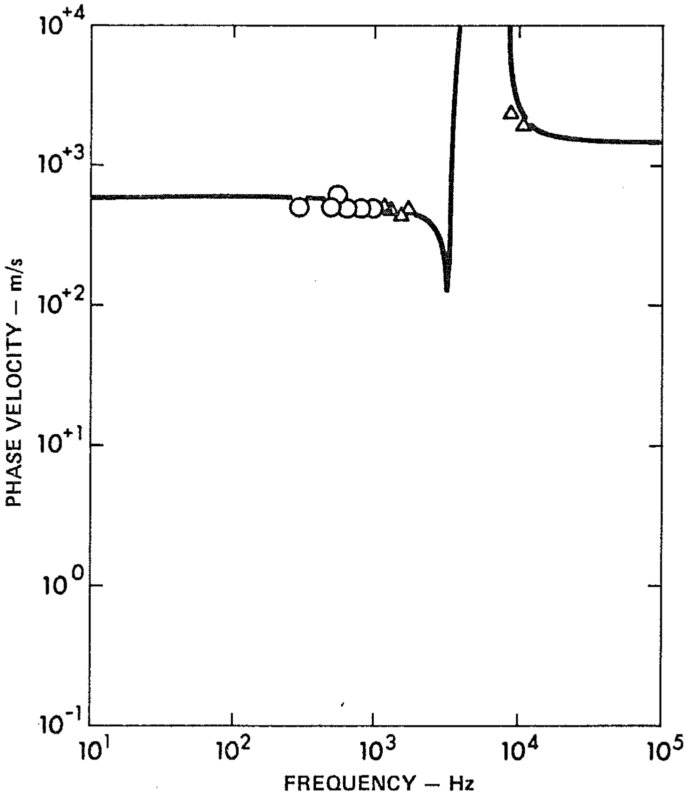


Fig.2 Comparison of measured and predicted compressional velocity as a function of frequency for water with bubbles.

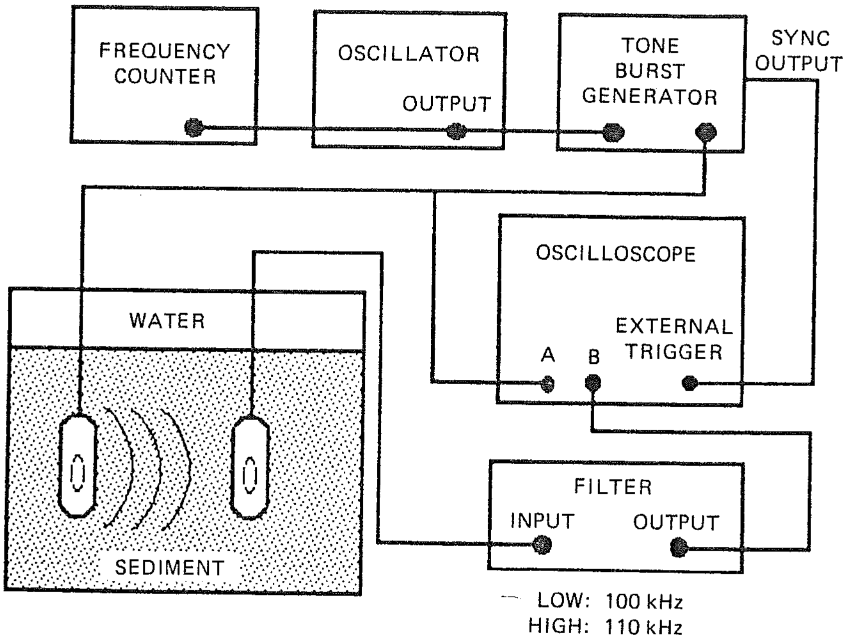
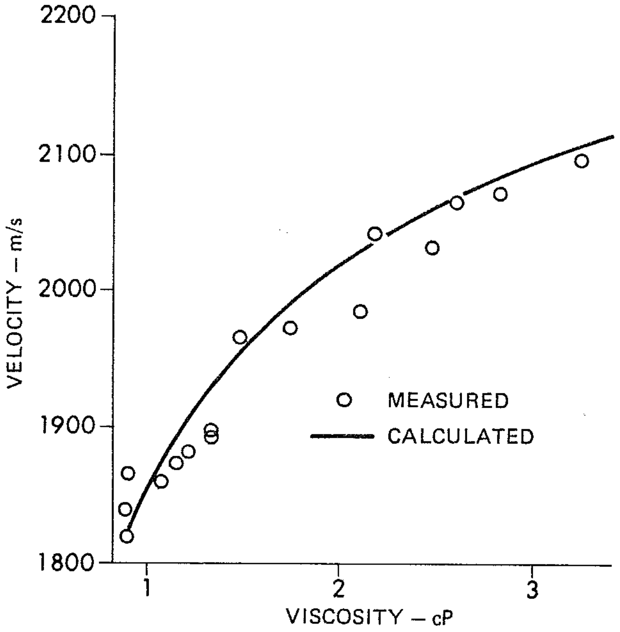
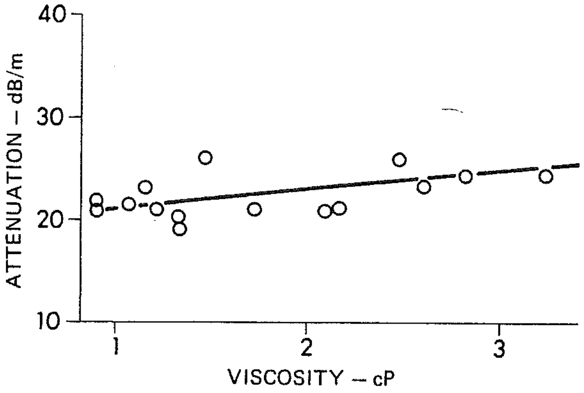


Fig.3 Schematic of Experiment



(a) PHASE VELOCITY



(b) ATTENUATION

Fig.4 Comparison of measured and calculated compressional phase velocity and attenuation as a function of the viscosity of the pore fluid.

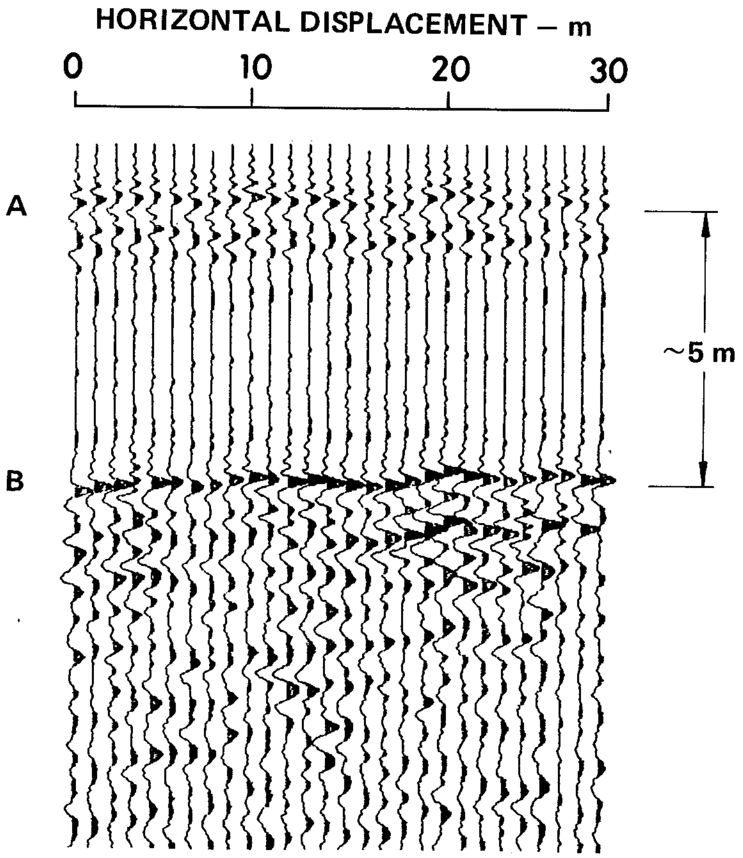


Fig.5 Example of high resolution seismic profiling using a parametric array.

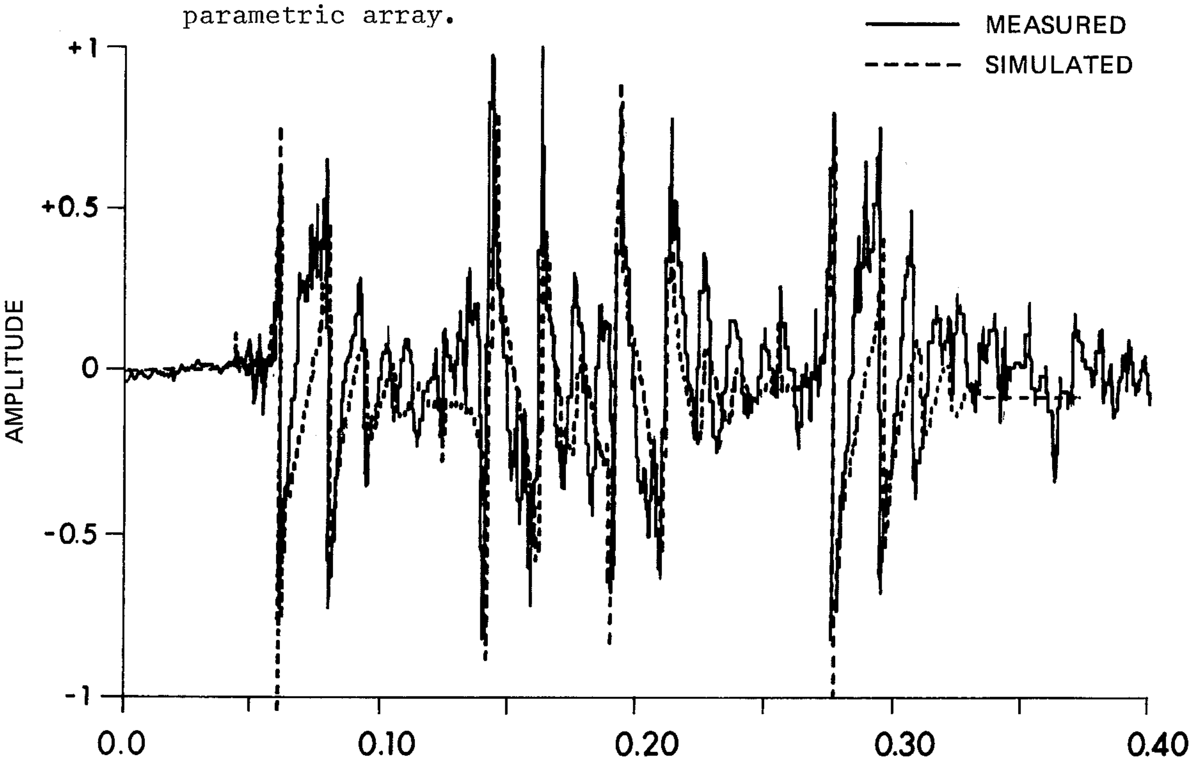
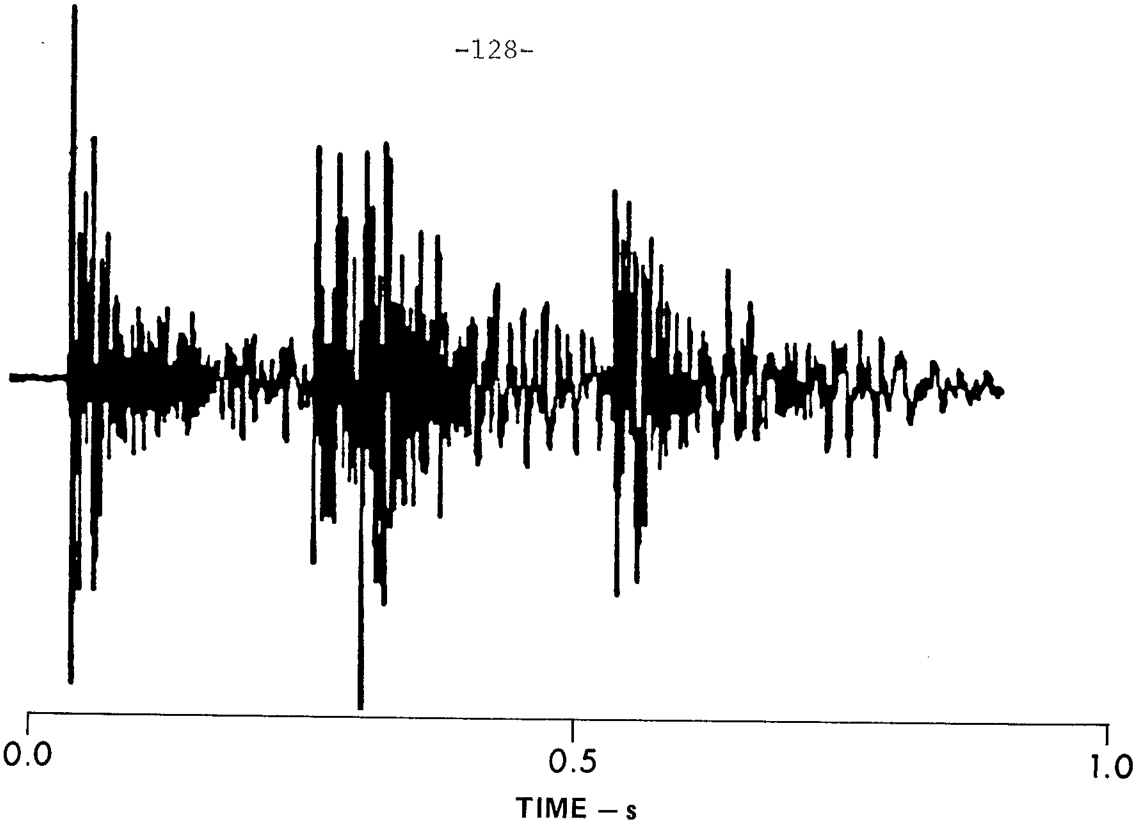
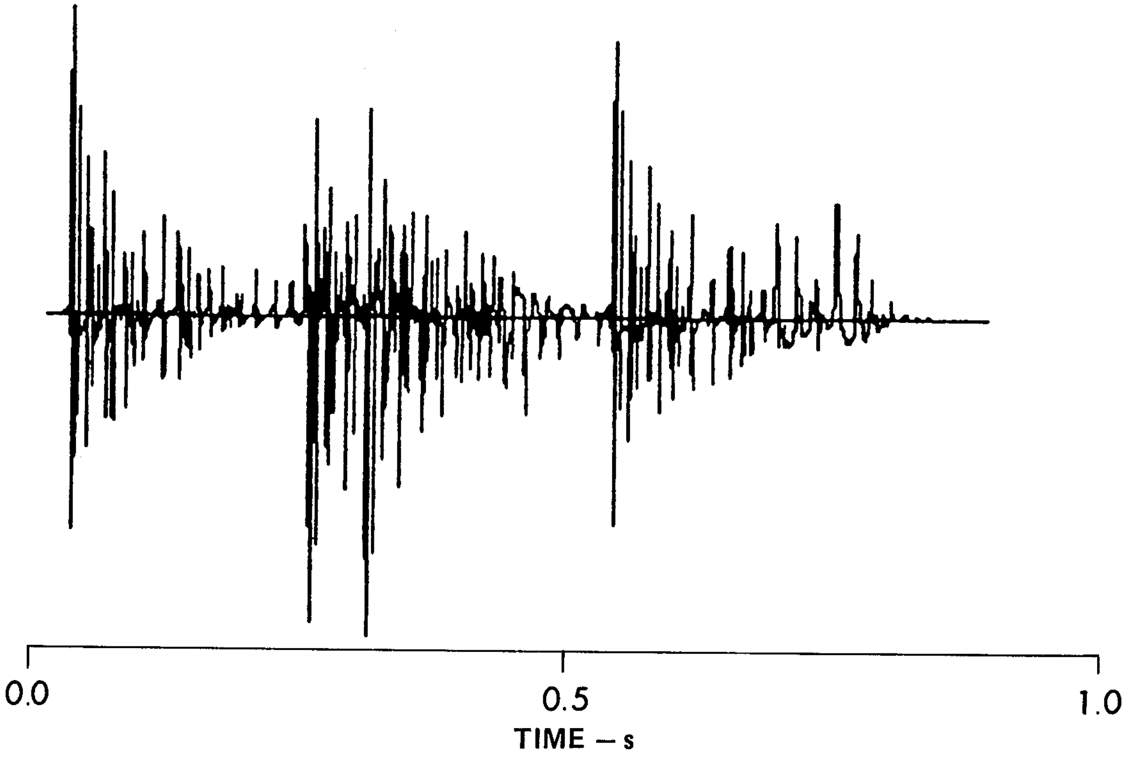


Fig.6 Comparison of measured and simulated bottom interacting waveforms. Single sediment layer 200m thick.



(a)
MEASURED



(b)
SIMULATED

Fig.7 Comparison of (a) measured and (b) simulated bottom interacting waveforms. 35 layers in top 335 m of sediment with 775 m overall thickness.

PROBLEMS IN CALIBRATION OF SYNTHETIC AND ACTUAL SEISMIC DATA

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The traditional approach to correlation between synthetic seismic traces and actual recorded data often breaks down when subtle stratigraphic changes are involved. It can be demonstrated that rock properties other than velocity and density are involved, notably Poisson's Ratio, and these have an influence on the reflected signal as a function of offset.

Early work by Koeffoed (1955) and later presentations by Ostrander (1984) have demonstrated the effect of Poisson's ratio and offset and indicated the need to revise our thinking with respect to conventional Common Depth Point (CDP) stacking.

This presentation will address the basic questions and suggest approaches to processing seismic data which may reduce the term "seismically invisible" to simply "acoustically invisible".

INTRODUCTION

In this paper we will review some of the more recent major advances in exploration geophysics and in particular the methods of correlating subsurface lithology to seismic data. In addition we will discuss the variation in amplitude of the seismic signal with the angle of incidence and some mention will be made of the loss of information due to standard stacking procedures.

REVIEW

From the post war era to the early seventies the prime focus of the exploration geophysicist has been to map the earth's structure using deep reflecting horizons. All the research work in this period had a similar goal. However, in the 1970's geophysicists discovered that changes in amplitude along a reflector could indicate velocity changes. Sudden increases in amplitude, or "bright spots" could often be due to gas sands but similar effects could also be caused by coal seams. The other major advance in this period was the realization by Vail (of Exxon) that the appearance of reflector patterns was a method of interpreting the depositional environments of the subsurface geology. This was largely applied to Tertiary and Mesozoic deposits offshore.

"BRIGHT SPOT" DEVELOPMENT

"Bright Spot" technology is generally used to relate character changes along a reflector to changes in lithology in the subsurface. The normal method is to take an acoustic log which when processed provides a velocity profile of the sediment column. Using these data and similar density profiles an acoustic impedence profile can be obtained and used to generate a series of reflection coefficients for the section. The reflection coefficients can then be convolved with a wavelet to produce a synthetic seismogram. The process is shown in Figure 1.

The synthetic seismogram can then be compared with actual seismic data and velocity changes related to the various reflectors. This information is then correlated with actual lithology as inferred from the velocity logs.

DISCUSSION

Several problems exist with the interpretation techniques described above. Seismic data is measured in time and logged data measured in depth. Seismic data is generally band limited whereas logged data is broad band. Random noise also affects both the synthetic and actual seismic data. However, in the case of the original log data used to generate the synthetic seismograms, noise can be edited out. Elimination of noise completely in actual seismic sections is an unrealizable goal but geologists, geophysicists and processors are tending to work more closely together in recognizing the effects of noise and interpreting around it.

A more recent problem concerns the effect of the "phase" of a seismic signal in comparing synthetic and actual seismic data. In wavelet processing the synthetic and actual seismic data are compared statistically (and sometimes visually) to produce a good match. Having solved the usual problems, discrepancies still exist. It is now realized that the difference may be caused by the fact that the synthetic data results from a single series operation whereas one vertical incidence record is the result of stacking many traces together. Figure 2 shows the normal CDP stacking procedure. What is gained by this multiplicity is some improvement in signal/noise ratios and an attenuation of multiples but what is lost is amplitude, frequency and phase information of a reflector. Figure 3 shows that a change in pulse shape is due to the change in the P wave reflection coefficient at two interfaces as the angle of incidence changes. Figure 4 shows the extent that reflection coefficients of an interface changes with angle of incidence and varying Poisson's ratios.

The present technology is at a point where amplitude changes by factors of two are investigated to see if they represent a drillable target or are simply changes in porosity. Thus the amplitude changes of the reflector shown in Figure 3 are of interest. When stacked they may average to zero. This would cause a disagreement with the synthetic seismogram which would show a definite event.

SUMMARY

Hilterman has said that the CDP section is "useless" for stratigraphic information. However, we have changed that comment to say "subtle stratigraphic information" since in reducing the signal noise/ratios by stacking we are destroying "subtle" anomalies. One possible solution is to "unstack" data and examine two or three traces at various offsets. This partial stacking technique has been of great advantage in detecting anomalies (Figure 5).

Our future aim in this direction is to develop a modelling system in order to study amplitude variation with offset. This will give us an advanced tool in order to prospect for subtle stratigraphic traps.

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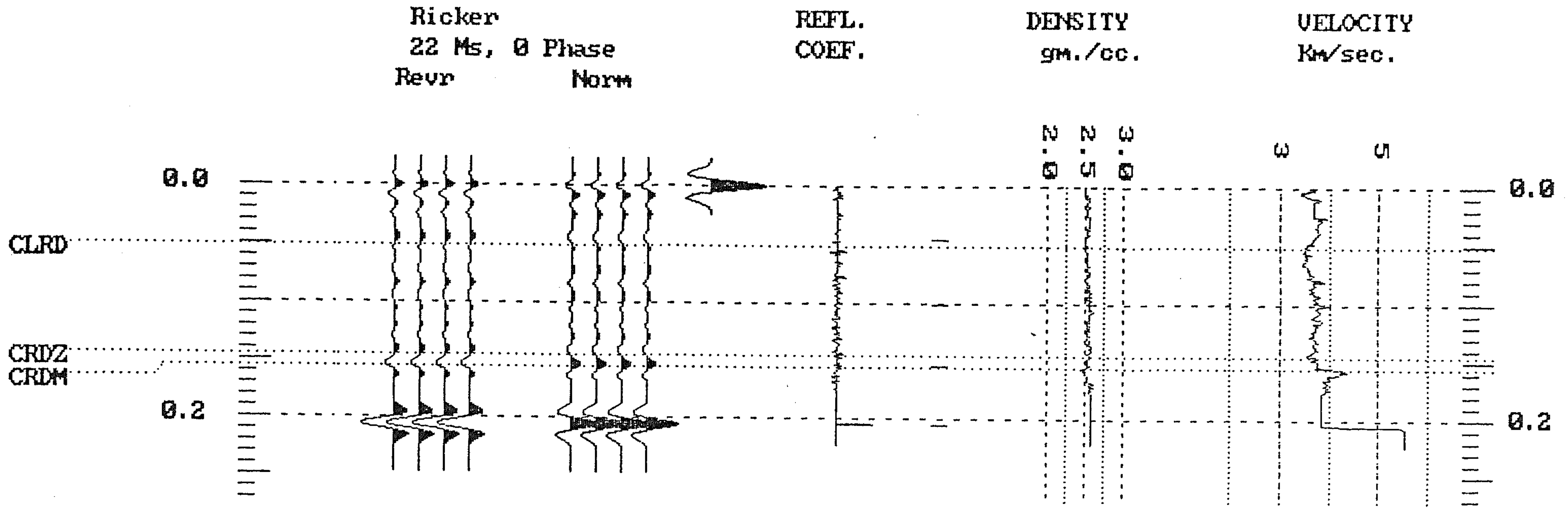


FIGURE 1: Synthetic seismogram for a Cardium Formation oil well, west of Edmonton, Alberta. Reflection coefficients were calculated from the velocity and density logs, and convolved with the 22ms Ricker wavelet to produce the synthetic trace.

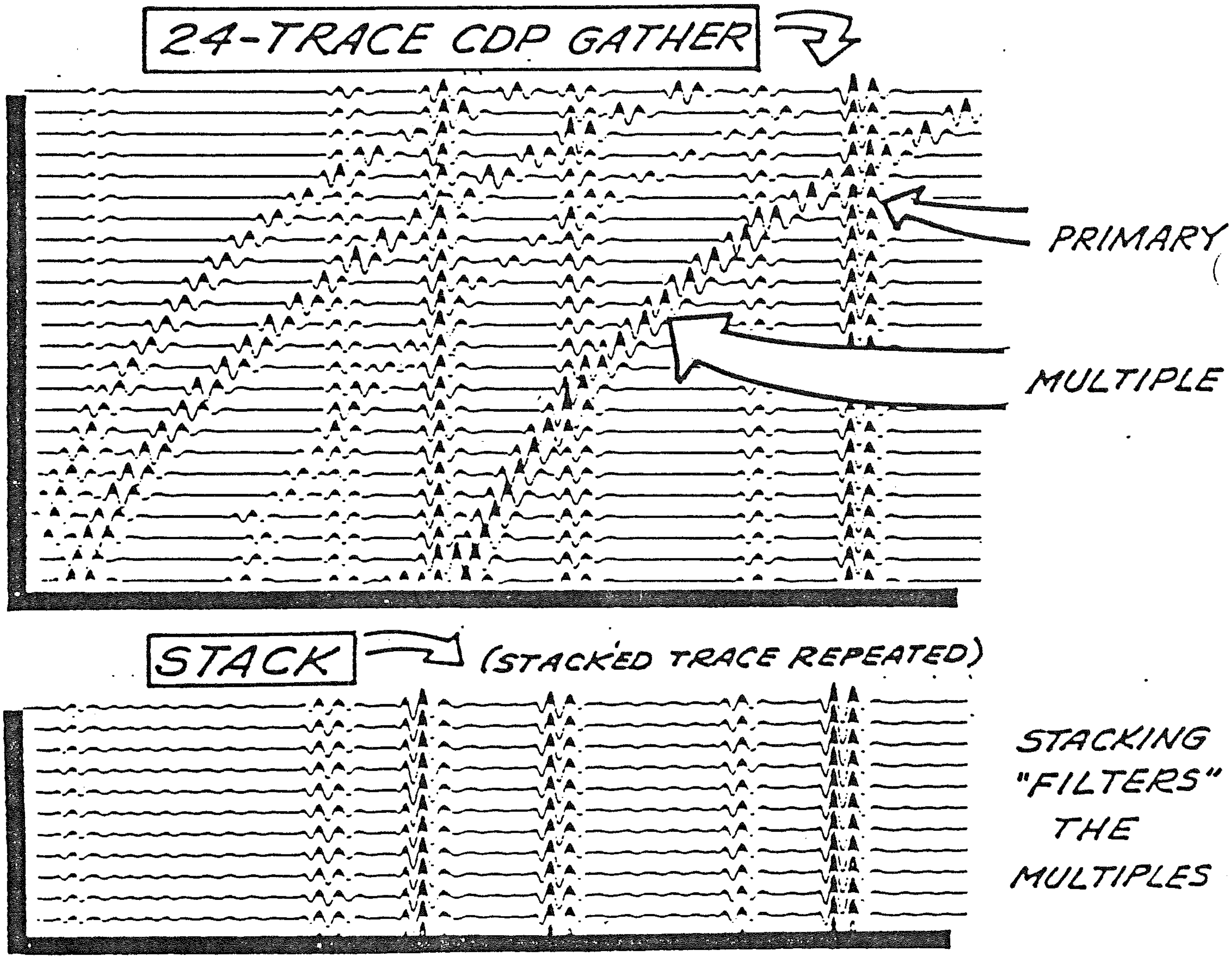


FIGURE 2: The 24 trace common depth point gather, corrected for moveout, shows primaries as flat reflectors while the multiples display residual curvature. Stacking sums the 24 CDP traces into one stacked trace, attenuating the multiples and enhancing the primaries. The single stacked trace is repeated for visual effect.

SHALE-GAS SAND

	Vp	σ	ρ
SHALE	3000	.27	2.5
SANDSTONE (gas)	3300	.1	2.4

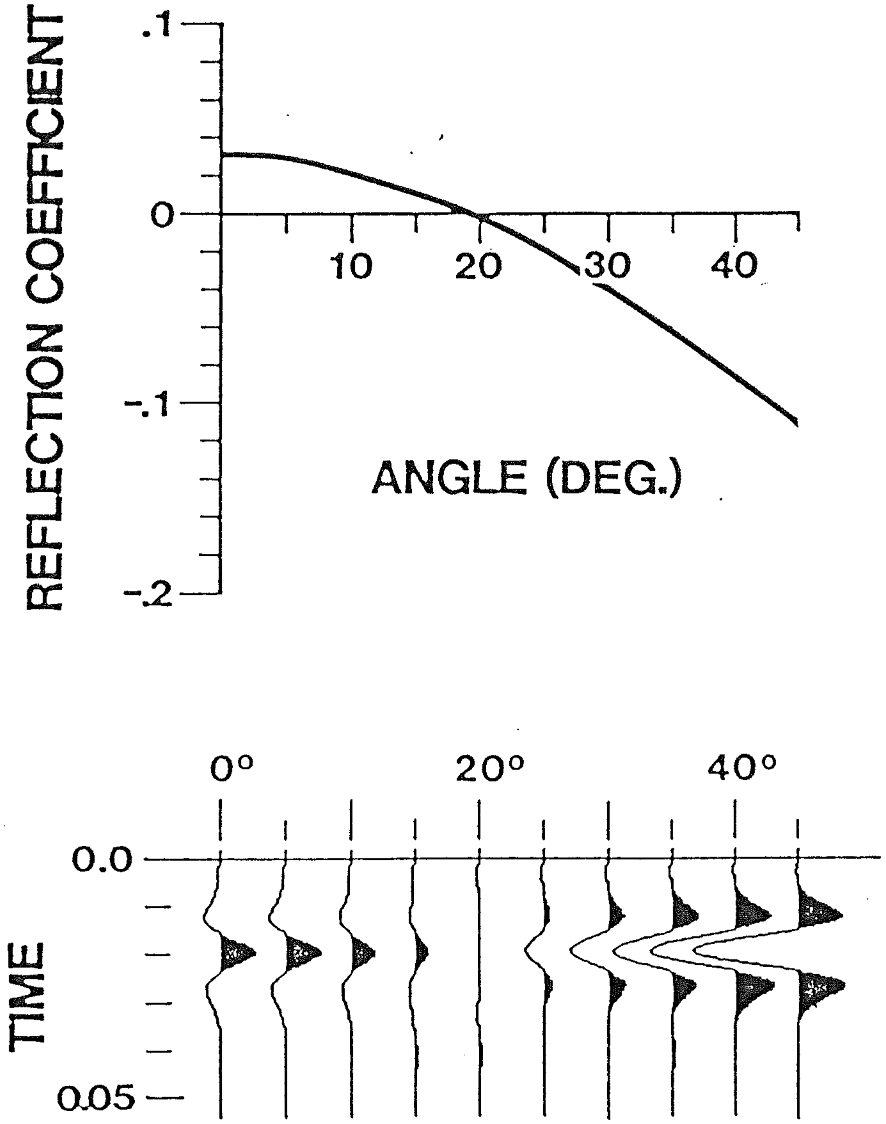


FIGURE 3: For an interface between a shale and a gas bearing sandstone having Vp, σ (Poisson's ratio) and ρ (density) as indicated, a polarity reversal occurs as the incident angle of the seismic ray increases. Stacking these traces would result in the loss of important information.

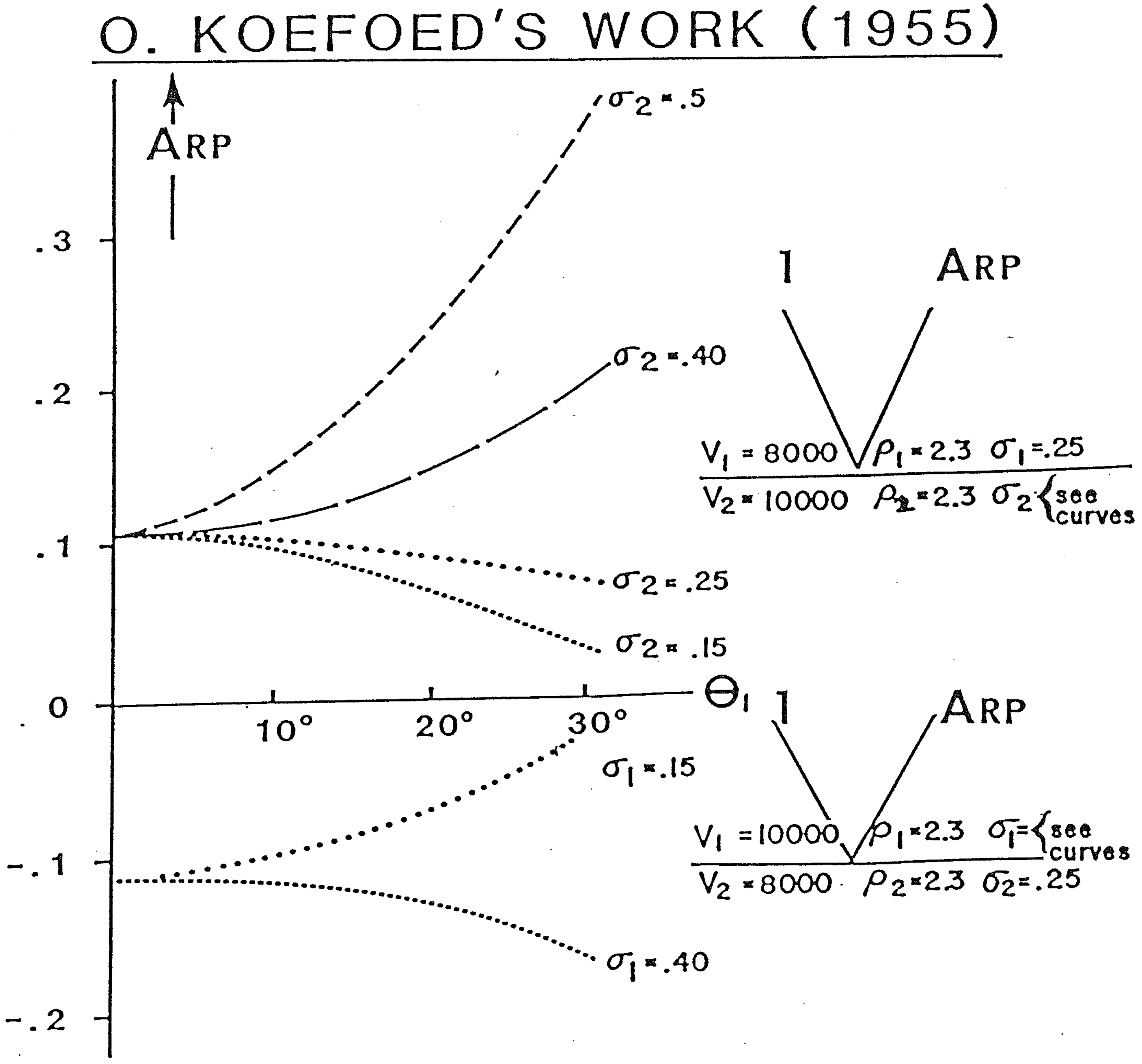
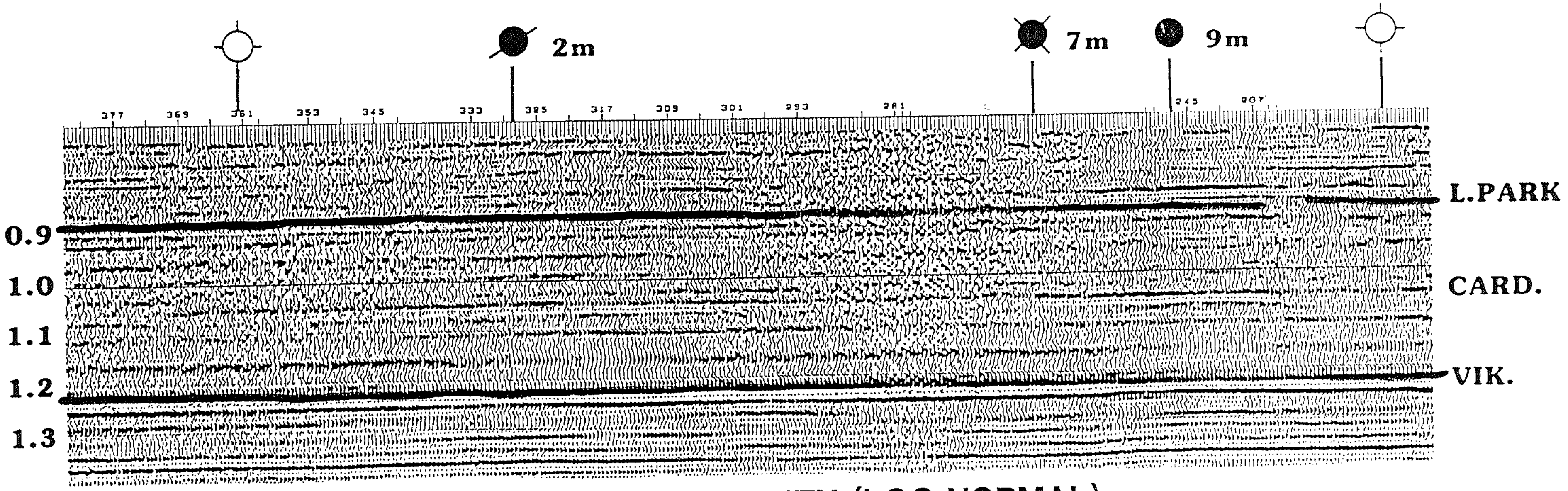
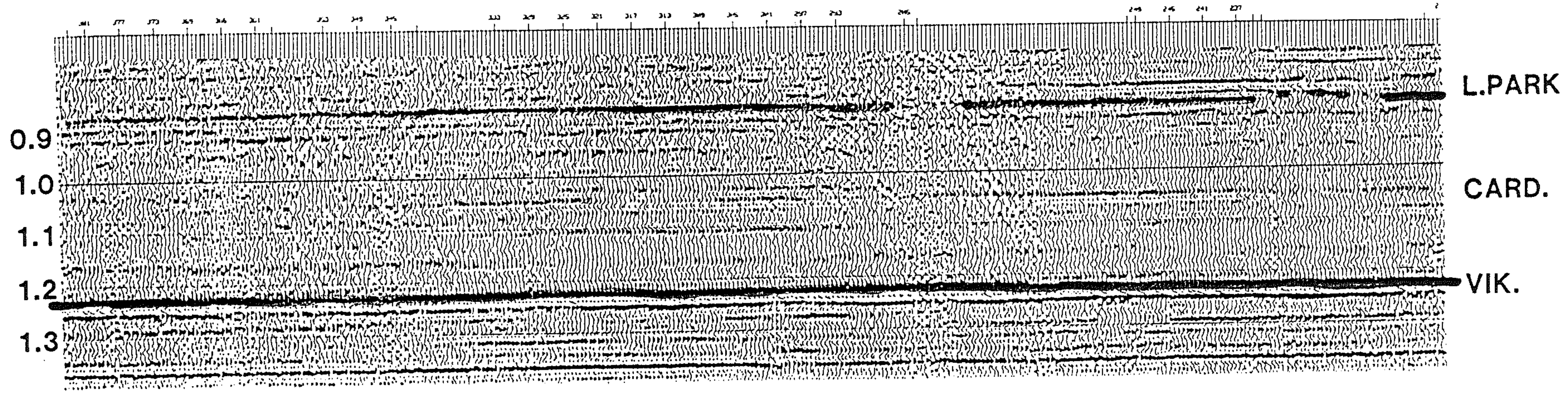


FIGURE 4: Changes in amplitude of reflected P waves as a function of incident angle and Poisson's ratio.



REVERSE POLARITY (LOG NORMAL)



PARTIAL STACK REVERSE POLARITY (LOG NORMAL)

FIGURE 5: Full stack (1200%) and distance limited stack (400%) over Cardium oil pools. The 1200% stack shows a continuous event at the Cardium whereas the distance limited stack reflector develops only at the Cardium oil pools.

A DOWNHOLE SEISMIC CONE PENETROMETER

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A newly developed *in situ* soil test device is described which allows the direct measurement of shear wave velocity through soil at intervals of about 1 m along with the logging of core parameters like bearing, friction and pore water pressure. A generated surface shear pulse is picked up by a 28 Hz miniature seismometer in the cone. The standard downhole incremental technique to calculate shear wave velocity over increments of 1 m of depth are compared to a direct method of measurement using a matched pair of seismometers separated 1 m apart in the cone penetrometer device. Results are also compared to traditional cross-hole shear wave velocity measurements.

INTRODUCTION

In geotechnical engineering there are several ways to obtain design information. Laboratory tests on samples is the standard method to extract specific parameters but more recently in situ testing with the emphasis on minimum disturbance of the medium, is attracting more attention. Table 1 lists various in situ tests commonly used in industry and of these the cone penetrometer test (CPT) will be discussed in this paper.

THE UNIVERSITY OF BRITISH COLUMBIA CPT SYSTEM

The cone penetrometer test is based on an instrumented cone that is forced into the soil as indicated in Figure 1. The cone itself, shown in detail in Figure 2 is comprised of several transducers housed in a 35.6 mm diameter tube. These transducers generate signals as the cone penetrates the soil and the signals are transmitted by wire to the recording vehicle.

A force transducer above the tip measures the total downward force applied to the cone tip and a second transducer measures the friction force acting against an outer sleeve. The sleeve is known as the friction sleeve. Other transducers measure temperature, pore water pressure, and the angle of penetration.

A CASE STUDY

During an operation all the measurements are continuously recorded. After processing the results are plotted as shown in Figure 3. The upper 16 m of this section consists of an organic silt with the top 6 m interpreted from the friction ratio of 10% as being a fibrous peat. The friction ratio in the organic silt below is less than 4%. The friction ratio for sand is generally less than 1%. The sand zone between 16 m and 28 m clearly shows the effect of the silt layers. The differential pore pressure ratio in the sand zone is zero. This also corresponds to the very high bearing resistance. The silt layer at 28 m has a very low bearing resistance in comparison to the sand above.

There are other correlations that can be used. An approximate relative density value for the sand can be derived and used with other correlations.

The stratigraphic detail of the silt interbedded with sand partings can be clearly seen. The interbedded sand and silt structure from 44 to 66 m presents different characteristics as does the lowest zone comprising of well defined sand and silt layers.

Estimates of the undrained shear strength of the plastic material, which is interpreted as increasing with depth, can be obtained from correlation curves.

As the probe penetrates, pore water pressure increases above the equilibrium. At rod changes (1 m intervals) the excess pore pressure is allowed to dissipate. We measure the time for the pressure to dissipate to 50% of its real value and from this derive the coefficient of consolidation. If we allow the pore pressure to dissipate completely, the equilibrium water pressure can be determined. Another advantage of digitally recording the profiles is that it allows flexibility in display format. Interesting sections can be expanded to take advantage of the high density of information recorded.

For additional details concerning typical results and interpretation correlations and procedures, the reader is referred to Campanella et al, 1983 and Robertson and Campanella, 1983.

SHEAR WAVE MEASUREMENTS

Another aspect of our work has involved the in situ determination of shear wave velocity in an attempt to relate shear modulus with stress-strain characteristics of soil. With one of the penetrometers we have made downhole measurements using a source of shear waves on the surface and a simple horizontally oriented seismometer (detector) in the cone. Concern over the accuracy of the single detection system led to a true interval system being used as a reference. Figure 4 shows a typical shear wave response for single and polarized shear source and the results of a comparison test carried out with penetrations up to 13 m with 40 measurements every meter, are shown in Figure 5. The differences are very small. Figure 6 shows the deeper measurements up to 40 m penetration. The need for a 16 bit A-D converter was justified during these tests. Finally, a comparison of downhole and corehole is shown in Figure 7. The differences can be explained in terms of anisotropy of soil and ground stress conditions.

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QUESTIONS

Q. What size of cone do you use?

A. 36 mm dia. or 10 sq. cm.

Q. That last one was a 15 sq. cm cone, wasn't it?

A. We have several cones. The one that I did show was 15 sq. cm. We have the seismometers in both 15 sq. cm end area as well as 10 sq. cm. I should say that the 10 sq. cm is the accepted standard in the world today.

Q. (from Roger Hutchins) Why don't you measure the compressional wave velocity as well?

A. When we see the entire spectrum, the P wave comes through at very low amplitude compared to the S wave; perhaps because of the efficiency of the surface shear source we use. All I can assume is that the transducer is responding basically in the mode of 28 Hz. This must be a frequency range where the shear energy transmits very well. Our next phase is to put an accelerometer in the cone which has a flat response from zero up to about 400 Hz. This will allow us to do some analysis of the spectrum.

(Comment from Denzil Taylor-Smith) I think Roger Hutchin's point is that you could have put in a three component geophone which could have picked up the P wave on the other axis.

A. At all sites below the ground water table we tend to pick up the velocity in water. Even in the sand we get P wave velocity which is very close to the velocity in water.

(Comment from Jim Hunter) I would also agree that a three component cone would certainly be an asset. Some years ago, working in open holes of permafrost we used a three component pickup with a small explosive source on the surface with no special attempts being made to create a shear mode. By using particle motion plots, the onset of both the compressional and shear wave energy was obvious. I think that might be the route to go. One other additional question: When you measure the dynamic elastic moduli, should they not be stated with the dominant frequency in the frequency range that they're measured? I know of accounts where the static moduli and the dynamic are up to two orders of magnitude apart.

Q. What do mean by static and dynamic?

A. I'm told by these geotechnical types that one is measured by seismic methods using the compressional and shear wave velocities and density. The values obtained by these consultants can differ by up to two orders of magnitude.

(Comment from D. Campanella) Those large differences are due to strain level effects. The shear modulus decreases dramatically as the strain level increases. The shear modulus measured by seismic techniques is at very small strains (10^{-5} or less) and is referred to as $G(_{max})$. The shear modulus measured for static loading at strains of 10^{-1} will cause plastic deformations and is very much less than $G(_{max})$.

Q. (from Roger Hutchins) Aren't we also talking about strain rate dependent which is something that doesn't come out at any time?

A. I think you will find that for engineering problems the rate effect on the modulus is small compared to the strain softening effect. We're talking about the tangent to the curve which is getting flatter and flatter for larger strains. If you run that curve at a variety of strain rates, the curve will be different but not so different when compared to the order of magnitude difference with strain softening.

TABLE 1

IN-SITU TESTS

Type of Test	Type of Soil		Properties that can be determined	Remarks	References
	Best Suited To	Not Applicable To			
1-Standard Penetration Test (SPT)	Sand	Clay	Qualitative evaluation of compactness. Qualitative comparison of subsoil stratification.	(See Section 4.5.1.2)	1) CSA A119.9-1960 2) KOVACS ET AL (1981) 3) ESOPT II (1982)
2-Static Cone Test (CPT)	Sand Silt Clay		Continuous evaluation of density and strength of sands Continuous evaluation of undrained shear strength in clays.	(See Section 4.5.1.3.) Test is best suited for the design of piles or footings in sand. Tests in clay are more reliable when used in conjunction with vane tests.	1) SANGLERAT (1972) 2) SCHMERTMANN (1970) 3) ISSMFE (1977) 4) ASTM D 3441-79 5) ROBERTSON & CAMPANELLA (1983) 6) ESOPT II (1982)
3-Vane Test	Clay	Silt Sand Gravel	Undrained shear strength c_u.	(See Section 4.5.1.4.) Test should be used with care particularly in fissured, varved and highly plastic clays.	1) ASTM D 2573-72 2) BJERRUM (1972) 3) AAS (1965) 4) LO (1972) 5) SCHMERTMANN (1975) 6) LEMASSON (1976)
4-Plate Bearing Test and Screw-plate Test	Sand, Clay		Modulus of subgrade reaction. Ultimate bearing capacity.	(See Section 4.5.1.6.) Strictly applicable only if the deposit is uniform. Size effects must be considered in other cases.	1) ASTM D 1194-72 2) DAHLBERG (1975) 3) JANBU & SENNESET (1973) 4) SALVADURAI ET AL. (1979)
5-Dynamic Cone Test	Sand & Gravel	Clay	Qualitative evaluation of compactness.		1) ISSMFE (1977) 2) IRELAND ET AL (1970)
6-Pressuremeter Test	Soft Rock, Sand, Clay	-	Ultimate bearing capacity and compressibility.	(See Section 4.5.1.5)	1) MENARD (1965) 2) EISENSTEIN & MORRISON (1973) 3) TAVENAS (1971) 4) BAGUELIN ET AL. (1978) 5) WROTH (1975)
7-Permeability Test	Sand & Gravel	Clay	Evaluation of coefficient of permeability.	Variable head tests in boreholes have limited accuracy. Results reliable to one order of magnitude are obtained only from long term, large scale pumping tests.	1) HVORSLEV (1949) 2) NAVFAC DM7 (1971) 3) SHERARD ET AL. (1963)
8-Flat Plate Dilatometer	Sand & Clay	Gravel	Empirical correlations for soil type, K_o, OCR, c_u and modulus.	(See Section 4.5.1.7) Newest Test	1) MARCHETTE (1980) 2) SCHMERTMANN (1983) 3) CAMPANELLA & ROBERTSON (1983)

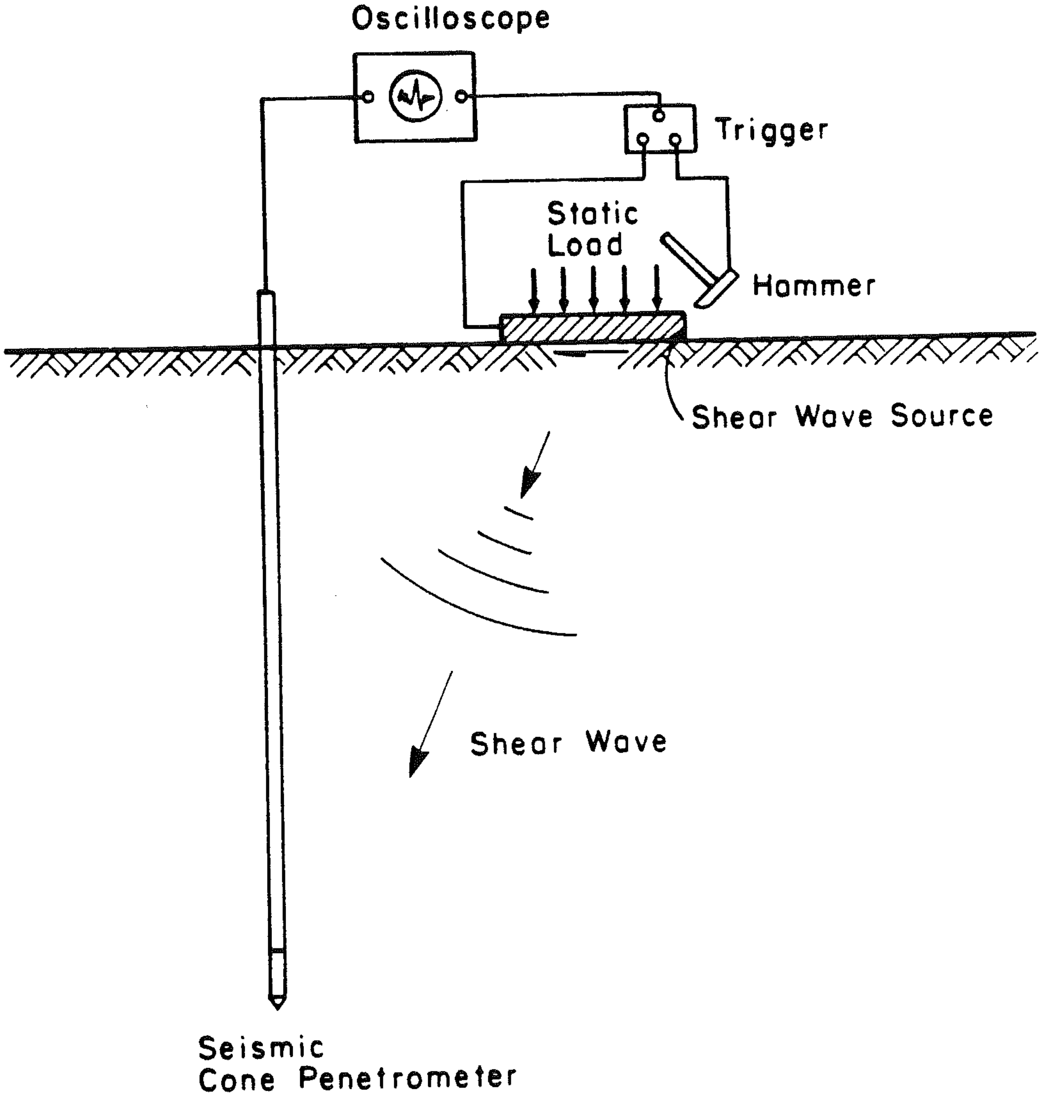

Fig. 1 Schematic Layout of Downhole Seismic Cone Penetrometer Test.

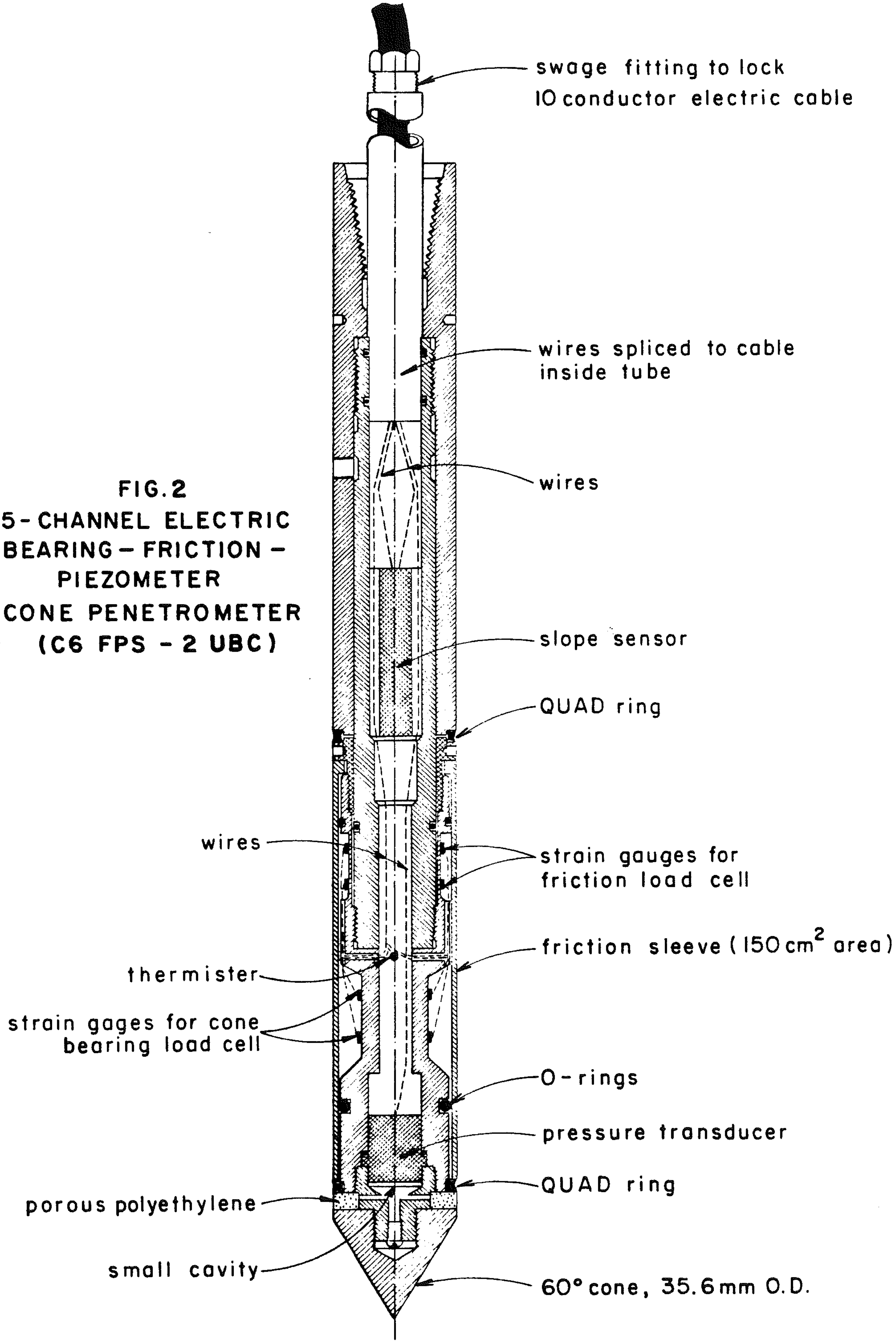

FIG. 2
5-CHANNEL ELECTRIC
BEARING – FRICTION –
PIEZOMETER
CONE PENETROMETER
(C6 FPS – 2 UBC)

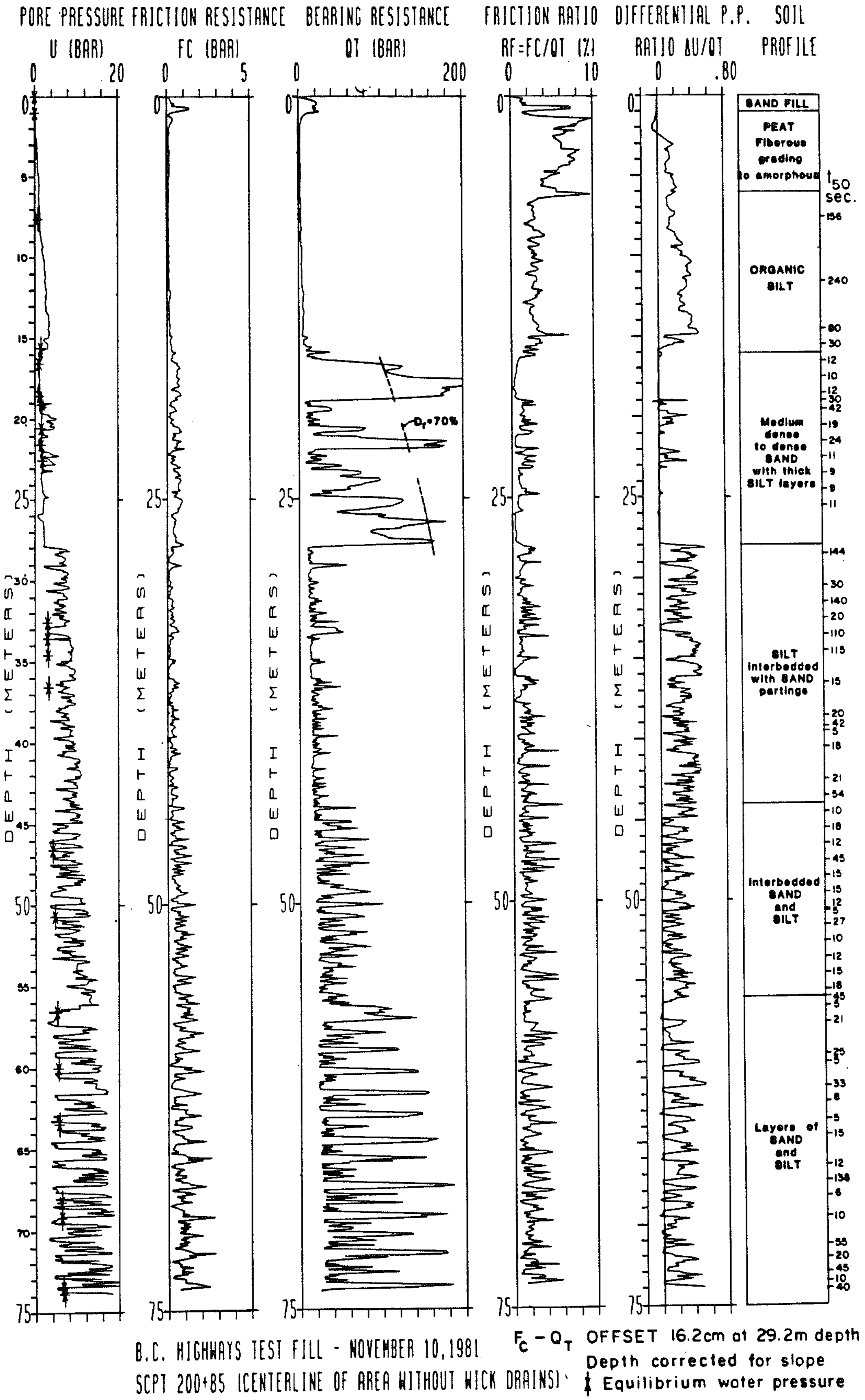

Fig. 3 Piezometer friction cone logging in stratified soils.

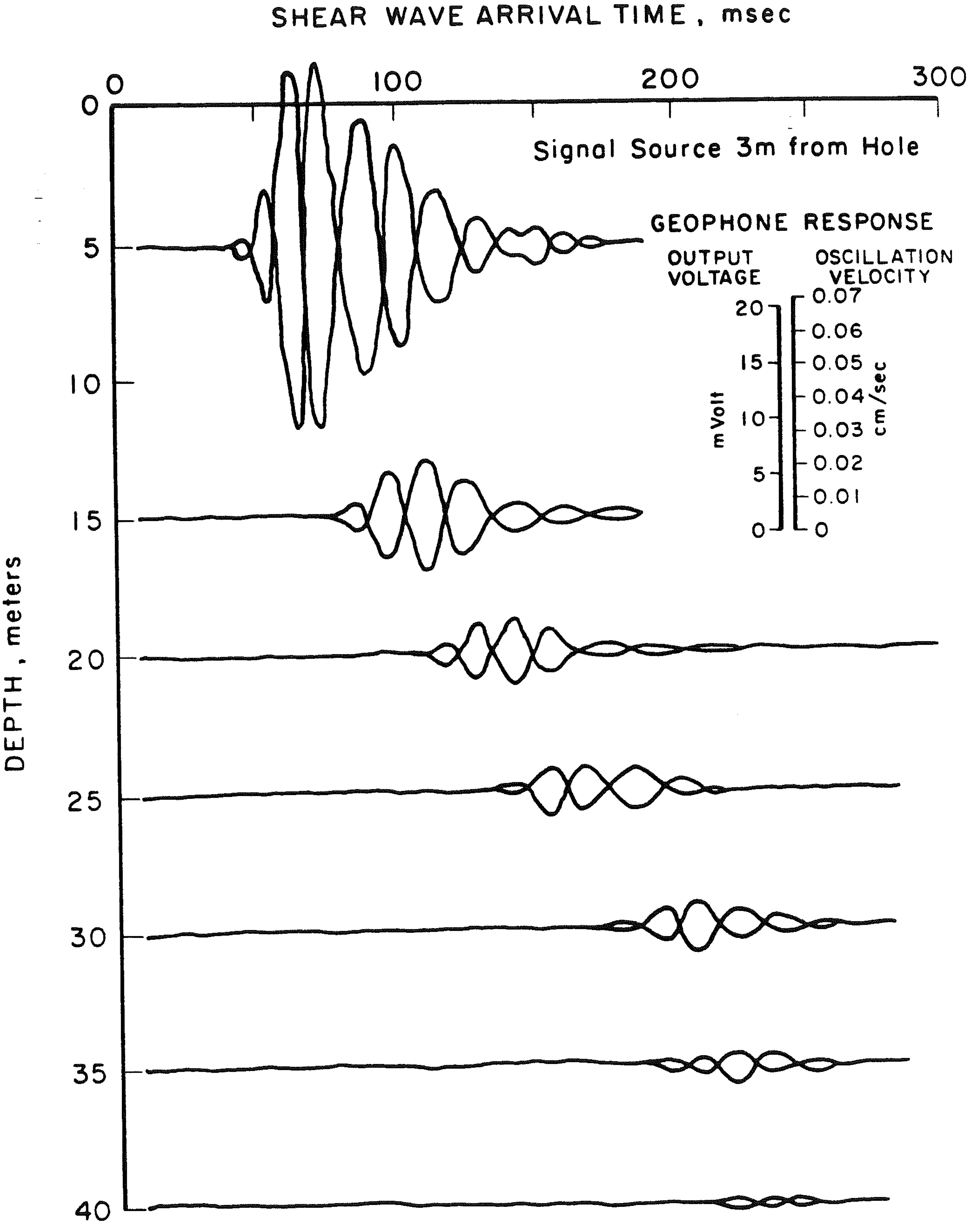

Fig. 4 Quantitative Comparison of Geophone Response Amplitude and Relative Shear Wave Travel Times from Seismic Cone Penetrometer.

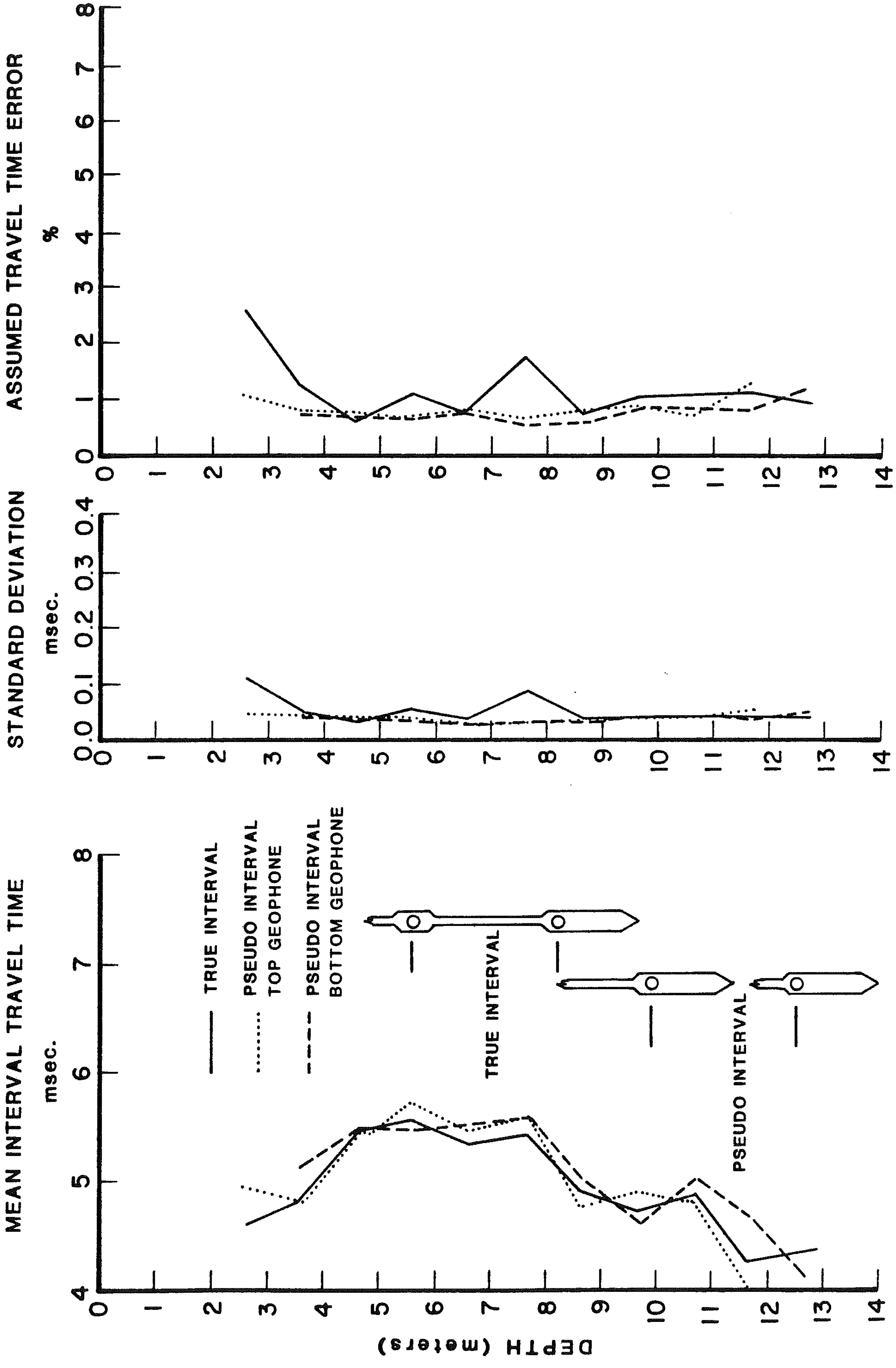

Fig.5 COMPARISON OF TRUE AND PSEUDO INTERVAL TRAVEL TIMES.

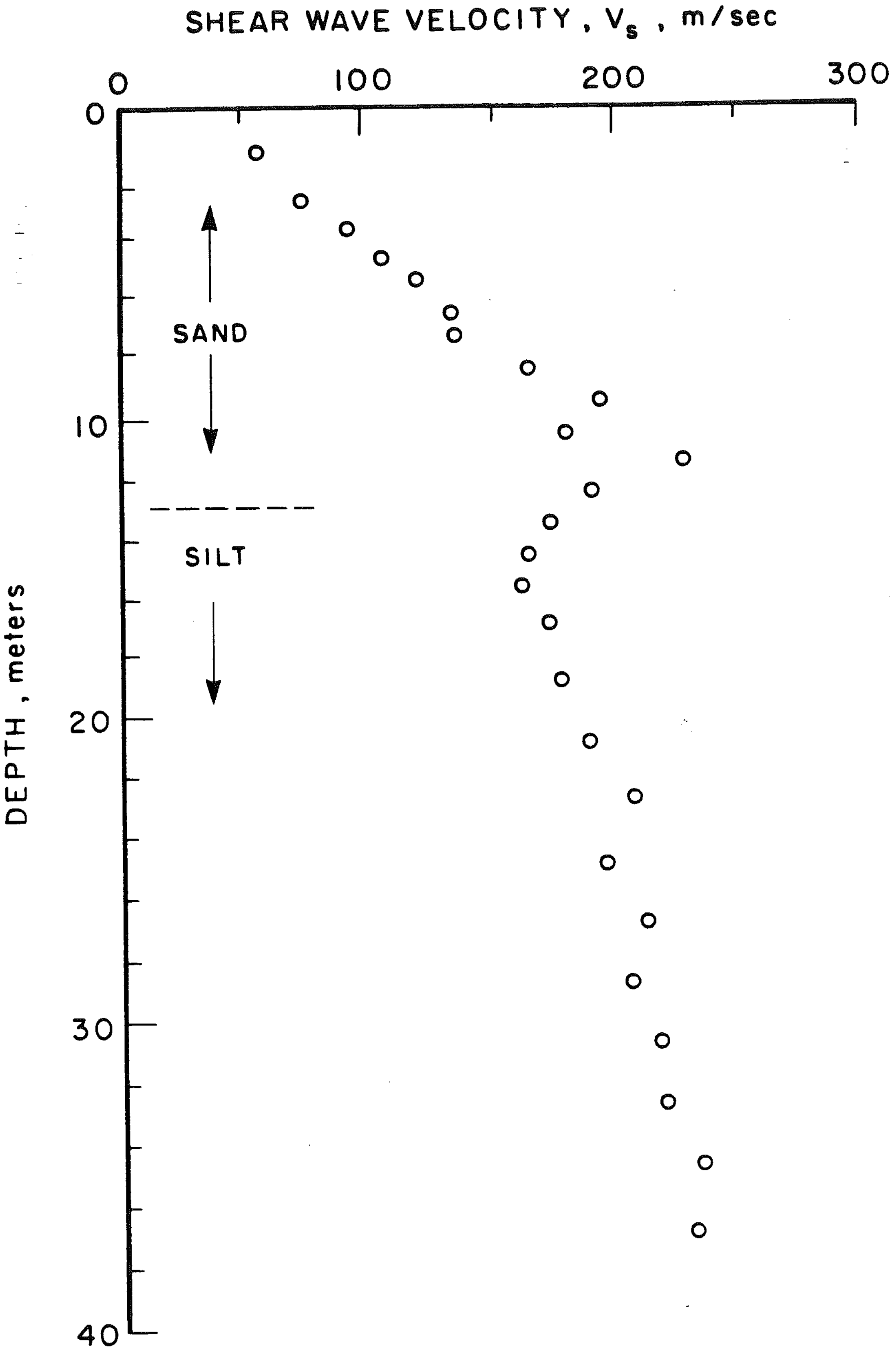

Fig. 6. Calculated Shear Wave Velocity Profile From Seismic Cone Penetrometer.

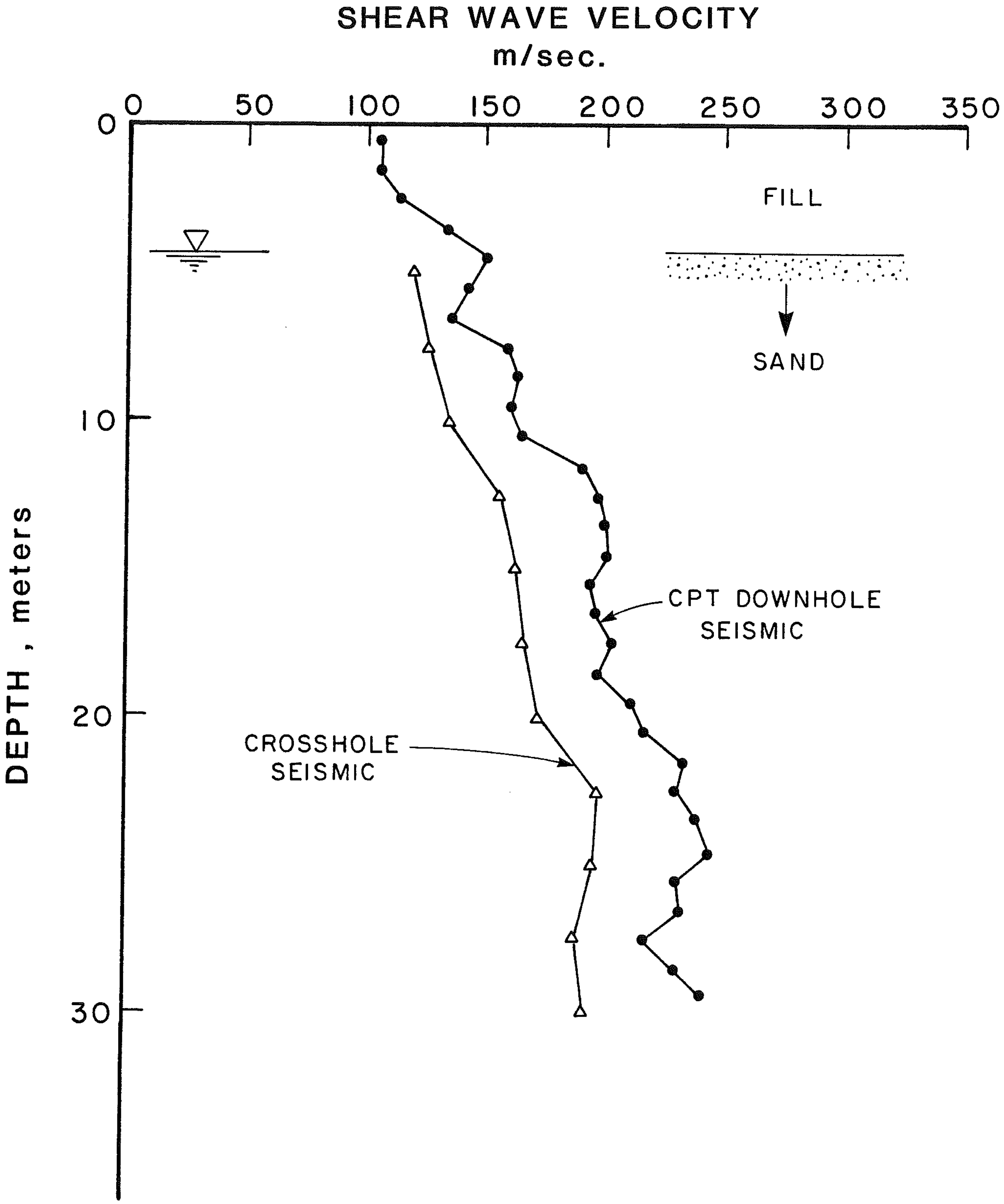

Figure 7 COMPARISON OF DOWNHOLE AND CROSSHOLE VELOCITY MEASUREMENTS ANNACIS NORTH PIER SITE.

SEDIMENT CHARACTERIZATION USING THE ACOUSTIC CONE PENETROMETER

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Berkeley, California

The cone penetrometer test (CPT) has been one of the most useful means for investigation of seafloor sediments for geotechnical purposes. The recent addition of pore pressure sensors to supplement the measurement of tip and sleeve resistance in the standard CPT test has yielded additional information useful for deduction of mechanical properties. When the CPT is used alone, however, some uncertainty always remains concerning the actual soil type penetrated and the boundaries between strata.

For several years research has been in progress in Berkeley using an "acoustic cone penetrometer". (Mitchell et al., 1983; Tringale, 1983; Tringale and Mitchell, 1982; Villet, 1981; Villet et al., 1981). A sensitive microphone located in the tip of a standard electrical cone penetrometer is used to record the sound as penetration proceeds through the soil at a constant rate of 2 cm/sec. It has been found that the amplitude of the sound is a sensitive function of the soil type as indicated by the mean particle size. The acoustic signal provides a good indication of boundaries between different strata. Additional interpretations based on analysis of the frequency content of the acoustic signal are being studied.

This presentation focussed on the apparatus, instrumentation, and illustration of typical acoustic behaviour for different soil types.

INTRODUCTION

This brief paper describes the progress made in combining an acoustic measurement with a standard cone penetrometer test (CPT) using what we at the University of California call an "acoustic cone penetrometer". The CPT is a simple test which gives continuous information about certain engineering properties as an instrumentated cone is forced into a sediment. Interpretation methods can range from very simple empirical correlations to elegant theoretical analyses. In general, CPT measurements remain a relatively low cost means of generating information about soils in situ. In particular, CPT data are very useful when sampling is difficult and when disturbance has taken place, for example, with clean sands, or in hostile enviroments like the Beaufort Sea. There are some practical limitations, of course, in that it is difficult to penetrate hard soils with the penetrometer unless a dynamic cone is available, and there is always some uncertainty about soil type unless an actual soil sample is obtained. Some cone units have an inclinometer to measure verticality of the instrument, and some contain pore pressure measuring devices.

We felt that a measurement of the acoustic noise generated by the cone when moving through the soil could provide useful information. To this end a small electret condenser microphone was embedded into the tip of a core so that the noise generated by soil grains rolling and sliding past each other and of grains being crushed could be recorded.

APPARATUS AND INSTRUMENTATION

Two systems have been developed at Berkeley, the undamped unit (Figure 1b) and a damped penetrometer (Figure 1a). The damped unit, although of higher performance, has a load capacity limitation of 50 kN; whereas the undamped penetrometer capacity is 100 kN. In both systems the cone transmits a large amount of data, which requires a data acquisition system. The acoustic information detected by the microphone is preamplified and then tape recorded in analogue form for later analysis. Real time monitoring includes oscilloscope displays, loudspeaker outputs and an analogue output of the rms signal level displayed on a strip chart recorded. The recording instrumentation shown in Figure 2 is normally housed in a field truck or on board a drill ship. Full details of the acoustic penetrometer system are given in U.S. Patent No. 4,382,384.

ACOUSTIC RESPONSE OF SOIL DURING PENETRATION

The majority of the developmental work has been undertaken in a calibration chamber located in the Soils Mechanics and Bituminous Materials Laboratory in Berkeley, California (see Figure 3). The chamber contains a large, carefully prepared sample of soil that can be tested under controlled stress conditions. The samples can be either dry or saturated, and control for both horizontal and vertical confining stress is available.

Penetration is usually done at a rate of 2 cm/s . Tests also have been done to investigate the influence that penetration rate has on acoustic response and friction sleeve resistance and tip resistance. Penetration rate has been found to have little effect on tip and friction sleeve resistance, as shown in Figure 4. Tests have been conducted using various sands at different confining stresses and densities. Figure 5 shows a typical acoustic signal. Early in the testing program it became evident that penetration rate was an important parameter influencing the amplitude of the acoustic response. The relationship between signal amplitude and penetration rate appears to be linear (Figure 6). This indicates that the rate of penetration must be well controlled if quantitative data from the actual field are to be interpreted correctly.

An alternative to this procedure would be to control penetration force and use the resulting penetration rate as a measure of some soil strength property. For regular testing however, cone advance at a constant rate is preferable.

Off line processing of the recorded acoustic data has included spectral analysis, but at this stage of development we are a little uncertain about the detailed interpretation of the characteristic spectra. For the soils that we have studied so far the spectral characteristics show that the majority of the energy is in the 2 kHz to 16 kHz range (Figure 7), that spectra shapes are generally similar, and that the frequency at maximum spectral amplitude increases with increasing penetration resistance. Much more work is needed on interpretation of acoustic frequency response during penetration.

We have obtained acoustic amplitude data from five sites, one example is shown in Figure 8, others are shown in Tringale and Mitchell, 1982. At the Salinas site (Figure 8) a fine silty sand overlies a medium coarse sand. The acoustic response is seen to increase rapidly in the second layer, reflecting the important effect of grain size on signal amplitude. In all tests so far grain size has been the dominating influence on signal amplitude, however, the degree of saturation is very important, as well as the penetration rate, as mentioned earlier. For example, if we go from a dry sand to wet sand across a water table, the acoustic amplitude decreases by a factor of about two.

There is always some question about the influence of underlying layers on penetrometer response and the precision with which interfaces can be detected. If a penetrometer had zero diameter, then in terms of resistance to penetration, a layer would not be detected until contact had been made. However, resistance to a larger diameter device would be affected to some extent by the material ahead of the cone. Although little investigation has been undertaken in this area, it is our belief that the acoustic response would not show a significant effect of an underlying layer until it is reached and that the sound that we do receive is generated primarily at the cone/soil interface and immediately adjacent to it.

We had hoped that useful information would have been obtained concerning density and confining stress, but to our initial surprise we found that the influences of these factors are not great. For a given sand the amplitude of the acoustic response decreases slightly as both the stress and the density increase. It also tends to decrease as the core tip resistance increases.

Our suspicions are that the acoustic response is not very sensitive to these effects, because what is being measured is the soil response after it has reached its failure state. The area around the cone tip is very disturbed, so that initially loose sand has densified and vice versa. A parallel can be made by listening to a piece of chalk on a chalkboard. There will be a certain pressure where the sound produced will attain a maximum volume. A decrease or increase in force will reduce the sound generated.

Figure 9 is a correlation between the average grain size and the acoustic amplitude for 14 different soils. The results show that a cone with an acoustic sensing device provides reasonably a good method for estimating mean particle size.

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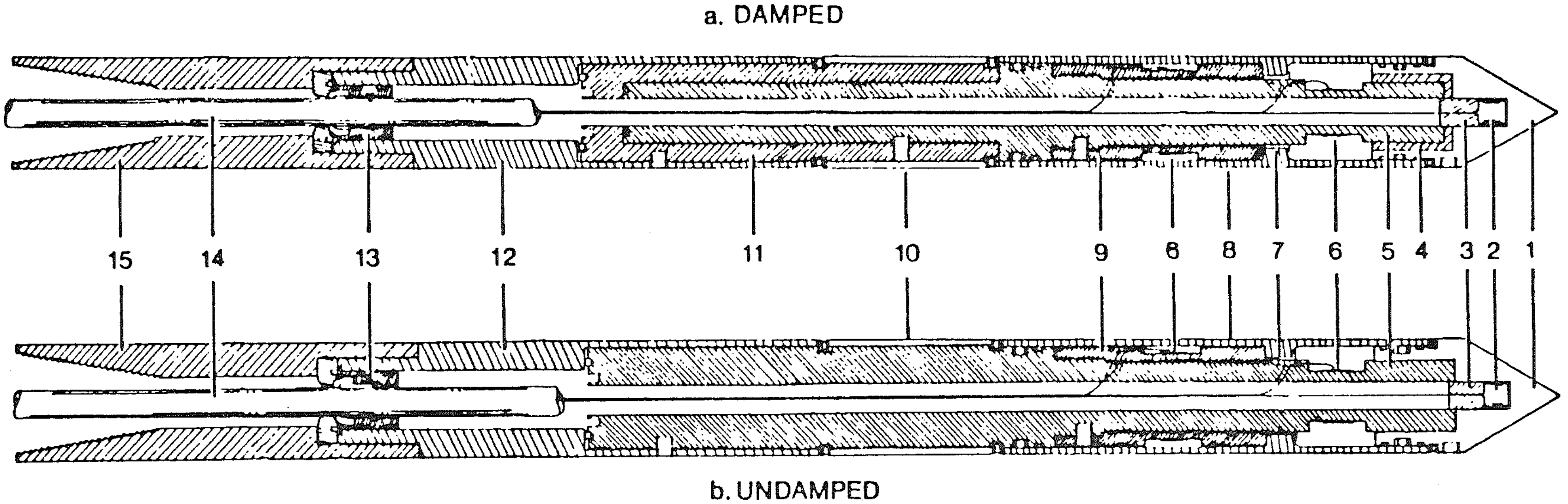


1 CONE (10cm^2)
2 MICROPHONE
3 PLASTICENE
4 DAMPER RING
5 CONE LOAD CELL
6 STRAIN GAGES
7 DELRIN GUIDE
8 FRICTION SLEEVE (150cm^2)
9 FRICTION LOAD CELL
10 ADJUSTMENT RING
11 DAMPER SLEEVE
12 ADAPTER ROD
13 WATERPROOF SEAL
14 ELECTRIC CABLE
15 PUSH ROD CONNECTOR

FIG. 1. UNIVERSITY OF CALIFORNIA ACOUSTIC CONE PENETROMETERS (a) DAMPED PENETROMETER (b) UNDAMPED PENETROMETER

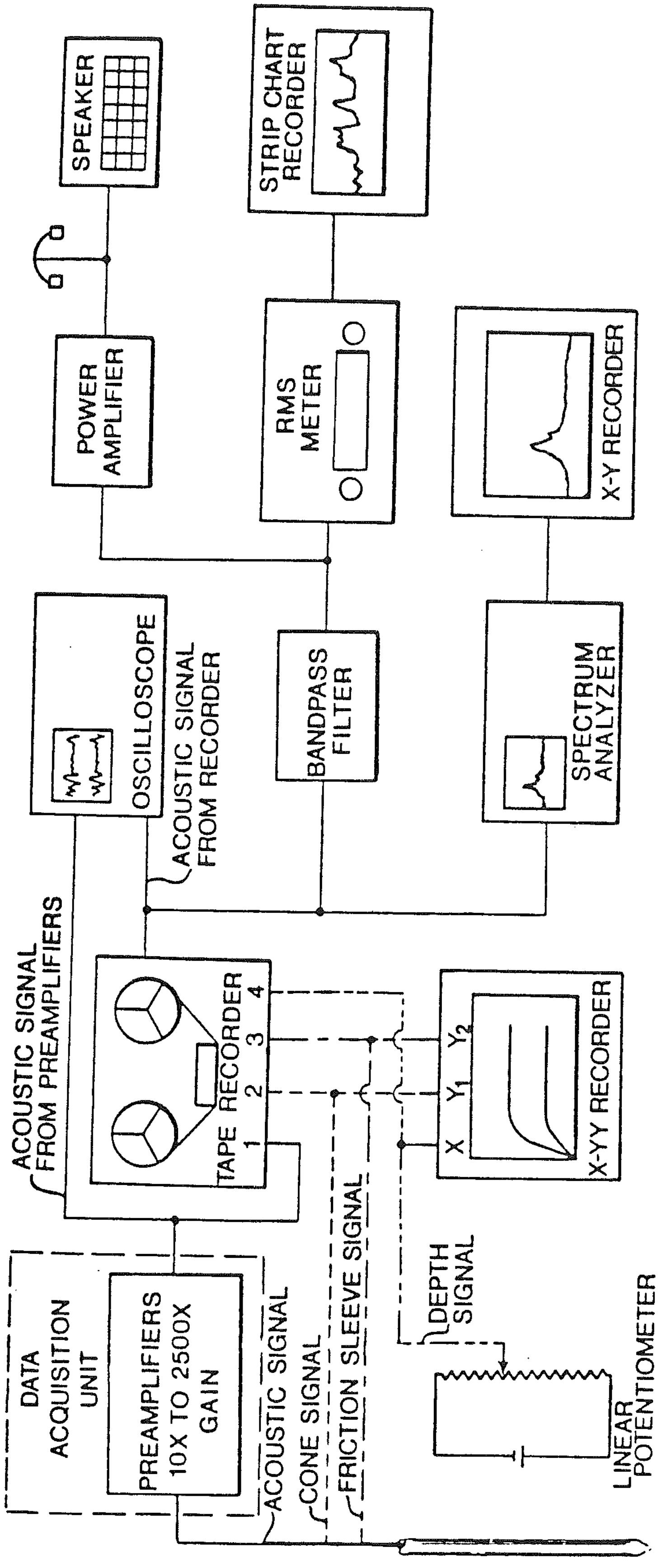


FIG. 2. SCHEMATIC ILLUSTRATION OF DATA ACQUISITION AND ANALYSIS SYSTEM

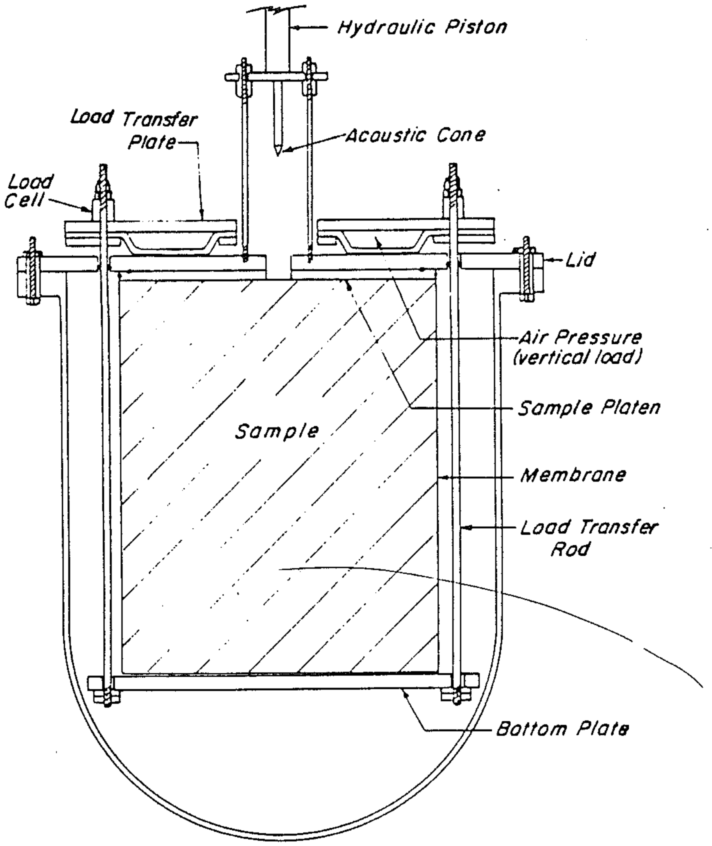


FIG. 3 SCHEMATIC ILLUSTRATION OF THE PRESSURE CHAMBER. SAMPLE DIMENSIONS ARE 800 mm (32 in.) IN HEIGHT BY 750 mm (30 in.) IN DIAMETER

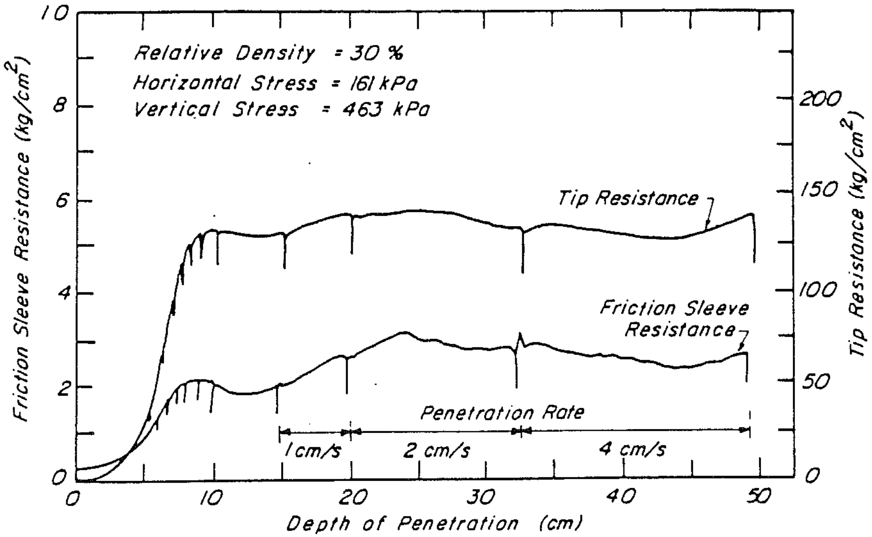


FIG. 4. TIP AND FRICTION SLEEVE RESISTANCE AT DIFFERENT PENETRATION RATES FOR TEST 4.

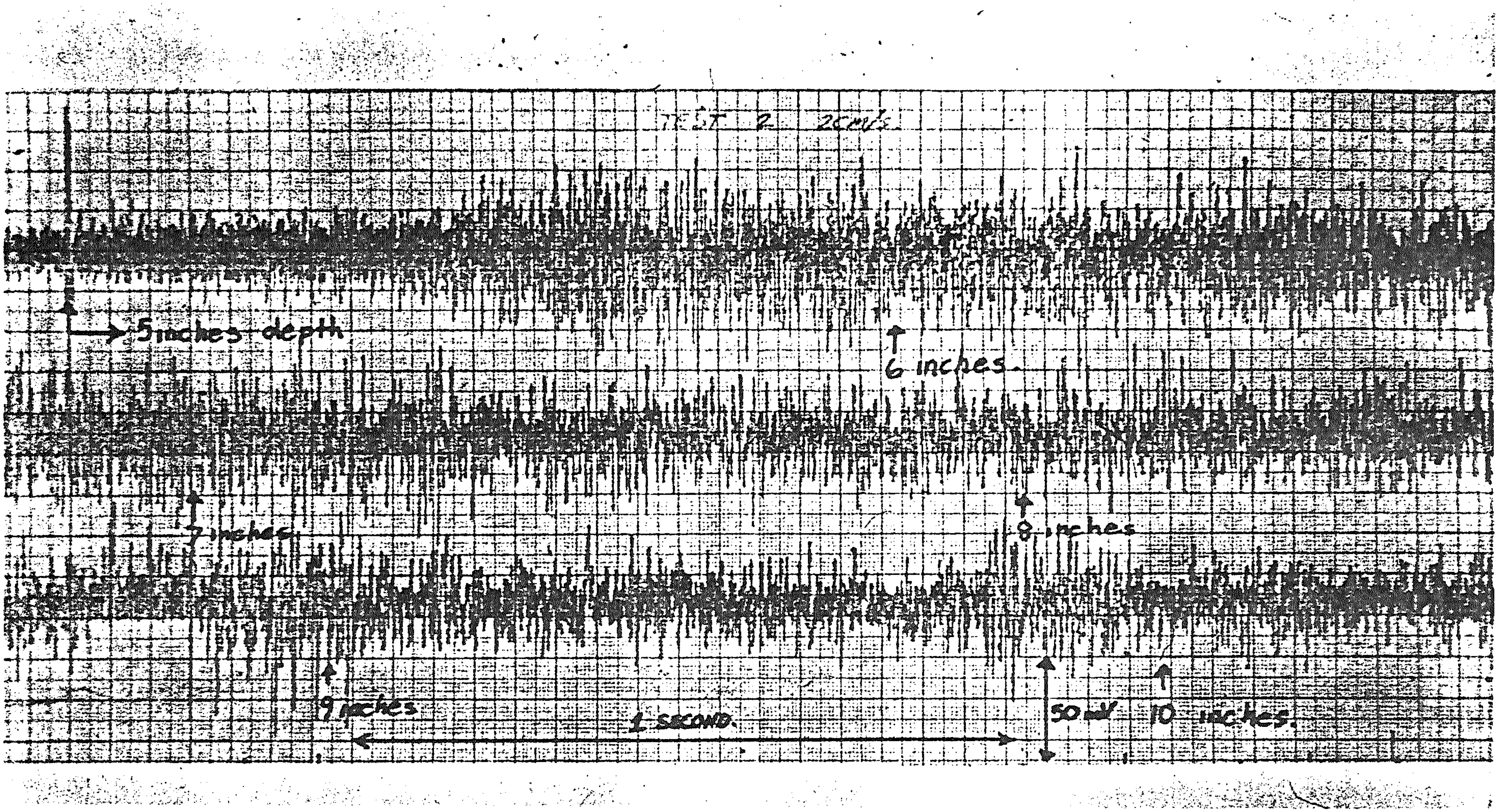
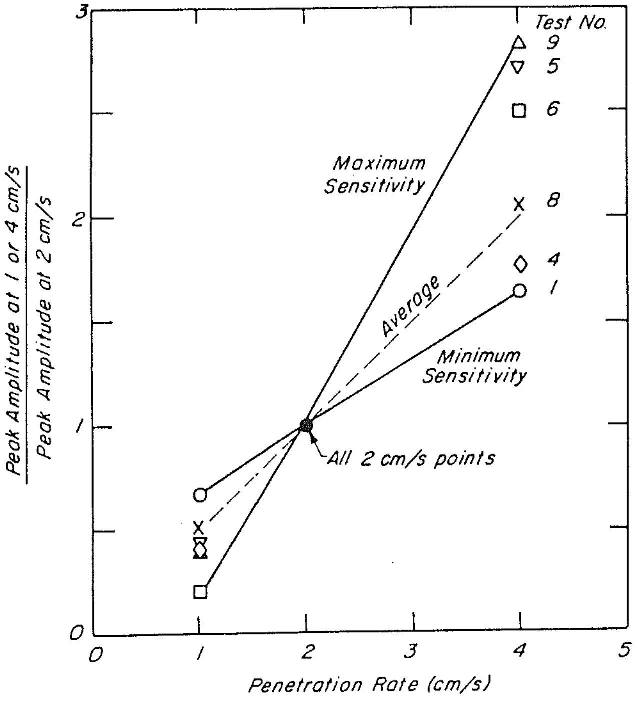


FIG. 5. PEAK TO PEAK VOLTAGE CONTAINED IN THE FREQUENCY BAND 60Hz TO 3kHz for Test 2



Averages are for 33 data points.

FIG. 6. NORMALIZED PEAK AMPLITUDES AS A FUNCTION OF PENETRATION RATE

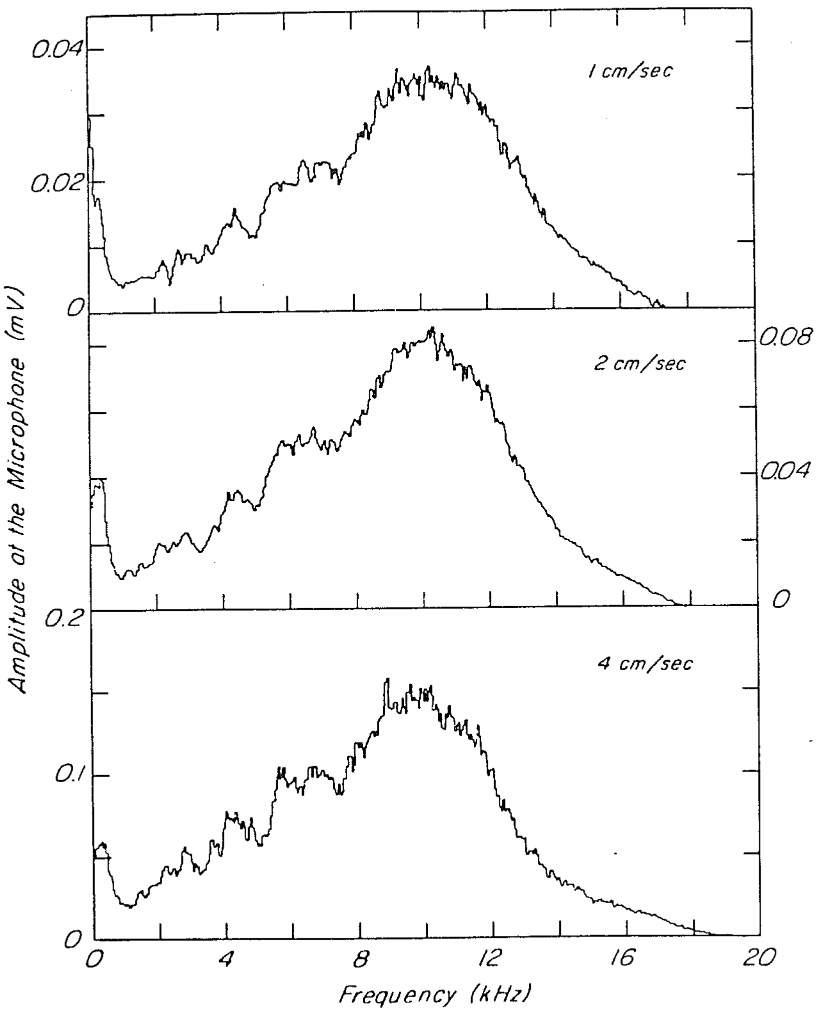


FIG. 7. FREQUENCY DISTRIBUTION CURVES FOR TEST 4 - EXPANDED VERTICAL SCALES

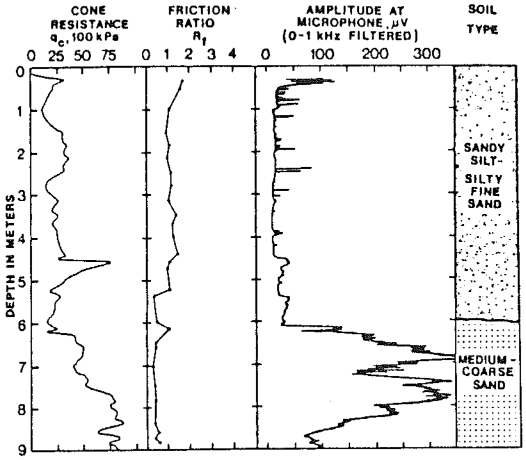


FIG. 8. ACPT RESULTS FROM SALINAS SITE

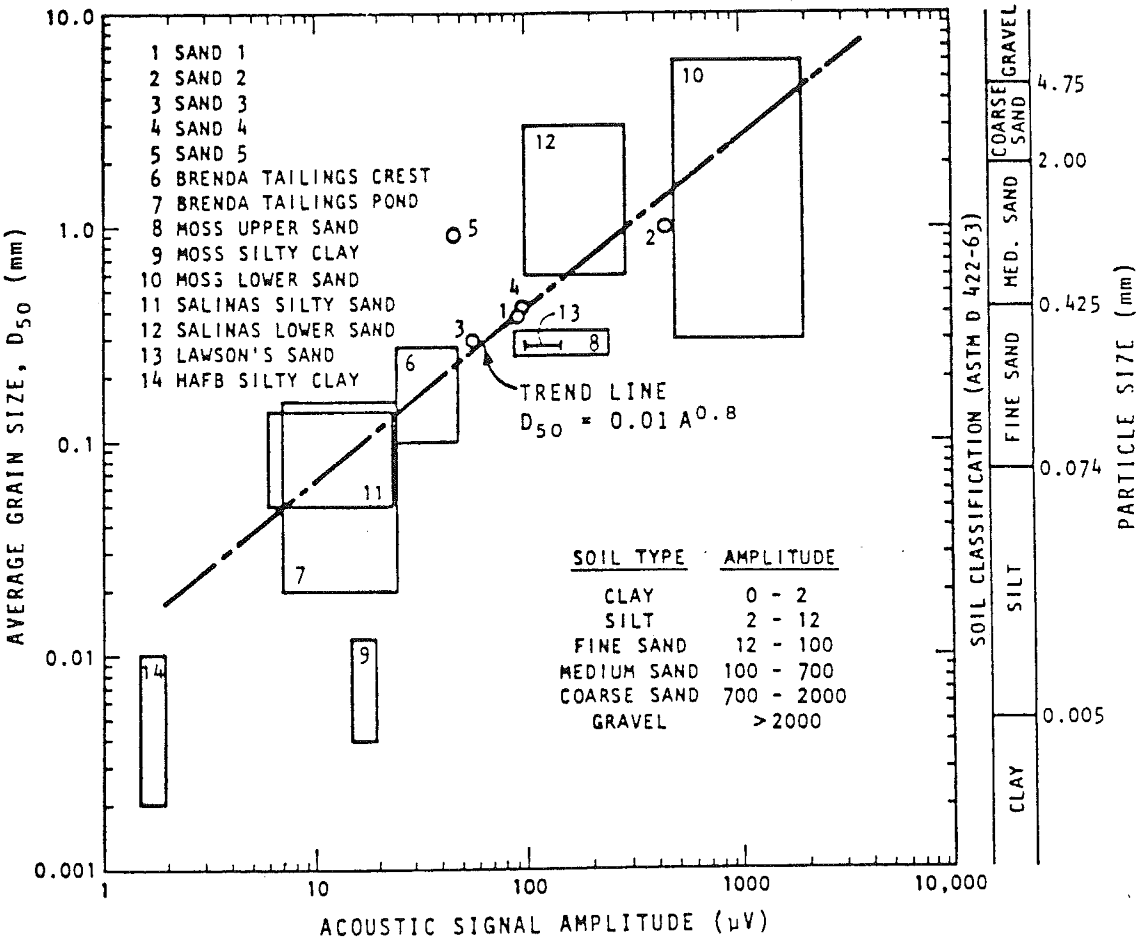


FIG. 9. CORRELATION BETWEEN GRAIN SIZE AND ACOUSTIC SIGNAL AMPLITUDE

OFFSET PANEL FOR LOCATING SHALLOW DRILLING HAZARDS

Thomas Fulton
Gulf Oil Exploration

INTRODUCTION

An offset panel of seismic data has been developed to locate shallow, high pressure gas zones which constitute drilling hazards. The offset panel displays six sets of common offset single channel data taken from a conventional marine seismic survey. The single channel profiles are displayed below one another and arranged vertically by offset and horizontally by common depth point. This arrangement causes effects due to near-surface geologic changes to generate geometric patterns that are different from patterns due to changes in seismic source or receiver.

The offset profiles can display reflections on the near traces, reflections and refractions on the mid-range traces and only refractions on the far traces, depending on both the actual offset and the velocity distribution.

The offset panel uses refraction data which are commonly muted by the processor. While reflections indicate the presence of near surface acoustic boundaries, refractions transmit these boundaries and may indicate velocity differences. Conventional marine seismic spreads may be as much as 3,200 m in length and may record refractions penetrating to a depth of about one fifth the maximum source to receiver offset. In a display of common offset refraction breaks, velocity differences in the travel path will alter refraction arrival time or amplitude or both. The offset panel organizes these differences to form predictable patterns by which the velocity anomaly can be identified. Patterns due to geologic changes are different from patterns due to changes in source or receiver.

FUNCTION

Solutions to interpretation problems can often be recognized if the data can be organized in such a way as to highlight certain interrelationships. Consequently with regard to both conventional multichannel reflection seismics and refraction displays we have developed an organizing method called an "offset panel" which rather than organize data on the basis of shot record, organizes by equal offsets. Figure 1 is an example of an offset panel display over a possible low velocity zone. The offset panel is constructed from near trace reflection data and far trace reflection/refraction data which are assembled below each other. Providing that no lateral velocity variations exist, the display from all the channels will be consistant, but, if a zone of differing velocity is encountered, then its effect will be felt by the various receiver groups at different times and hence at a different common depth point (CDP). Thus as the vessel and source move over a high velocity to a low velocity zone all traces associated with the source will be delayed. The lag will appear on the COP along the source diagonal. Separating the various traces vertically will have the effect of displaying this time difference along the track with the result that if the zone is sufficiently large with a detectable change in velocity, a pattern develops with a slope that indicates if the source or receiver is moving over zones of different velocities. Two effects can indicate that an anomaly exists. A refraction event from the furthest offset channels can be delayed as described above. The second effect is the delayed subsequent reflection with a decrease in amplitude. Figure 2 shows shallow, high amplitude events that are to be identified. Offsets of 825 and 1,300 m show the relative amplitudes of the events decreasing with offset and their location moving closer to the first refraction arrivals. At an offset of 1,775 m neither reflections with high amplitudes nor changes in the refraction breaks are apparent. Finally, at an offset of 2,250 m a decrease in the amplitude of the refraction becomes apparent. Near and far offsets of these data are shown in Figure 3. (The data appear different because of scale changes and because no deconvolution or filtering is used in that figure.) Idealized refraction paths 1, 2 and 3 are highlighted on the near traces. The traces representing these paths are shown at the 2,665 m offset. Analysis of the constant offset refraction breaks leads to the conclusion that paths 1 and 2 show delay and attenuation while path 3 does not. The high amplitude anomaly at the time of 0.53 seconds can then be identified as a low velocity because it delays the refraction breaks. The depth of the anomaly is about 400 m. The positive identification of this event as a potential hazard makes it possible to predict that deeper anomalies of similar characteristics are also hazards. Drilling results from a well positioned to avoid the anomaly at 400 m verified the presence of these hazards.

Sometimes we have the situation where the amplitude increases to a certain level for a particular offset and then decreases beyond a further offset. This would be interpreted as a thin high velocity layer an example of which is shown in Figure 4. The high velocity layer is assumed to be thin because no refraction events are seen at the furthest offsets. Finally the offset panel can be used to identify diffraction patterns from hazards that are close to but not directly beneath the seismic line.

CONCLUSIONS

The identification of shallow gas drilling hazards on the offset panel of conventional data is less subjective than with the high resolution hazards surveys because the identification is based on both high amplitude reflections and delayed refractions. The offset panel also allows better use of reflection phase and amplitude as a function of offset. The presence of hazards in a grid of conventional data suggests that the driller must either have great faith in his hazard interpreter, locate a well on a seismic line or shoot a hazard survey. The offset panel of conventional data can add significantly to the interpretation of shallow gas drilling hazards.

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Fulton, Thomas K., "Offset Panel Locates Shallow Drilling Hazards". Paper presented at the Joint SEG/China Geophysical Society Meeting, Beijing, China, September 1981.

Fulton, Thomas K. and Darr, K. Michelle, "Offset Panel", Geophysics, V. 39, No. 8, August 1984, pp. 1140-1152.

THE OFFSET PANEL: A POWERFUL ANALYTICAL TOOL

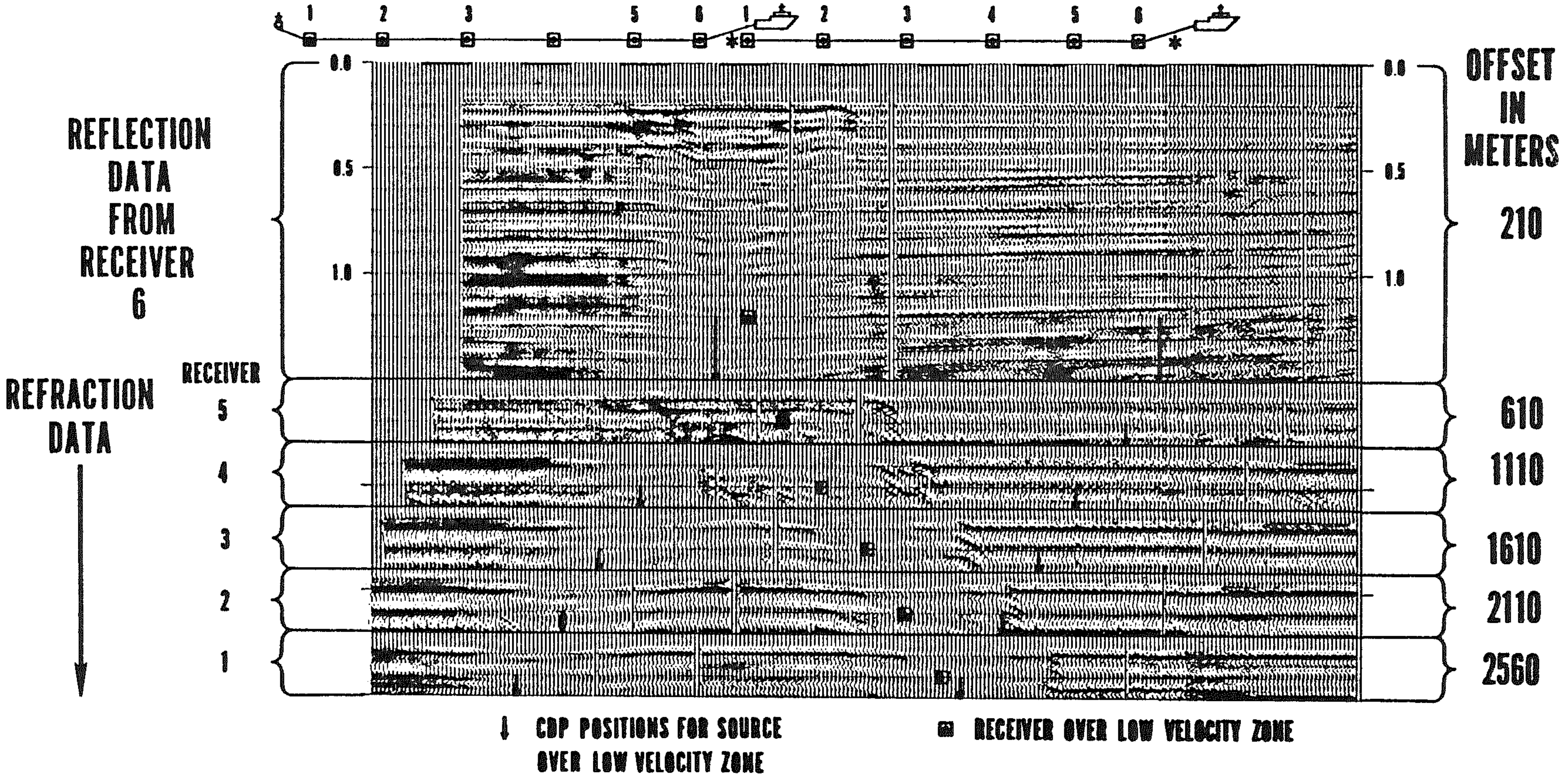


FIGURE 1

Offset Panel Display from a possible Low Velocity Zone

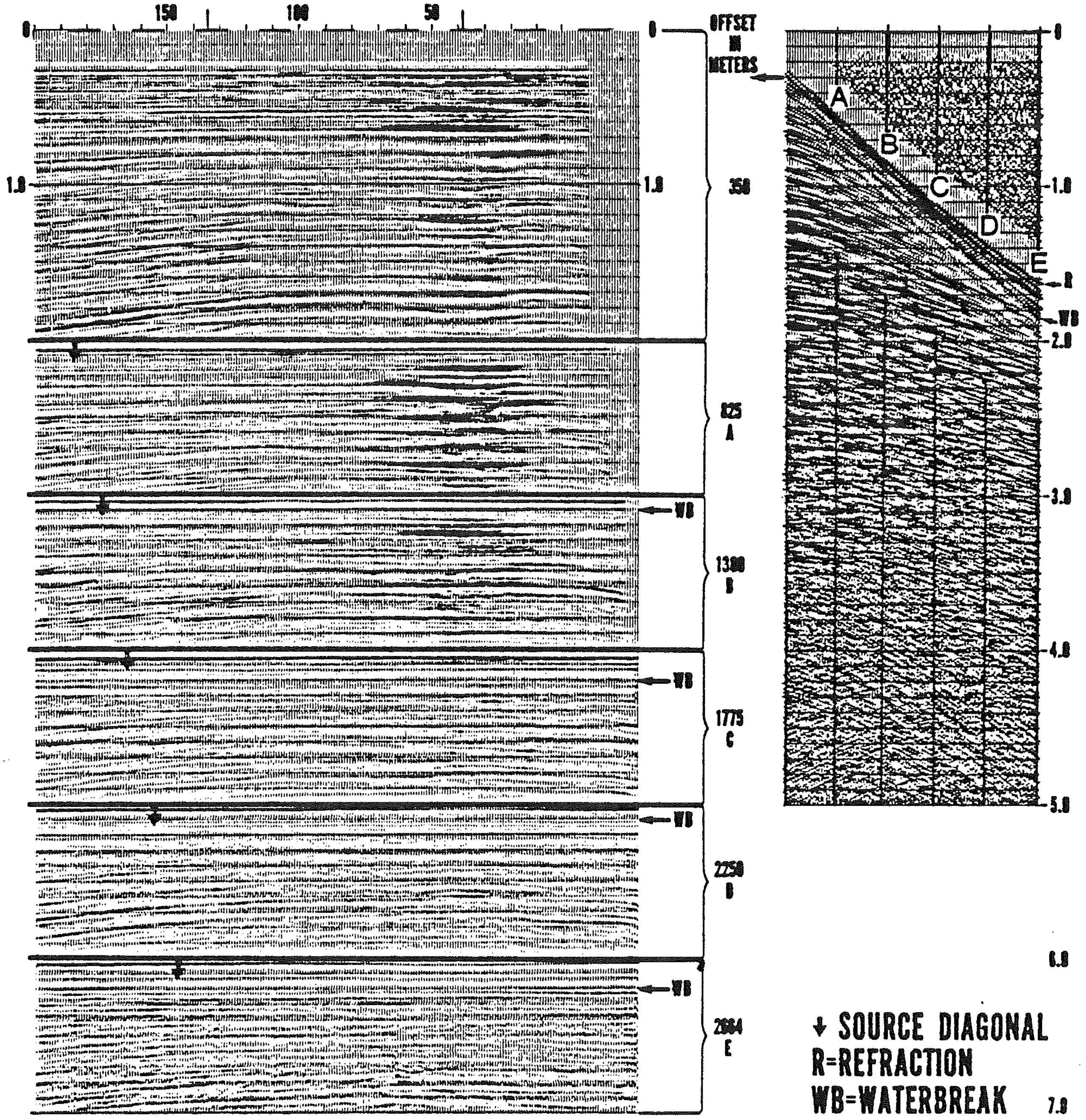
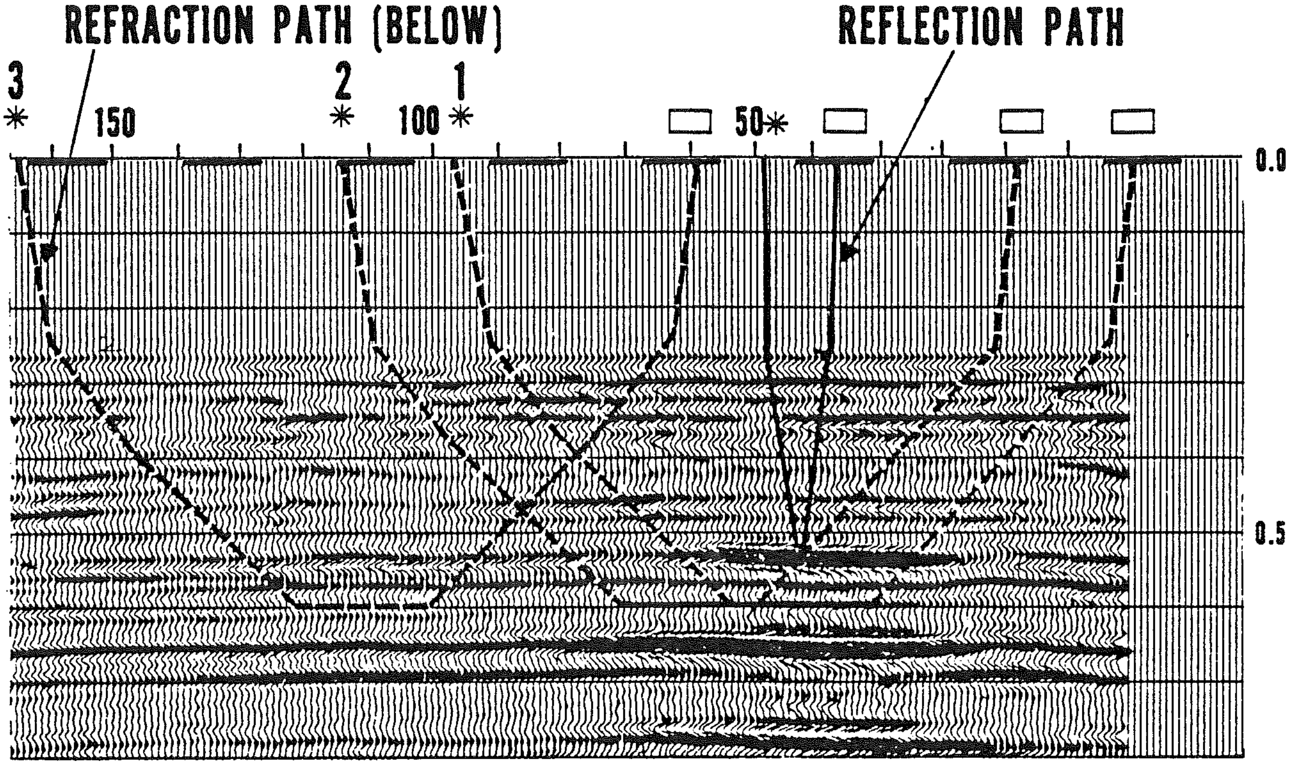

OFFSET PANEL: A DATA-ANALYSIS TOOL

FIGURE 2

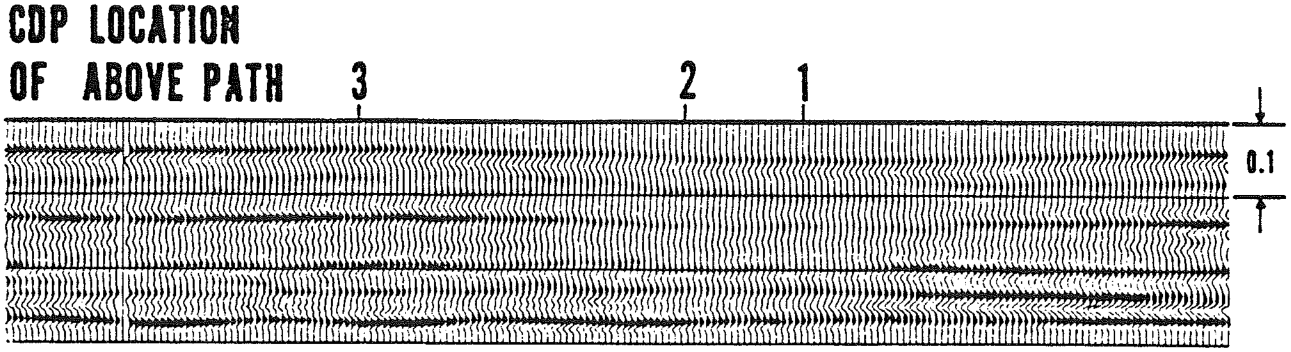
Offset Panel showing shallow, high amplitude event

HAZARD IDENTIFICATION

REFLECTIONS AT OFFSET OF 350 METERS



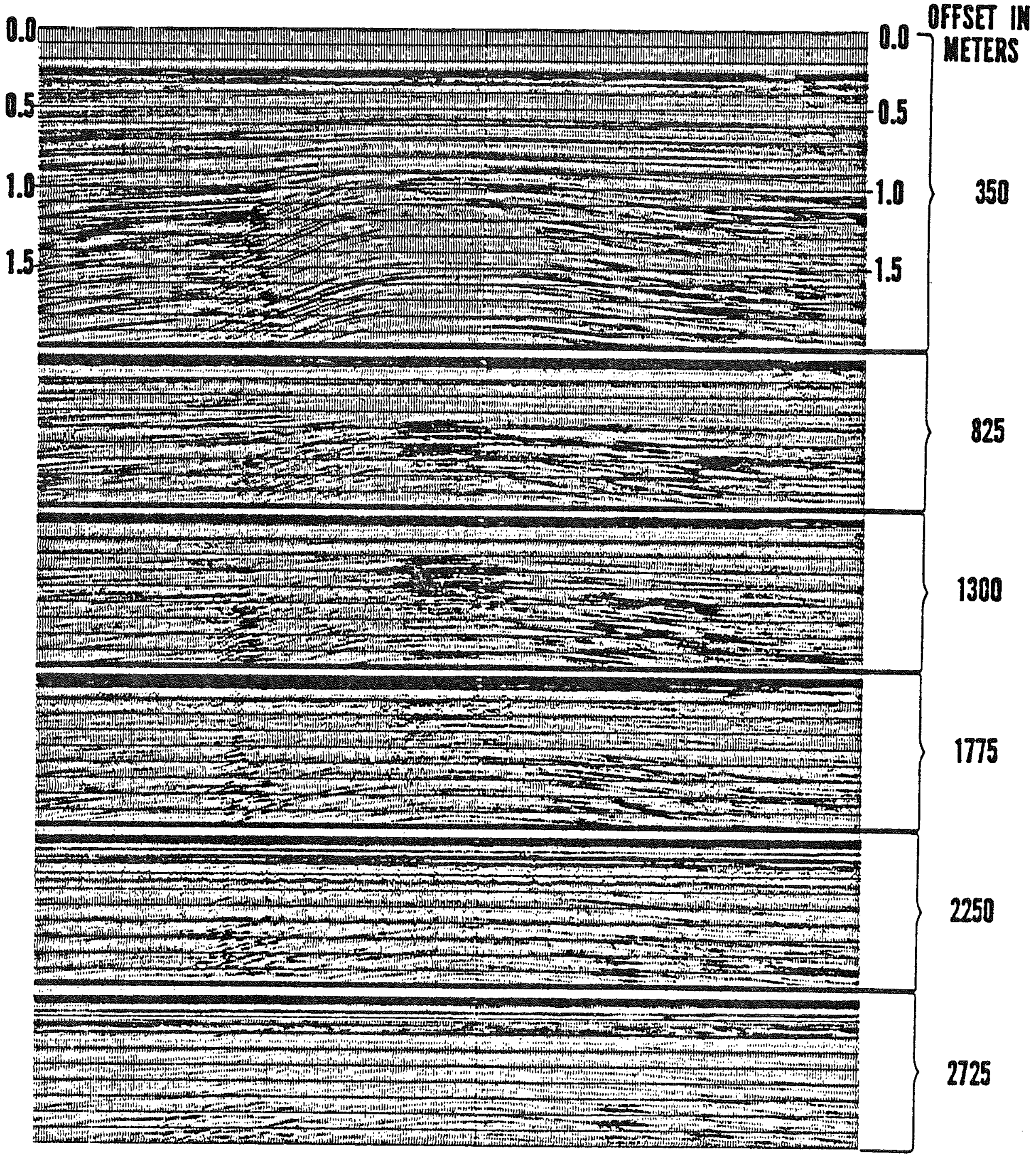
REFRACTIONS AT OFFSET OF 2664 METERS



∗ SEISMIC SOURCE ▭ SEISMIC DETECTOR

FIGURE 3

Near and Far Offset Panels from previous figure



ANOMALOUS AMPLITUDES SUGGEST THIN LAYERS OF HIGH VELOCITY SEDIMENT

FIGURE 4

Offset Panel of high velocity layer

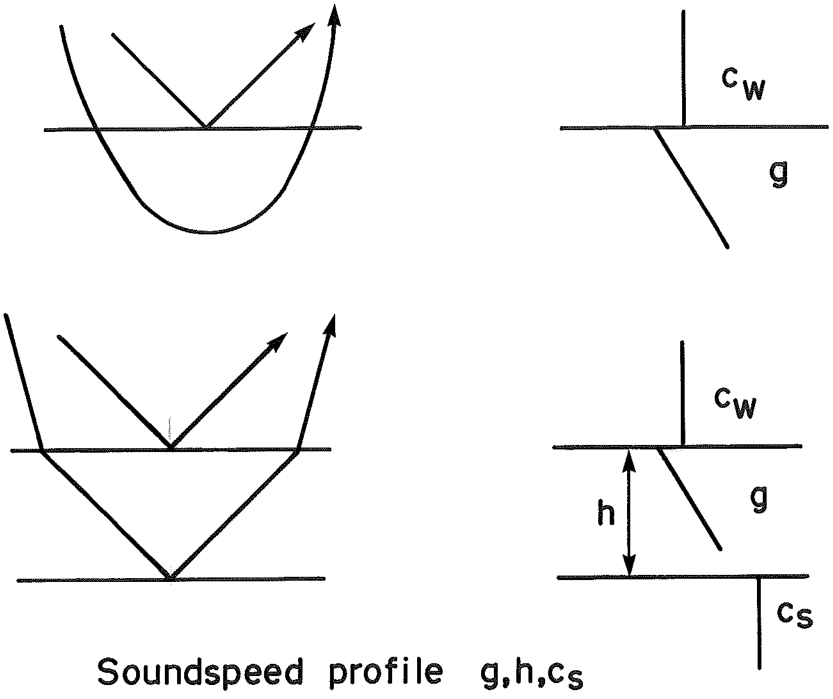
SHORT PRESENTATION BY ROSS CHAPMAN

DEFENSE RESEARCH ESTABLISHMENT PACIFIC

At DREP we are interested in deep ocean sediments and have developed techniques to measure sound speed profiles. We are presently continuing this work in order to obtain density profiles. Unlike the work being carried out by DREA (see Phil Staal's presentation on the first day of workshop), our main interest is in the effect of the ocean bottom on propagation in deep water. Most of our work has been conducted in the deep ocean and abyssal plain area and our interest lies in the effect of the upper 100 m of seafloor on propagation over distances up to 100 km. Our work involves wide angle reflectivity experiments using small explosive charges provided by the Navy. The main thrust of our processing procedure involves the deconvolution of the bubble pulse. The experiments involve two ships with a vertical array of hydrophones suspended within 300 m of the surface. We have developed a method using the L^1NORM which uses a replica of the source wavelet derived from the data itself. Following deconvolution we derive the ocean bottom impulse responses and then invert these measurements to give an estimate of the sound speed profile in terms of the sound speed gradient of the sedimentary layers. Two simple geophysical models are used, one is a half space of sediment with a constant sound speed gradient, and the other is a layered model where the layers would either be constant or with a gradient (see Figure 1).

Figure 2 is an example of wide angle reflectivity data following the deconvolution process. From this analysis we are able to determine the sound speed gradient and the ratio between the speed of sound of the seafloor and the sea itself. Another aspect of our work is the estimation of the plane wave reflection coefficient for a simple model. For angles less than the critical angle, a phase change in the reflection coefficient will be observed. We hope to measure where this phase change occurred and then estimate the density ratio at the seafloor. This method, developed by Doug Oldenberg at UBC, has been tried on reflectivity data collected from an area of silty clay in the abyssal plain region. The sound speed ratio and gradient produced by this method compares favourably with data given by Hamilton. Ground truthing is difficult, particularly in deep water. Some cores in the particular region have been collected by Jim Matthews from NORDA and again sound speed estimates agree favourably with those determined by the reflectivity method.

The advantage of the deconvolution technique lies in its speed and small storage requirement. In addition, it can be used on any type of seismic data.


a) Refraction Model

b) Reflection Model

Figure 1 Two simple geophysical models for Sea Bed/Acoustic Interaction studies

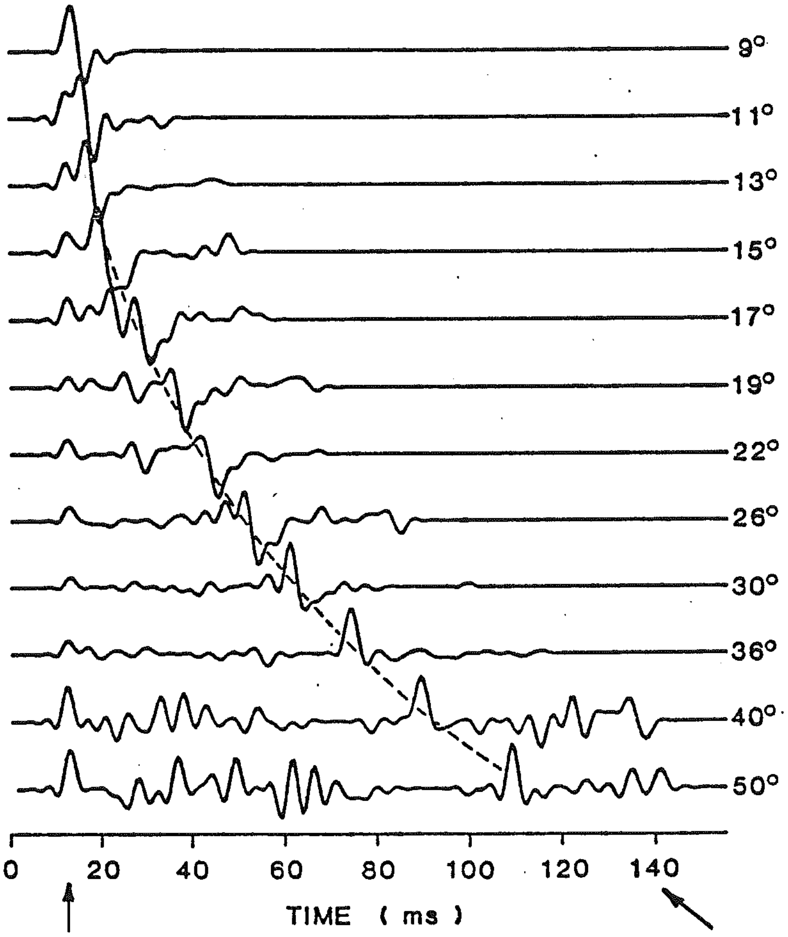


Figure 2 Wide Angle reflectivity data after the deconvolution process

QUESTIONS

Q. (from floor) I wasn't quite sure how you determined the sea floor gradient?

A. We used this model of the interaction and calculated the time differences between pulse A and pulse B (see Figure 2) and then we could parameterize that in terms of the gradient and the difference in the ratio of sound speed at the sea floor with sound speed in the water. We then measured from our data the arrival time differences versus grazing angle and plotted the results.

Q. (from floor) It's a question of are they really gradients or is really many fine scaled layers?

A. It probably is a fine scale layer. But in a low frequency sense I'm looking at a simple way of characterizing the bottom so that I can explain acoustic propagation. The simplest way of doing this seemed to be by using an average gradient. I agree that the sediment structure is probably much more detailed but Hamilton, for example, persists on measuring average gradients so our figures are not unreasonable.

COMMENT - FROM FLOOR

It's relevant to you because the sources you use are low frequency.

COMMENT - FROM FLOOR

If I understand Dr. Mayer's question correctly, you will start to lose your refracted arrival at about 300 Hz. Below 300 Hz, the refracted arrival accounts for most of the returned energy.

SEISMOSTRATIGRAPHIC ANALYSIS - BLACK ART OR LEGITIMATE DISCIPLINE?

Gordon B. J. Fader
Atlantic Geoscience Centre
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

As a Marine Geologist with the Geological Survey of Canada, I have been involved in the so-called "Black Art" of interpretation of high resolution seismic reflection data for the past 15 years. During this period "seismic stratigraphy" has emerged as a legitimate discipline and taken its place with lithostratigraphy, biostratigraphy and chronostratigraphy, as one of the essential tools in the study of earth processes and materials.

This has largely been driven by the exploration for hydrocarbons and has resulted in the development of sophisticated computer processing techniques for seismic data. The techniques have largely been targeted for deep multi-channel seismic data and the shallow, engineering, high resolution information, of particular interest in hydrocarbon development projects, has been largely neglected.

In this presentation I would like to explore the problem that many in the engineering community apparently have in accepting the "Black Art" interpretations of high resolution seismic reflection data by the geologist. On any given research or development project it is ultimately the geologist who is charged with the responsibility of describing both regional and site specific earth processes that have given rise to a wide variety of geotechnical conditions of the earth materials involved. To these purposes, the geologist relies on a wide variety of techniques and analysis such as textural, lithological, stratigraphic, magnetic, gravity, biological, structural, environmental and age dating, to provide a data base from which a reliable model or process interpretation can be made. Usually these results are extrapolated over the survey or project area through a network of seismic reflection profiles. In this manner the geologist can identify the geological processes that have taken place and the resultant sediments (rocks) and their characteristics that have arisen in response to these processes over a broad regional area. Herein lies the sources of the weakness as seen by the site specific engineer.

At this stage of interpretation the geologist (who generally has a lack of intimate knowledge of acoustics and physics) is seen referring to reflections on seismic profile as "beds or particular geological events". What is missing is the correlation of the litho-bio, and chronostratigraphic data (previously obtained through exhaustive sample analysis) with the seismic reflection data, and on which such statements are based.

As often is the case, project reports only refer to the seismic reflection data base through a poorly reproduced seismic profile that consists of interpreted geological labels overlying a section that is barely convincing. To help prevent such misunderstandings and elevate the legitimacy of the so-called "black art" of seismic interpretation, the geologist or geophysicist must present the seismic data analysis independently before correlation. The reflection profile interpretation should include such quantifiable characteristics as presence or absence of coherent reflections, amplitude, continuity, spacing, relief, structural form and boundary relationships and these must be tempered in terms of system specifications and data processing. In addition ample reference to published, interpretated acoustic signatures would help provide additional support.

For much of the east coast Canadian continental shelf, this approach has been adopted for mapping seafloor surficial and bedrock geology by the Atlantic Geoscience Centre, Geological Survey of Canada. This research has resulted in a suite of offshore geological maps (Figure 1). With the development of the Huntec Deep-Towed Seismic Reflection System (DTS) considerable subsurface detail has been provided and a quantified estimate of seafloor reflectivity obtained. The surveys are conducted on both regional and site specific formats and the data obtained has provided the framework for most of the offshore hydrocarbon development engineering underway for both the Venture and Hibernia Development Projects.

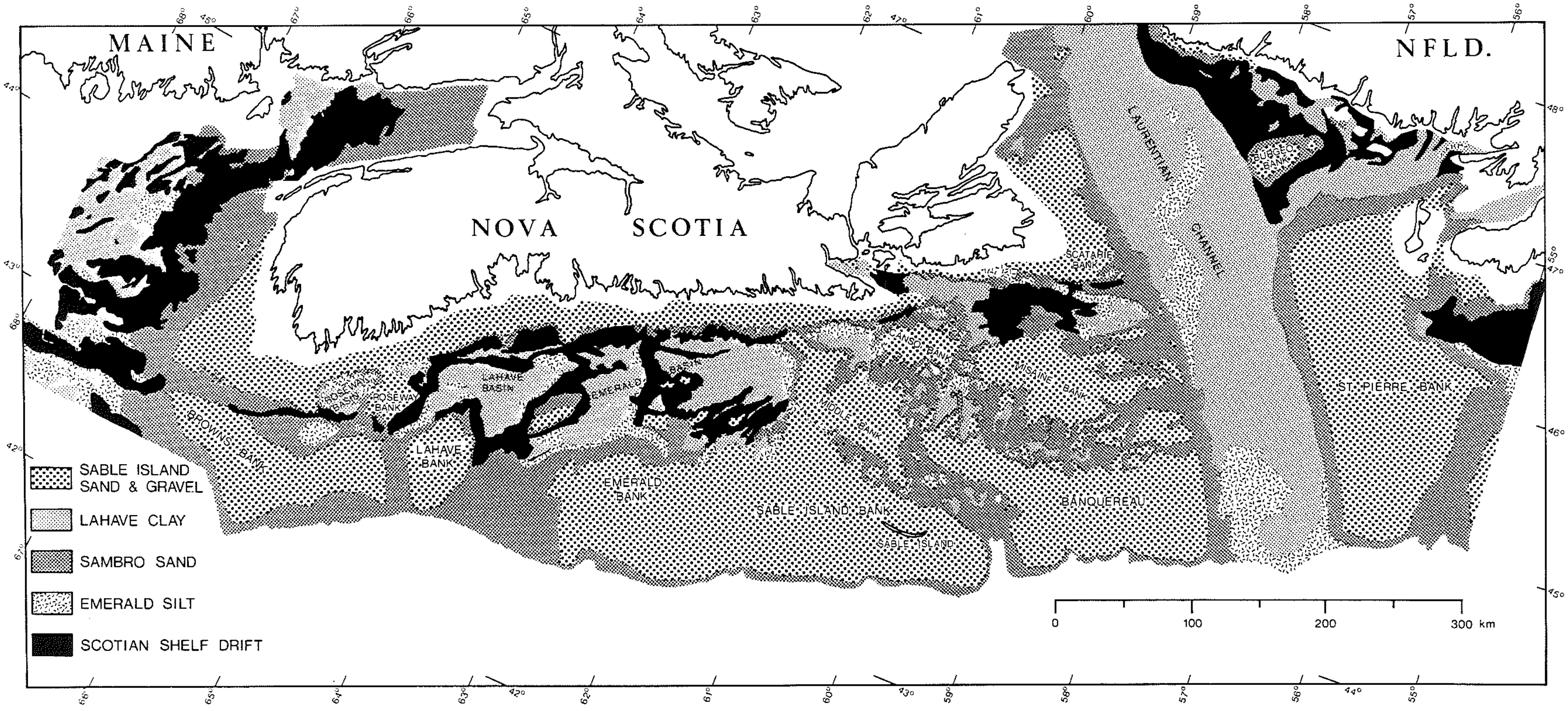


Figure 1 SURFICIAL GEOLOGY OF SCOTIAN SHELF AND ADJACENT AREAS

REVIEW OF FIRST DAYS PROCEEDINGS

W. Roggensack
EBA Engineering

I was asked to participate in this workshop as a non-specialist with a geotechnical background to evaluate the extent to which today's speakers appreciate the problems encountered by geotechnical engineers in understanding geophysical data. From what I have heard today, with all of the doubts regarding systems and instrumentation, recording and processing techniques, and correlations; geotechnical engineering must now look like a precise science. One aspect that I was able to extract from David Caulfield was that without "ground truth", interpretation of records is always subject to a high degree of uncertainty. As a geotechnical engineer, we still have to put down borings, take samples and do in situ tests. Alisdair McKay showed very clearly that you can generate a signal or a record from a wide variety of stratigraphies and that very major changes in the velocity profile with depth often produces only subtle changes in the record. This tells us that we must in all cases have a few points of reference upon which an interpretation can be based and against which it can be tested.

The acoustic techniques seem very well suited to detect changes in sediment properties. I would suspect that these changes must invariably correlate well with facies changes and perhaps the directions we've often taken in trying to come up with exact numbers of density or porosity, or some of the other soil parameters, are premature. Perhaps our intention should move more to detecting lateral variability in a unit and using that as an indicator of changes in depositional facies.

The indications from the deep exploration work are that we have to look very carefully at the techniques being employed to make sure we're not destroying or eliminating the very information that we want the most. Again, from a geotechnical engineer's standpoint we have tended to accept and rely upon geophysics in the marine environment. I'm not sure whether this is out of desperation and frustration or whether we truly believe in what we're getting. We even use the results occasionally in geotechnical analysis and design, of course backed up by sampling and testing. Nevertheless, we can look at the geophysical records and obtain an indication of site variability, and of events that might suggest to us that we should attempt to optimize the location of something like a pipeline or an offshore structure. For instance, the last thing you want to do with a gravity structure is straddle a channel; and channels are fairly well defined on the geophysical records. The question that comes to mind immediately then, is: "If we generally accept geophysical techniques offshore for incorporation in the geotechnical design process, why have these techniques not been used and adopted to a wider extent offshore?" Certainly the cost would be lower onshore and my conclusion is that onshore, when an engineer can look at air photos and walk around on a site, he or she, generally has sufficient confidence on what's below the ground that they do not feel that geophysical exploration is warranted. In many instances offshore, the geophysical records have been wrong or wrongly interpreted and bore holes often don't tell the full story. Time and time again we find that moving just 100 m this way or that can produce significant changes in soil conditions that would have a major impact on the design and costing of the structure.

Many contributors to this workshop were talking about acoustic properties and it surprises me that greater effort hasn't been made into attempting to correlate those acoustic properties with some of the more fundamental geotechnical parameters. We base most of our practice on the concept of effective stress. It deals with the component of stress that is equal to the geostatic stress minus the pore water pressure. The premise is that the portion of stress taken up by the water is not felt by the soil skeleton. Hence, the soil skeleton responds to changes in stress and responds to that effective stress from the standpoint of shear strength and deformation. Even if we're dealing with very small deformations as in the passage of a compressional wave it appears that perhaps some of the empirical relationships we've seen today could be readdressed and assessed more carefully in terms of an effective stress framework. In order not to lose sight of what the end user would like to do with geophysical data, I've listed a few things:

1. The use of geophysics in a presurvey to allow anticipation of geologic hazards such as gassy sediments, near surface faulting, ice scouring, channel infilling, etc.
2. To replace our air photos in some of the assessments of bathymetric or micro-bathymetric features in berm construction where the roughness on the surface is a factor that has very major structural implications.
3. As mentioned previously the use of data to optimize site locations and also to assist in selecting boring locations relies upon some preliminary interpretation usually involving people with expertise in this particular area.
4. From my viewpoint, the most important requirement is to develop methods of assessing lateral variability or continuity of both stratigraphic and structural features. Impedence may be a possible parameter to use for texture or stress state studies.
5. The inference of selected properties is another problem that relies on a high degree of empiricism but there is an indication that good correlations between lithology and to a lesser extent inferred velocities can be made with stiffness and strength data.

6. Although gas in entrained sediments were not seriously discussed today there was an indication in one of the profiles of a near surface, low velocity layer which is tied to the presence of gas bubbles in pore spaces. Reference was made to the use of nuclear magnetic resonance to obtain measurements on unfrozen water content. I would predict that a good correlation between the percentage ice bonding, or unfrozen water content would occur with the acoustic properties.
7. Time domain reflectometry may be of use in the field with respect to logging permafrost samples immediately on collection.
8. Finally, although geophysics may benefit the consultant a drilling contractor may think otherwise. The last thing he wants is a reduction of his services.

Geophysical surveys are generally of two types, a linear investigation consisting of a single or series of parallel tracks for a pipeline corridor, for example, and a survey with a dense coverage in the form of a grid for offshore structures, etc. Some of the parameters that we seek are lithology, density, shear strength of material, rigidity or deformation characteristics and permeability. Recognizing that we are dealing with small strains, I think that these parameters will result from correlations and inferences rather than by direct means. Secondary factors would include detection of sediment gases, improving our ability to define seabed topography, looking at the definition and identification of stratigraphic and sedimentary structures that could suggest depositional facies, and finally, detecting the presence of permafrost and ice bonding. The interpretation of these secondary results requires some knowledge or assumptions regarding the primary components, presently this is acceptable.

Most of the acoustic response appears to be tied up in impedance and velocity which are not independant. If we adopt KS^m as an expression of shear modulus then it is clear that for a given soil we do have an increase in shear modulus as effective stress increases. With regard to the shear modulus changes with time; we have an initial stress and apply an increment of total stress. As pore pressure dissipates, the shear modulus increases with time and curves at about the point where materials reach the end of their respective primary consolidation. In a sand, drainage occurs rapidly and little or no change is seen. The over consolidated clay is stiffer and consolidates more rapidly than the normally consolidated clay. Effective stress plays and important role in determining some of the acoustic properties that have been described today.

SUMMARY AND REVIEW OF SESSION

Denzil Taylor-Smith
University College of North Wales

One of the main problems faced by the geophysicist or acoustician working in the geotechnical field, as has already been pointed out by Bill Roggensack, is that of marketing his techniques to the Civil Engineer. The engineer requires some material properties which he can use with confidence in his design; regrettably, little of what has been said today would inspire such confidence. Compressibility, permeability and isotropy - parameters of some importance to the engineer - have only been briefly mentioned. A major problem in foundation design is the ability (a) to recognize that preferred orientations exist within the foundation material, (b) to measure the relative magnitudes of the directional properties and (c) to incorporate the acquired data into the design so as to counter preferential failure directions. Today we have heard a great deal about complex instrumentation and signal processing - Roger Hutchins even made mention of beam pattern control - but unless we can study seismic propagation in orthogonal directions we cannot offer a geophysical solution to this important problem in civil engineering.

I imagine that some of our difficulties arise out of the general availability of high power computers leading to a near-obsession with geoacoustic models. Such models, in order to proceed easily through the computer, require that average values of the properties are designated for the various media. Alisdair McKay has illustrated the possible pitfalls in such procedures leading to a number of models representing the same geophysical data. What is often overlooked is the fundamental physics of the problem in hand. Thus the seismic determination of, say, a soil's compressibility may have little relevance to the compressibility required by the design engineer because of the different physical situation. Jim Hunter commented that the geophysical quantity is often 2-3 magnitudes greater than the quantity derived by traditional means (see Figure 1) - but is this comparing like with like? The seismic determination is carried out rapidly at a low strain amplitude whereas the traditional test (say an oedometer) can take days and has a high strain amplitude; the former is in effect an "undrained" test while in the latter drainage of the pore fluid takes place. Most certainly like is not being compared to like. Again the seismic determination of the particular modulus is based on perfect elasticity theory whereas soils are poroelastic or viscoelastic or even plastic. In fact if Biot's equations for stress-strain relationships and wave propagation in a porous medium are used, where permeability becomes an important parameter, the static-dynamic relationship begins to make some sense. In fact it is in this area - the solution to the Biot equations - that the improvement in instrumentation to give better determinations of the seismic velocity will have its main reward. Although if Dr. C.I.D. Green (Shell, The Hague, Holland) were here he would argue against an over-elaboration in instrumentation: his recent trials seem to indicate some doubt about the use of long arrays for investigations of near-bottom sediments where short arrays or even single hydrophones give more meaningful results.

Another subject that has not been addressed today is the effect on material due to biological action. Do burrowing organisms strengthen or weaken a seafloor sediment and what is acoustic propagation like in such a medium? In a similar vein, I was impressed by the work on definition of depositional environments, such as Larry Mayer's paper on carbonate variation, as well as those on permafrost. While this work may seem to be only of academic importance, undoubtedly the type of the depositional environment, along with its level of biological productivity, is of considerable engineering significance but one which we know so little about.

One common theme today has been that of "ground truth". The engineer consistently thrusts this idea at the geophysicist: that the ultimate interpretation of the geophysical data is "ground truth". I think it is time for the geophysicist to throw back the idea at the engineer, that there has to be ground truth in engineering also. For example, geotechnical site investigations always specify that strain levels should ideally be around 10^{-2}, largely because traditionally this amplitude was the strain induced by their tests. But surely there should be a better reason than this? Should not the ultimate "ground truth" be building performance? And would not the latter specify the strain level of the test required?

In my own particular field I have been associated with a large number of comprehensive site investigations for the design of nuclear power stations. These structures are heavy and, because of this, each has a large base area somewhat akin to gravity base hydrocarbon production platforms.

In the limited number of sites for which data are available, the geophysical values (similar to those shown by Dick Campanella) agree well with the building performance. This comparison is made by a "back analysis" of the performance, thus providing a variation of the rigidity modulus G with depth. It seems that for such large structures the relevant modulus is G_{max}, a quantity easily provided by measuring shear wave velocity in the medium. Figure 2 shows a comparison at one depth level between building performance and G obtained by all the tests. It may well be of course that for these structures with a large base area the ground behaves elastically, within the elastic limit, which ensures a good seismic comparison whereas the high strain amplitudes induced by the traditional tests are a result of soil failure under an elastic or even plastic conditions; so far it does seem that the performance of a building can be defined better by a Biot poro-elastic type of theory than by other methods of analysis. More work needs to be carried out to prove this, and I recommend this to you.

Another problem which we have little experience of and which has not been discussed today, concerns the geophysical assessment of pile performance. Piles in the North Sea are often driven to 100 m below the seafloor in comparable water depth and, with the possible exception of wire line measurements, cone penetrometer and pressuremeter tests rarely go beyond 30 m. There is a need therefore to assess the rate of penetration of the pile and its subsequent performance to the full depth of interest. One relevant parameter required is the variation of soil stiffness with depth which can be determined if the rigidity modulus is known. The latter can be given if shear wave velocities are measured and the depth variation of these calculated. But this requires some sophisticated seabottom seismic instrumentation and data processing not yet available.

Sophisticated instrumentation is also needed for an associated problem: the location of very thin bands of clay in otherwise sandy competent beds. The clay layers are of the order of 2-5 cm in thickness and these are potential hazards for they become failure surfaces along which the foundation can slide. The identification of these slip surfaces poses a considerable instrumentation resolving power, to recognize the impedance mismatch and to measure the seismic contrasts involved. While the instrumentalists and the signal processors have obliquely touched on resolution, in their considerations of pulse length, bandwidth, etc.; in our discussions today, the requirement to achieve recognition of this very real problem in marine geotechnics at all depth of interest does involve a new generation of instrumentation. But how magnificently such instrumentation would heighten the respectability of geophysics in the engineers' eyes!

QUESTIONS

Q. At what depth were you seeing those thin bands of clay?

A. About 30 to 40 m.

Q. How thin are they?

A. About 3 - 4 cm.

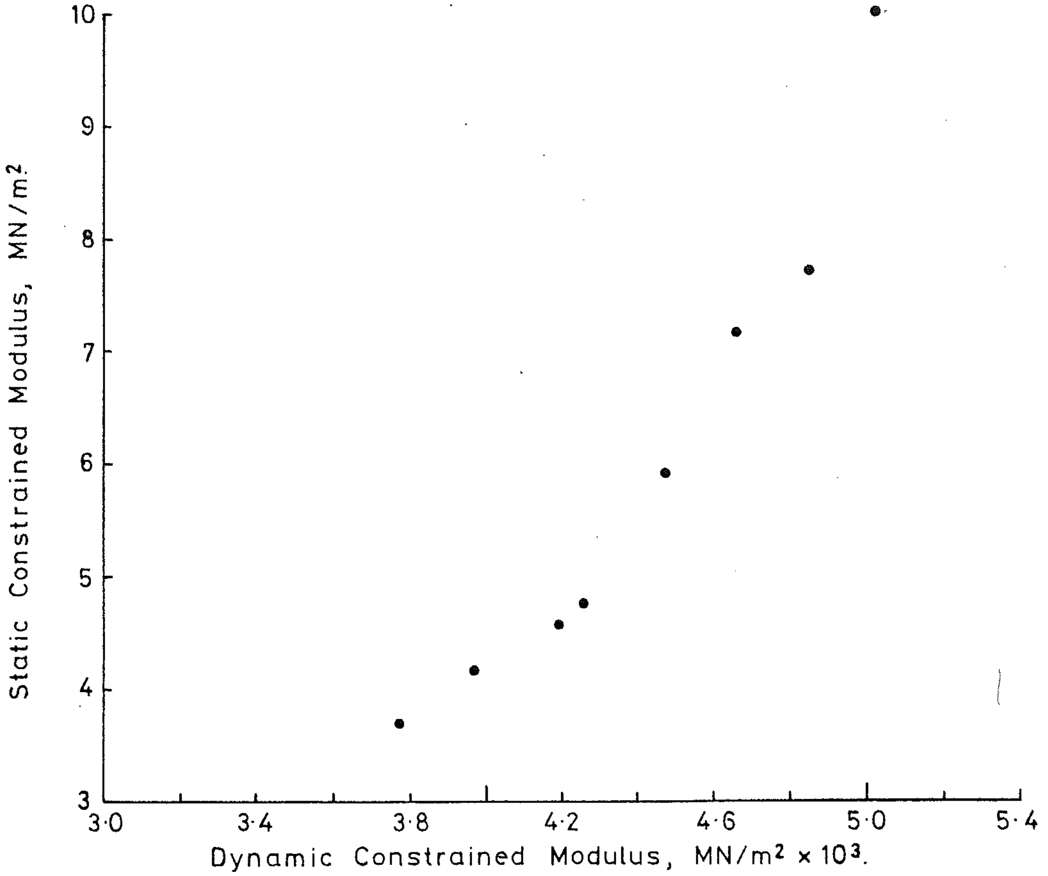


Figure 1 Static Constrained modulus D, for seafloor clays and silts compared to the same quantity determined by elastic theory from sea bottom acoustic measurements (D = v^2)

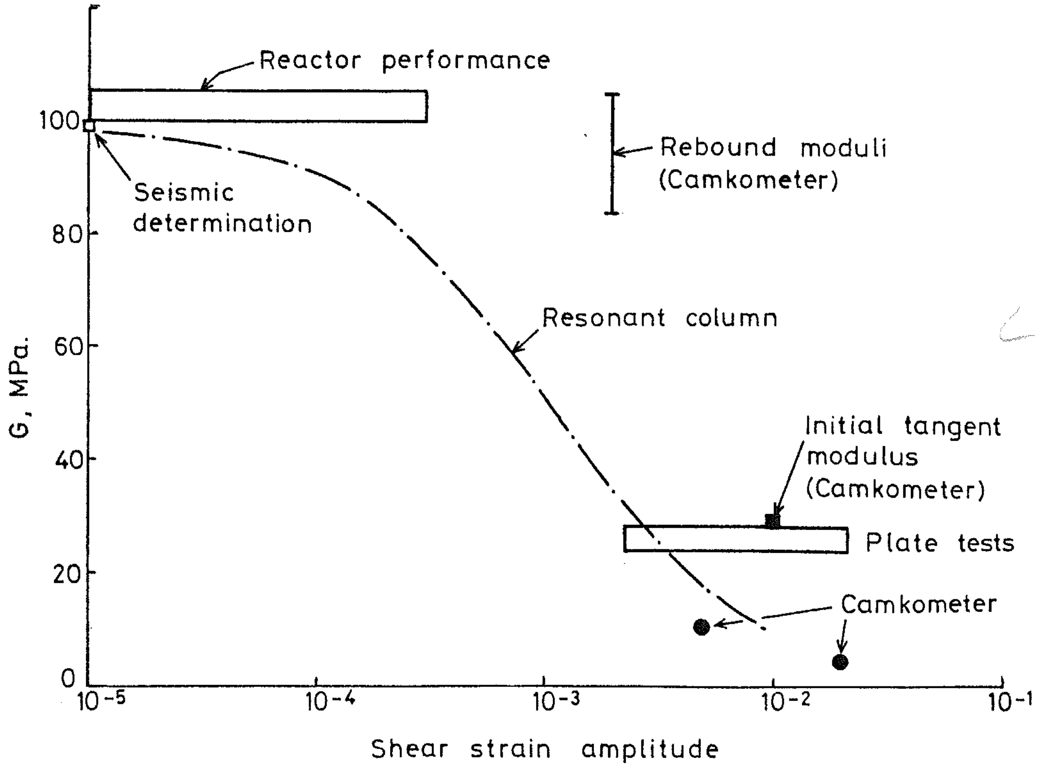


Figure 2 Rigidity Modulus - strain amplitude relationships for various testing procedures compared to building performance.

DAY 2

INTRODUCTORY PRESENTATION BY DR. STEVE BLASCO

GEOLOGICAL SURVEY OF CANADA

In Day 2 of this workshop, we shall address the problems of deriving acoustic properties from a seismic response and also discuss the significance and reliability of interrelationships between physical, geotechnical and acoustic properties of natural sediments. We hope that this morning's discussion will provide the opportunity for geotechnical engineers to express their desires as far as their requirements for engineering properties are concerned. By the end of the day, we expect to have a better understanding of the status of present technology together with an idea of future needs and priorities.

As far as the Geological Survey of Canada is concerned a project called "The Geotechnical Evaluation of Seafloor Sediments in the Southern Beaufort Sea" commenced earlier this year and presently the field program is in its final stages. Engineering geologists, geophysicists and marine geophysicists from various branches of the GSC and from other agencies and universities were involved. The project can be divided between geophysical and geotechnical aspects and the major portion of the geophysical work was carried out by Sue Pullan and Jim Hunter of the GSC who are present at this workshop The first major task was in surveying the boreholes between Pullen Island and Hooper Island. In total, 22 boreholes were drilled and surveyed. The majority of the 22 boreholes were drilled to a depth of 20 m, however, one borehole was extended to 25 m and one to 40 m. The borehole locations were chosen in areas that have been previously studied and that were likely to be of interest to the industry at large. This proved a difficult task in light of the prevailing conditions. Geophysical measurements included <u>in situ</u> equilibrium temperature measurements, <u>in situ</u> thermal heating experiments to obtain an indirect estimate of ice content and uphole seismic measurements. Seabottom refraction seismic experiments provided sound speed estimates.

The geotechnical and engineering geology work was divided between the Terrain Science Division and between the Atlantic Geosciences Centre. Their responsibility involved logging the core stratigraphy in the field and subsequently conducting sedimentology via stratigraphic and geochronological analysis in order to compare the results with the existing offshore stratigraphic model.

Other work included field and laboratory measurements of the geotechnical and physical properties of the core samples and a field program to evaluate the water regime in the MacKenzie Delta area. Of particular interest here is the effect of the fresh water plume on the permafrost of the area.

The second part of the geotechnical program, which was carried out by the Terrain Science Division included drilling and interval sampling of the borehole. Field measurements of the acoustic properties were obtained followed by laboratory measurements which included shear wave and uniaxial compressional tests. Future laboratory tests will include density, moisture content and also triaxial tests.

Another aspect of this work was a study of the effects of transportation and handling of the core samples. This involves repeating field measurements under laboratory conditions at a later date.

The long term goal of this program is to correlate the geotechnical data with the acoustic data obtained from both direct measurements and from seismic and refraction programs. It is hoped that the data will be released by the end of May this year, however, some of the laboratory measurements will not be available for some time.

INTRODUCTION - DR. LARRY MAYER
DALHOUSIE UNIVERSITY

We have chosen to divide the discussion into two aspects. This morning we are going to discuss our ability to go from a seismic response, basically a voltage representing pressure as a function of time, to acoustic parameters with acoustic impedance being of particular importance. This afternoon we will look at our ability to go from acoustic parameters, assuming that they can be measured, to physical or geotechnical properties. Although many of us yesterday talked about normal incidence reflection techniques and resulting observations, we have to look at our ability to measure other properties directly. For example, a compressional velocity rather than measuring just acoustic impedance or measuring shear velocity, attenuation and similar parameters.

I think we should set some constraints on the panel's input and turn to the users (guests) in the workshop and ask the question: "What kind of resolution is needed?" This was mentioned yesterday by Denzil Taylor-Smith. A good place to start may be to ask the question: "What constraints can be placed in terms of vertical and horizontal resolution, and penetration in order to distinguish between two events, and over what area can spatial averaging be realistic?" Denzil Taylor-Smith suggested yesterday that he would like to see 4 cm resolution at 30-40 m depth. Can we attain this figure?

Q. (from Roger Hutchins to Denzil Taylor-Smith) What is the horizontal extent of these features?

A. Up to 20 km but locally they could be 500 m in extent. I think Jacques Guigne said yesterday that he is working on a system that will do that.

COMMENT - ROGER HUTCHINS

I think this is highly unlikely, primarily because if you are talking about normal incidence reflectivity, in order to resolve layers that are 4 cm thick you'd need a very high bandwidth. This is not the same as high frequency, a portion of the bandwidth of a signal that is frequently lost. I see very little hope in doing this except possibly by pure brute force methods. The advantage of Jacque Guigné's method is based on the fact that it uses a parametric source and the compelling advantage of a parametric source is that it has no minor side lobes and consequently the volume of the sediments which are insonified is small. Thus the reverberation or back scattering level is greatly reduced over what it would be using any other source. I think it is unlikely that sufficient penetration using frequencies in excess of 10 KHz will be achieved.

Q. (from floor) Is this problem unique to the North Sea?

A. (Roger Hutchins) I think there is another problem in the North Sea involving the detection of sand lenses prior to piling operations. We are talking about a point of refusal at 40 m depth and identifying sand lenses which are relatively small in the horizontal sense. Here we are looking for sand within a clay and detection may be possible, but the inverse situation, of a clay within a sand, is more a problem because of the scattering involved.

A. (Jim Mitchell) There is a related problem that I have heard about. It is a clay within a clay. There has been much discussion and a small amount of data that suggests that maybe at a depth of between 15 and 20 m within overconsolidated clays, there can be a layer of quite soft clay. The cause of this situation is thought to be either thawing permafrost, gas or whatever and it is not clear whether it really exists. But there is some evidence to suggest that it does. I wonder if these (geophysical) techniques might reveal the presence of such a condition, where the shear modulus would drop perceptively at a depth of several metres. In this case, water depths are 30-40 m.

Q. (from floor) How thick is the soft clay?

A. That is not clear either, but it may be a couple of metres at the most.

Q. (from Denzil Taylor-Smith) Supposing that we have these clay layers in a sandy matrix, what would be a size that could be detectable?

Q. (Roger Hutchins) Bandwidths of 10 kHz correspond to a resolution in the order of 10 cm. To what depth in sand can we get sufficient energy at this frequency?

A. The loss mechanisms are pretty high.

Q. What is the attenuation at 10 kHz?

A. (Jacques Guigné) It would be around an average of 0.2 dB/kHz/m. This figure ignores scattering.

COMMENT - ROGER HUTCHINS

If there is any hope of achieving the specification then I think that a parametric source offers the best potential because the beam geometry does not change with frequencies and these kind of frequency bandwidths can be obtained. The beam geometry is a second order effect.

COMMENT - LARRY MAYER

I don't think the parametric source is going to get round the problem of attenuation. In a sandy area you are going to have to use brute force to get the signal down there.

COMMENT - JACQUES GUIGNE

One thing that I think we should clarify is that this problem occurs at a particular location. If that is the case you could place a parametric source in that location and ping for one or two hours. Evenutally the signal to noise ratio would increase and you may have enough energy to penetrate through sand. In considering clay, I don't think any of us here has the answer. Certainly, we can test a system fairly easily in a model situation with a layered sediment structure and record the sediment's response. In this way, I think you can derive some of the answers to the above questions.

COMMENT - ROGER HUTCHINS

I would like to challenge that last statement. Just on the simple point that you cannot average for two hours because any incoherent noise or incoherences in your averaging process reduces the resolution of your stack. This would result in a loss of high frequencies. Also, you cannot hold a source stationary with a sufficient accuracy over a long time period. So you are probably talking about stacking a hundred pulses and this may result in the same limitation that you have in a chirp sonar, that is time bandwidth product limitation due to velocity anomalies in the medium itself.

COMMENT - FROM FLOOR

Perhaps a closely spaced areal array could increase the resolution. We've seen very high resolution produced with very small signals in satellite imagery by simply increasing the array size.

COMMENT - ROGER HUTCHINS

Increasing the receiving aperture would reduce your bandwidth.

COMMENT - LARRY MAYER

I'd like to continue on the point of bandwidth for a moment because figures like 10 kHz bandwidth for a boomer source are frequently mentioned. Bandwidth has many definitions and when I talk about bandwidth I refer to the -3dB point.

COMMENT - ROGER HUTCHINS

I refer to the bandwidth of the boomer source with a whitening filter. The rate of roll off in the high frequency components of the spectrum from the boomer is slower than the rate of roll of the ambient noise so a whitening filter can increase the effective bandwidth of the source without degrading signal to noise. I'm not saying that the boomer is a solution to this.

Q. (from floor) I'm wondering what is the difference, in terms of time and costs, when using a parametric source versus taking a core sample?

A. (Jacques Guigné) I think that when we're talking about penetrating 30-40 m through glacial till, then using a passive acoustic device is by far cheaper. We have experience of this in areas off the east coast of Canada, for example in the Straits of Belle Isle where drilling costs of millions of dollars have been involved in collecting 20 cores of limited length. Simple over the side piston cores will not be adequate. Certainly with layers mentioned earlier the most realistic approach is some type of remote sensing.

COMMENT - LARRY MEYER

I think there is also the problem of extrapolating between (sample positions). Invariably there will be a finite number of core sites and extrapolating between them is the problem. If you want to go to the effort, you can look at the acoustic drill described by Jacques Guignè as a method of obtaining an intermediate transfer between the type of response we get from a more conventional profiling system, the parametric system and the actual core. If you have a borehole you could position an acoustic drill nearby and create a transfer function between the borehole and the acoustic drill. It is now much easier to create a transfer function between the acoustic drill and the conventional profiler than it would be from the borehole directly to the conventional profiler. This could be thought of as an intermediate step in terms of being able to run surveys in between boreholes.

Q. (to Denzil Taylor-Smith from Roger Hutchins) This (thin clay layers) is a problem because these layers represent possible failure mechanisms and presumably civil engineers want to know how to design a foundation for that kind of an environment. He is surely not going to design a foundation in a certain spot unless he takes drillings and borings.

A. (Denzil Taylor-Smith) The problems are actually in determining if the clay layers are there in the first place. Conventional boring is such that a 3 cm layer can be missed if you have two competent bands either side of the thin layer.

Q. (Roger Hutchins) Aren't you logging these holes or are you just talking about taking the cores?

A. (Denzil Taylor-Smith) Not at all. The cost of (logging) becomes quite considerable. No engineer logs every hole.

Q. (Roger Hutchins) Are you talking about 40 m, because that represents the stress zone of the structure?

A. A hundred metres in some instances.

COMMENT - FROM FLOOR

I think the problem is that in many cases when you get below 20 or 30 m the sampling is no longer conducted in a continuous manner. Generally, samples are taken at 5 or 10 foot centres and they may be two feet long so it is very possible that although you are doing a diligent job of logging the hole, you can miss minor stratigraphic or geological details. A 3 cm bed would not be detectable with open hole logging techniques either.

COMMENT - FROM FLOOR (concerning resolution)

The minisleeve exploder developed by EXXON does have a significant amount of high frequency energy and in the North Sea I have seen energy returned in the 700 Hz range that was very coherent even in water depths up to 350 m giving detail 100 m or more below the ocean floor. In that area, I feel that the mini sleeve source would allow you to detect metre size boulders providing that the spatial sampling constraints are met. A short array of many groups may be necessary here.

COMMENT - ROGER HUTCHINS

That is certainly true. If you want high resolution and high intensity the best source is probably the water gun.

COMMENT - LARRY MAYER

We are talking about two different scales. Even water guns do not have much usable energy above 700 Hz.

COMMENT - DAVID CAULFIELD

There was some land seismic work undertaken several years ago by the English National Coal Board. Land seismic techniques were used to detect small coal seams and by spatial stacking they were able to resolve thin layers down to about 1/8 of the wavelength. Maybe a similar process could eliminate some of the volume scattering problem.

COMMENT - ROGER HUTCHINS

By keeping this source stationary you will get back the same scattered signal all the time.

COMMENT - DAVID CAULFIELD

Not necessarily. You would move along.

COMMENT - ROGER HUTCHINS

We are not talking about translation here. I agree with spatial moving if you have a one and one-half degree beamwidth which can be produced by a parametric source, but if you are looking at the horizontal extent of a sand layer, you may be able to see defraction patterns from the edges, but at what cost.

Q. (from floor) Is this not a significant engineering problem to ask the geophysicists to solve at this time?

A. No I think that the problem we can't solve here is geotechnical. We are looking for help and asking the geophysicists if they can help us.

COMMENT - JACQUES GUIGNÉ

I would like to comment on that. Basically if you can resolve these problems, all the other problems are by far much easier.

COMMENT - FROM FLOOR

I did not have synthetic aperature in mind when I mentioned short arrays. I had actual aperture in mind. I do believe that with (short) arrays there is enough spatial coherence say, that a bed of almost any size could be detected if you shoot often enough. I believe if the coherence is good, we may see impedance contrasts much lower than we believed possible.

COMMENT - ROGER HUTCHINS

I agree with the statements about large systems, etc. If we can improve acoustic methods at the rate that has happened in the submarine detection area (about 1 dB per year since World II), then we may be in a better position to do the same thing for the civil engineer, but where is the $100,000,000.00 going to come from?

COMMENT - DENZIL TAYLOR-SMITH

I think the point is that once you have a hole you can log it and find out about the problems that are in the hole. What we would like to do before a hole is drilled is to find the areas where anomalies exist. I think the money is available, certainly on the other side of the Atlantic, to devise some technique of that sort.

COMMENT - ROGER HUTCHINS

Can I make one more comment about the problem that occurs with this continuous method. The biggest source of disturbance and noise of any acoustic measurement on the scale which is being discussed is motion. Shell International are presently financing a project in Norway to the extent of $15,000,000.00 (recently increased by $15,000,000.00) to build a super high-resolution beam-forming sonar for monitoring the exact geographic position of a pipeline.

COMMENT - JACQUES GUIGNE

A cheaper way to do it is to go to a spot and use a calibrated source to get an acoustic core that can then be correlated directly with the continuous seismic profiles. This would give some confidence in the interpretation. That is not $30,000,000.00 or anything like it. The resulting geophysical model may not be absolutely perfect but at least it will be an order or magnitude or better than any system that is presently available.

COMMENT - ROGER HUTCHINS

I agree.

ACOUSTIC CORE - JACQUES GUIGNÉ

The acoustic core is designed to be lowered to the seabed to collect acoustic data. After a period, the core would be raised and allowed to drift for a period, then lowered again until data from many stations has been collected. The resulting acoustic core map could support and give meaning to interpretations from traditional seismic profiles.

Q. (from floor) How far can we go with profiling in identifying changes in actual physical properties? Our requirement is to minimize ground truthing. We are very interested in rapid reconnaissance techniques. How far can we go with that and how often are you going to have to ground truth? In other words, how far can we go with profiling apart from the resolution question?

A. I think you will never replace ground truthing but what you will hope to do is to reduce the expensive type of ground truthing that involves collecting a very detailed core at depth. What you are trying to do is to provide an inexpensive method of spot reconnaissance with sufficient detail to enhance your geophysical model.

COMMENT

I agree, I think you need several levels of ground truth.

COMMENT - LARRY MAYER

The answer to that question is going to be a function of the regional geology. There are some areas where we can go for thousands of kilometres and see very consistent depositional processes that result in very consistent seismic profiles and changes in seismic properties. With a minimum amount of ground truthing we can extend our results over large areas. There are other areas, however, particular nearshore areas that are very dynamic environments where the lateral changes are quite distinctive and closely spaced. Such areas will require a much larger amount of ground truthing.

COMMENT - FROM FLOOR

I think the military people would agree that baffling is quite important for an array. If you are working in reasonably shallow water where it is not too difficult to operate why not use an old wooden barge that is acoustically quite dead. Cover the bottom with $10 hydrophones and fill it full of gravel. A large area of array that's correctly baffled can have fantastic resolution.

COMMENT - DAVID CAULFIELD

I believe there is enough expertise at this workshop to solve the problem. We know that if you have a given signal-to-noise ratio and a given bandwidth and a given budget, a system with the required penetration could be designed. The oil companies and civil engineers ought to tell us exactly what they want.

COMMENT - ROGER HUTCHINS

I would like to return to the original question which concerns resolution and comment on what you can expect from geophysics as a reconnaissance tool. When you go out to the same area on different days at different times, you should be able to get a consistent and highly reproduceable measurement. If you know that your system can reproduce consistently then the variability observed is geologically-related as opposed to system-related. You can then measure variability geographically. You can say something about depth and material hardness. Also, the thickness of the first layer and the stratigraphy. You may be able to provide information on the statistics of the roughness or microtopography. To answer the question, no one will deny that geotechnical parameters cannot be determined from geophysical measurements but at the best such parameters are indirect estimates and geotechnical engineers in my experience are very direct people. They like to measure a number and they will extrapolate a single drill hole through 10 sq. miles. The geophysicist will average 10 sq. miles and boil the results down to a single drill hole. This is where the disagreement is. Information on the variability of structures is important so that representative sampling intervals can be determined, however, in my estimation, sampling and drill hole logging will never be replaced. But in situ testing will become more important. I think there is a convergence between the geophysicist and the civil engineer, in particular in the offshore because the engineer has to use geophysics.

COMMENT - LARRY MAYER - To Roger Hutchins

You bring up the point of a reproduceable signal which I think is very important. It has been of great concern to me, especially in studies that use "off the shelf" seismic high resolution profiling systems. With a near field hydrophone you have a good idea of the form of the outgoing pulse. This is of particular importance with the chirp sonar but my concern is when contractors use profilers without direct monitoring of the source. I wonder if this is a problem that we should concern ourselves with in terms of a type of quality control. If we are looking at styles of reflections we have to be sure that the system is transmitting the same pulse form over long periods.

COMMENT - JACQUES GUIGNÉ

Source testing is essential if we are to proceed with interpretations of the type described by Gordon Fader earlier. He raised an important point concerning mapping on the basis of formations. This procedure may be unsuitable for the engineer although acceptable to the geologist. Nevertheless by looking at the sequences an overall picture can be composed based on acoustic signatures. We then say "this is the type of acoustic response that comes back and we believe it indicates sands". From now on, we will be consistent in looking for that particular acoustic signature and relate it to sand. However, no matter how sophistocated the signal processing is, without knowledge of the system's response, you will not be able to express any confidence in the resulting interpretation.

COMMENT - LARRY MAYER

To conclude the discussion on resolution, I would like to ask Kevin Hewitt of Dome, what thicknesses of clay layers are creating problems in the Beaufort Sea?

ANSWER - KEVIN HEWITT

We don't know. We are looking at many site specific areas that are completely different. They may be sand or silty sand and may be partly frozen. We may have a completely different interpretation with a silty clay or a clay silt. There have been two different organizations logging a hole in two years and we found a discrepancy between the two sets of results. We do not know whether we are looking at the same thing or if the difference is in the interpretation. We find that the geophysicist has problems in making a distinction between sediment types. We look at the seismic data and ask, "Is there any correlation here?". I am not a geophysicist but I give it to the geophysicist that he cannot really make any interpretation between one and the other. We would like to know the extent of the good and poor foundation regions and presently the geophysicist cannot give us that information.

Q. (from floor) Do you have some idea in terms of the thickness of these beds? Are they a metre on 10 m thick?

A. They could be 5 or 10 m thick.

COMMENT

They certainly could be resolved given the constraints that we've heard so far.

ANSWER - KEVIN HEWITT

Geophysics does not tell us whether it is a sand or a clay. I do not have much confidence predicting sediment type based on geophysics.

Q. It is not just a question of the thickness of the bed, you want to know the type of bed?

A. Exactly.

Q. (from floor) Could anyone comment on shear wave seismics? The reason I became interested in shear wave is because the range in shear wave velocities is considerably more than the range in compressional velocities. We are looking at well over an order or magnitude variation in shear wave velocity in soft sediment, but I am not familiar with any ongoing seismic work.

Q. (from panel - probably Larry Meyer) Could we have a comment on shear wave sources? There is much concern about having a source that can generate shear wave for VSP work (vertical seismic profiling). If you want to penetrate 300 m of sediment in the Beaufort Sea, what kind of shear wave source is available?

A. (Roger Hutchins) It is a measurement problem.

COMMENT - JIM MITCHELL

I think that the general form of the relationship between some of the properties that you derive from acoustics like shear modulus and confinement pressure is well known.

COMMENT - DENZIL TAYLOR-SMITH

There is a lot of work going on in the UK on the development of shear wave sources for the sea bottom.

COMMENT - FROM FLOOR - on resolution

There will always be a need for a transportable seismic device for regional studies, but multi-channel seismics may not be ideal for the type of geotechnical data we seek. Certainly longer ranges are not ideal; near offset or maybe one or two channels with minimum offsets are more desirable.

COMMENT - LARRY MAYER

Let us wrap up our discussion of resolution. I think that within the capability of the systems discussed we feel that we have the bandwidth necessary to achieve resolutions in the order of 10 cm. Laterally, we probably can obtain resolutions of the order of tens of metres. In terms of penetration, depths of 100-150 m for high resolution systems may be possible. We have seen problems that these systems cannot meet and there has been discussion on probable approaches of addressing these more specific problems. There have been arguments for longer arrays, large receiving arrays, spatial stacking, etc. There is probably the potential to address specific problems. Cost is always a concern and we have to be presented with a specific need before looking at trade offs in terms of cost. Some of the discussions we have had this morning have generated some response on part of the contractors and I ask Rick Quinn as a contractor to make a few comments.

COMMENT - RICK QUINN

I am involved in the collection and interpretation of geophysical data as it applies to problems in the offshore. What I wish to clarify to some extent concerns the capabilities and feasibility of geophysics to map some of the seafloor features. Every tool has its capabilities and every tool has its limitations and weaknesses. Normally, whether we're working on the east coast, the west coast, or the Beaufort Sea, we have a number of parameters and geological factors that require solutions, so traditionally we take a package of geophysical equipment on board a vessel. We have a high frequency precision echo sounder, perhaps 50 kHz which basically gives a precise water depth without penetration. It may give some indication of certain morphological perturbations on the seafloor. Side scan sonar with a frequency of the order of 100 kHz gives lateral information of seafloor morphology but again without penetration. To penetrate a little deeper, a 3.5 kHz sub-bottom profiler will distinguish clays, silty sands from sands with several metres penetration. The next step will be the boomer and high resolution sparker which can penetrate deeper than the sub-bottom profiler and provide the stratigraphy of the sand. These techniques work in the range of shallow geotechnical boreholes and correlation with geotechnical work is possible. For deeper work, frequencies in the range 50-250 Hz are used; not so much for geotechnical properties but rather for defining deeper geological features, faults and bright spots. These features are much deeper and may be petrogenically related to bright spots that are stratigraphically trapped below 1,000 m. We then get into the question of multi-channel streamers. A common question is: do you have a short streamer array or a long streamer array? The point I am trying to make is that every tool has its capabilities. So if we are looking at a multi-channel system we are looking for deep features and process the data to suit. It does not necessarily mean that deep seismics is a useless tool because it does not give very shallow seafloor geotechnical information. The reason we have these suites of geophysical equipment on board the boat is because the existing hardware technology is such that you have to go to a different frequency spectrum to achieve different depths of penetration. Perhaps in the future we will have a technique that enables a single system to be towed behind a vessel and combine all the requirements. You can then vary the signal processing techniques to achieve your particular goal. Another point, that is a factor when you are collecting seismic data is the roughness of the sea and the suitability of the ship. Ship generated noise and wave noise will be superimposed on the seismic record and will degrade the data. Wave and swell compensators help to define the stratigraphy in the near surface unconsolidated sediment. But there are many factors that tend to influence the usefulness of acoustic data and the interpreter always has to keep those limitations in perspective when analysing data.

COMMENT - JIM HUNTER

Rick Quinn mentioned that high resolution multi-channel streamers are used for very deep penetration. The argument has been going on for several years about the length of these arrays, specifically in the Beaufort Sea.

Q. (from Jim Hunter) I would like to ask Rick Quinn his opinion of the suggestion of a short multi-channel array. Do you think it is a viable way to go and what additional information can we get with it?

A. (Rick Quinn) My basic reaction is not to look to multi-channel systems for the very near seafloor detail. Rather to look at the single channel systems that have a very good signal characteristic. When you get into multi-channel systems, detail is limited due to the relatively low (one millisecond or half millisecond) sampling rate. However, I tend to prefer longer streamer arrays because once in the field, as much data as possible should be collected. On return to the processing centre data can be rejected if necessary. A 48 trace streamer in the Beaufort Sea is useful in determining refracted arrivals in the upper 200 m. I think the point was well made earlier that great care has to be taken in stacking or mixing the data when looking for shallow and deep information. Shallow information may only be obtained from the first trace.

COMMENT - JIM HUNTER

I can see the point but I didn't have in mind a conventional quarter millisecond sampling rate. We have designed and built a system for one particular problem involving the measurement of high velocities close to the seafloor. We use the array in a wide angle reflection mode with a sample rate of 50 microseconds. We are looking at much higher frequency than the conventional high resolution system and I am wondering if there is any useful information in the additional 12 or 24 channels.

ANSWER - RICK QUINN

I would tend to think the because you are stacking the information it should enhance providing everything is consistent.

COMMENT - TOM FULTON

Many of you assume that if we have multi-channel data then it is going to be stacked. That is a poor misconception. What is required is continuous coverage with spatial sampling that will allow the target to be seen. If you are looking for a 1 m diameter boulder, you cannot contend with successive traces 20 m apart. Consequently, if you do get hydrophones in a multi-channel streamer that are a metre long and you take shots every 12 m then you can build up a continuous coverage of single channel profiles that will give you adequate spatial sampling for detecting boulders. You will get better resolution as well. I am not suggesting here that the data is stacked, stacking always decreases resolution.

COMMENT - KEVIN HEWITT

I would like to clarify the perspective that I mentioned earlier. It is interesting to sit here and realize why we are using geophysics in the first place. We have a geotechnical group who are responsible for doing the wellsite surveys and also for the geotechnical engineering of the exploration and production structures. We really wear two caps. The reason that we go out in the field in the first place to collect geophysical data is really predicated on wellsite surveys alone mainly because the drilling people usually have more say in funding. They cannot drill unless a wellsite survey has been conducted. It is very difficult for us to obtain geotechnical data because of limited funds. We require bathymetry, we wish to know the extent of ice scours, shallow slumping, mud flows, shallow gas, depth of permafrost, etc. Everything is predicated on doing the wellsite surveys. As geotechnical engineers we have said "There is a lot of information here, let us use it". For example, one of our main concerns is to find clean sand with which to build sand islands. We have used geophysical methods to locate sand outcrops. Also, when we are locating an island, we say "We are interested in the amount of ice scour and in the soft surficial sediments". The sub-bottom profiler is excellent in that respect. The side scan sonar basically does the job of zero height photography corresponding to "walking the ground" on land. But beyond that, we have not used geophysics to detect or obtain geophysical properties, rather as a method of highlighting facies changes. We have never really used geophysical methods to distinguish between units of clay and sands as such. This is where we are right now. We've been using these methods as geological engineers, as geotechnical engineers the methodology is lacking. This becomes very important in detecting weak clay zones because of large horizontal ice floes that we have in the Beaufort Sea. We have never relied on geophysics to detect weak clay zones or sand zones at depth and what I am asking is, "Is there a possibility of obtaining that data by using some other methods than we are already employing?".

Q. (from Larry Mayer) Can we generate a quantitative seismic profile of some sort? If we had an ideal world where the sediment section was made up of loss free, laterally continuous homogenous layers with well defined boundaries and we had an ideal source, then every contrast in acoustic impedance would be marked by a reflection that could mirror the outgoing pulse. The polarity and the amplitude of the reflection would directly indicate the nature of the contrast but unfortunately that's not the case. There are many factors that degrade what we receive in the seismic section. We can take a look at some of these factors and see how serious each factor is and whether we think we can handle them now or in the future. Can some effects be corrected for? If not, why not? How realistic is it to address the kinds of problems that Kevin Hewitt has just brought up? One critical problem that I mentioned and Paul Vidmar demonstrated yesterday was the problem of interference caused by very closely spaced layers. This basically resolves into a resolution problem. If we do not have the bandwidth or the resolution in a seismic system to see the true geologic layer, can we ever get a seismic profile that would be representative of that layering?

A. (Roger Hutchins) I have to come back to the earlier question. I'd like to start with Jim Hunter's system. He mentions a 50 microsecond sampling rate which corresponds to time path differences in the order of 7.5 cm. Then your problem is whether to stack, or average. What could be used is a method that sonar people call focusing. In this method you take a specific point in space and adjust the time delays between the various hydrophones based on the exact knowledge of where those detectors are in relation to the source and where the source is in relation to the target you are looking for. Whether you convert these to geographic co-ordinates or not, does not matter. The geometry has to be fixed rigidly in space. If you have a streamer wiggling around behind a vessel you have to know where each one of the hydrophones is so that you can focus on a particular target. You could use use a non-linear form of beam forming, however, all this is defeated to the extent that in reality you don't know where the hydrophones are or how they are moving. I point out to you, if you are looking at travel times in the order of 100 milliseconds, the whole system will move appreciably during the transit time of the signal. Unless you correct for these variables, you will not realize the resolution that is theoretically possible in the processing. Not to mention the arrivals from the sea surface, multi-path arrivals, the baffling problem that has been spoken of, etc. Unless you are prepared to address these problems you cannot advance the state of the art. There is nothing wrong with geophysics, it is just the way it is practiced. Returning to Rick Quinn's question concerning site surveys. The oil companies will produce a bid document that calls for geophysical surveys to an industry that is actually bankrupt in terms of contractors and are saying "Well, we used geophysics and its doesn't work". I have to tell you that a 3.5 kHz profiling system and streamer towed behind the ship in a rough sea surface isn't geophysics in the way in which we are discussing it here and it is not going to work. Any contractor who promises that he can take the data from such a system and solve the kind of problems that are being asked here is not being honest with himself. That's not the only problem. Noise is a problem and in particular the kind of noise caused by spatial movement.

COMMENT - LARRY MAYER

Let me talk about two techniques of reducing that kind of 'noise'. Rather than tow the vehicle directly, we tow a dead weight and have a neutrally bouyant vehicle decoupled from the surface motion. We also measure the vertical component as accurately as possible with a pendulum accelerometer that seeks the vertical axis and a very accurate pressure gauge for depth. We feel that vertical position can be measured within 3 cm. Despite knowing the vertical position we have to correct the records with an additional inaccuracy of 3 cm.

COMMENT - ROGER HUTCHINS

You have to make transit time corrections also.

COMMENT - LARRY MAYER

That's correct. But I think there are ways to put constraints on the problems of motions.

COMMENT - ROGER HUTCHINS

It is a solvable problem, but it is not being solved by any geophysical system being used today for rig site surveys.

Q. (Larry Mayer) I think the fundamental question that we are asking is: Can we really measure impedance from a seismic profile? Can we go from the seismic profile to an impedance profile?

A. (Roger Hutchins) Yes.

Q. (Larry Mayer) What about the scattering problem? Yesterday Tim Stanton addressed the problems of scattering. Do you think we have sufficient control over scattering to be able to remove its effects?

A. I think under the circumstances where you have a flat plane with ripples or rocks to the order of a few centimetres you are going to have problems in the 1-10 kHz frequency range. One constraint is in making sure that the acoustic wave length is much greater than the roughness. I want to repeat that averaging will not give you a true reflectivity except in some circumstances when scattering is small. Under normal conditions and with frequencies below 1 kHz, then averaging may be feasible.

COMMENT - LARRY MAYER

Not only have we the problem with the surface, but the subsurface also. Scattering goes on at all levels. The volume scattering will look just like a rough surface.

COMMENT - ROGER HUTCHINS

The rate of decay of seismic energy is different for volume scattering than it is for surface scattering and you can use this property in attempts to resolve the ambiguity. The second point is that if you see that you have scattering you know the surface is rough and therefore the confidence in reflectivity estimates is lower. Thus you only measure reflectivity where the surface is smooth.

COMMENT - DAVID CAULFIELD

I agree entirely, but you do have one other tool here. If you have several systems with various frequencies then the resulting scattering phenomena will vary. This will allow you to characterize volume from surface scattering to some extent.

COMMENT - ROGER HUTCHINS

You do not have to use five different sources and five different frequencies. One source with sufficient bandwidth can produce all the frequencies.

COMMENT - DAVID CAULFIELD

I was just trying to make the point.

COMMENT - TIM STANTON

I think that if you are seeing a fluctuating signal, your surface is scattering even if you don't have a broadband source.

COMMENT - DAVID CAULFIELD

All I am trying to say is that there are techniques using a broad spectrum sources or multiple sources in which to attack the problem providing you have the financial resources.

COMMENT - LARRY MAYER

I'd like to bring up the question: How do we go about addressing the problem of generating an impedance profile if our profiling system cannot fully resolve the layering? What are we really seeing?

COMMENT - DAVID CAULFIELD

Our system correlates the acoustic properties with the averaged estimates of the geotechnical parameters obtained from core samples. Usually samples of the core are taken every five metres, however, lateral resolution must also be considered if vertical resolution is to have any meaning. Usually core sampling density in a lateral sense is a question of economics.

COMMENT - LARRY MAYER

I think I am not really asking a question of economics but of physics. If there are changes on a scale that cannot be resolved, can you present a quantitative profile?

COMMENT - FROM FLOOR

We have expected too much from our measurements. There are two problems: direct and indirect measurements. For a given acoustical property we can theoretically predict the exact signal behaviour but the solution from this signal behaviour to the acoustical property is not unique. For the same response we can have many combinations of acoustical properties and for these reasons we have to use other sources of information in order to select the real value of the acoustic property.

Q. (from floor) The question is: "If a seismic tool or acoustic tool can be qualitative?"

A. Up to now we have used a tool which is quantitative. I quite agree with the previous comment. When you use the inverse method for instance, there is no uniqueness of the solution. To answer if the seismic/acoustic information can be qualitative the answer is "Yes". We are talking about resolution. We often must yield the resolution, but the most important aspect of the resolution is the frequency of measurement. As far as a qualitative measurement is concerned, absorption is extremely important. Dispersion is also a fact of life and is a function of frequency.

COMMENT - DAVID CAULFIELD

We are looking at additional information such as absorption in our work.

COMMENT - FROM FLOOR

We are also neglecting the converted wave at the bottom of the sea. Mode conversion is extremely important because you can have an excellent generator of shear wave energy at the boundary between unconsolidated sediment and consolidated sediment.

COMMENT - LARRY MAYER

This brings up the point of absorption which I'd like to discuss from two aspects. One, that it affects signal amplitude therefore if we are going to generate a quantitative profile, we have to correct for absorption; and two, it is an attractive measurement in its own right in terms of characterization of sediments.

We can briefly discuss the above and then go to other types of measurement that we can make such as compressional and shear wave velocities. I do not have the confidence expressed by Roger Hutchins that we can indeed generate a truly quantitative profile. Yesterday, I presented some attenuation measurements that were made with a chirp sonar system. I presented an average result that was made over a line of length 1 km, however, the ping to ping variability in that measurement results in 60% error bars. This variability concerns me. I do not know if it is a fundamental problem with the instrumentation, the method, or, if it is a true indication of the variability within the sediment itself. I think we can accurately measure sediment absorption. Yesterday, I indicated how absorption affects the measurement of reflection coefficient. I believe we have a major problem in terms of generating a quantitative profile.

COMMENT - TOM McGEE

I believe there is a source of information that's not being widely utilized especially in the case of thin layers. It is the reverberations themselves. I think most workers look at the reflection as a single observation whereas in fact it is a complex pulse. In the case of water reverberation, changes will occur to that pulse on reflection. The water surface will also complicate the matter. The second reverberation will effectively be a squared term and the third reverberation a cube. So you can get repeated observations of essentially the same measurement on one trace. If you can solve that for a thin water layer then you can use the result on the next layer until the noise becomes dominant. You will also get reverberations between the seafloor and the first interface that will probably not be as significant as the water reverberation, but you will get some reverberated signal which can be utilized until the signal to noise ratio becomes too small.

COMMENT - LARRY MAYER

I think that's the problem. It is a very valid approach, certainly for the kind of sediments that I described. Maybe the people working in shallow water environments have had more experience with internal multiples being a problem.

COMMENT - TOM McGEE

I guess I am not saying they are not a problem. If you increase your sensitivity they can be the solution.

COMMENT - ROGER HUTCHINS

You have to be a little careful when estimating attenuation from a seismic signal. You have to define what you mean by attenuation or absorption. They are two different properties. Attenuation is `the total energy loss of the signal. Absorption is a particular mechanism where energy lost per cycle goes into heat and friction. If you'd consider the second mechanism, then what can really be measured in a seismic signal? I refute David Caulfield here, because all you can measure from the time series is time, amplitude and phase. The frequency is a reciprocal of time. Dimensionally, we are only dealing with three parameters that are measureable so you can only estimate by assuming an appropriate absorption law over a wide band of frequencies. You can look at the frequency dependent attenuation by a simple analysis of the sonograph. The best way to obtain attenuation is to measure it directly in the laboratory.

COMMENT - DAVID CAULFIELD

I am not disagreeing at all, in fact, I'm agreeing with you.

COMMENT - LARRY MAYER

I'll take your point of describing the overall attenuation and say that earlier we discussed scattered energy with Tim Stanton.

COMMENT - ROGER HUTCHINS

It's a widely held and propagated misconception that if you are using a 10 kHz sound source that you have a better resolution than if you are using a 5 kHz source. This is not true. A 10 kHz sound source may only have the bandwidth of 1 kHz.

COMMENT - FROM FLOOR

At lower frequencies we have been finding that Hamilton's laboratory values of attenuation are too high. We have tried to use these values unsuccessfully to fit into our results. I've also seen papers from Huntec that have actually corroborated this statement.

COMMENT - LARRY MAYER

That's why I raised the question, how good are laboratory measurements?

COMMENT - PAUL VIDMAR

Coming to Hamilton's defence. If you take a look at Hamilton's absorption curve versus porosity it shows quite a range of values. More recent measurements on clays are towards the lower end of this range. This represents a factor of 5-10 in the absorption values. A second comment on frequency dependence. Hamilton has collected all available information on absorption and has concluded that a linear relationship with frequency exists. That is why he reports absorption in decibels per metre per kilohertz. These laboratory measurements tend to be made at high frequencies of 10 kHz and above. To extrapolate these figures to lower frequencies is very dangerous and involves broad assumptions. This is why I feel the Biot theory has certain advantages. If the Biot theory could be tested in the laboratory, then extrapolation of absorption over a frequency range for a particular material may be possible. But this has not yet been done and it may be years before it is done.

COMMENT - JIM MATTHEWS

I'd like to make one comment on laboratory measurements that concerns wavelength to grain size ratios and wavelength to sample size ratios. I would venture to speculate that you could probably throw out half the data in the literature if you really paid attention to those two considerations. We cannot normally scan over a frequency range when we make velocity measurements because the waveform can change drastically. Another questions arises in measurement on cylindrical shaped samples. Are you measuring the body wave properties or are you measuring in a thin rod.

Q. (Roger Hutchins) Are you using a single pulse?

A. (Jim Matthews) No.

COMMENT - ROGER HUTCHINS

Well that's what you have to use. Your pulsed sinusoid does not have the necessary bandwidth.

COMMENT - LARRY MAYER

We've seen some of the constraints facing us in measuring quantitative impedance profiles. Acoustic impedance is a product of compressional wave velocity and saturated bulk density. If indeed we get an impedance estimate, can we then go from there to separate out the velocity and density in order to establish the basic physical properties? In addition, if velocity and density can be separated, can we extend this process in order to estimate geotechnical properties? We have discussed ways of measuring compressional wave velocity by wide angle refraction. Throughout the discussion, shear wave measurement has been seen to be important. I'd like to discuss our ability to make such measurements and what level of accuracy can be expected. I should like to ask Denzil Taylor-Smith to comment about how important the accuracy of the measurements can be?

ANSWER - DENZIL TAYLOR-SMITH

I think the question of accuracy is linked to the use of the Biot theory, particularly the measurement of changes in sound velocity and velocity dispersion. If geotechnical information such as permeability and compressibility are required then velocity estimates must be obtained to 1% or even 0.1%. Is this possible?

COMMENT - JIM HUNTER

Roger Hutchins and I were discussing this problem and I think the answer is that it only takes money.

Q. (Larry Mayer) What about shear wave velocities?

A. (Phil Staal) About the only measurements we have made have been of interference waves. I have a number of questions such as how are interface waves affected by rough interfaces, cracks, etc? Are they not easily scattered? Our measurements were made over granite and the interface wave appeared to be unaffected but all the energy in the higher order mode was lost in the water column. I am interested to know if there are ways of measuring shear properties remotely rather than by equipment being placed on the seafloor?

A. (Jim Justice) We are concerned with that problem, but I am not in a position to comment. Much of our discussion on laboratory measurements concerns a problem that has traditionally or historically been addressed by transmitting signals through samples although this method is open to question. Shear measurements on samples are being made by exciting resonant modes using torsional transducers. This method gives accurate results. What I would like to know is are these measurements acceptable to the geotechnical community? For example, can I use a shear modulus obtained by this method and infer a shear velocity for a range of frequencies much lower (30 Hz to 1 kHz)?

A. (Jim Mitchell) Torsional shear and the resonant column methods are used a great deal.

COMMENT - FROM FLOOR

Very often these methods are used to measure shear velocities in a well. Logging methods do exist to give you shear velocity. The major problem here is that very often we cannot see the shear wave once there is mud inside the well because the path through the mud predominates.

COMMENT - ROGER HUTCHINS

You cannot measure shear wave remotely at sea because the water doesn't propagate shear wave energy. You can only see them indirectly through mode conversion and these effects are very weak. You have to put geophones on the bottom and measure them directly. The attenuation of these waves is very high and the question of dispersion is important as mentioned by Denzil Taylor-Smith.

COMMENT - LARRY MAYER

In some environments it is not possible to measure velocity at all in order to go directly from impedance to density. In other environments it may not be necessary to measure density. Yesterday I showed a correlation of 0.99 between impedance and density so it can be assumed that if we measure impedance we have density. Velocity was basically invariant in 400 m of this sediment type. I think another approach is to understand the inter-relationship of the properties so that we can, with confidence, predict which of the two parameters we expect to be the dominant one in creating the variations of impedance. In many circumstances, velocity and density are going to vary significantly and we have to look for some other means such as measuring the velocity remotely in order to separate the out the two paramters.

Q. (Jim Mitchell) We've looked at all these influencing factors and you have to have a quick technique for calculating acoustic impedance profiles with depth. What is your confidence in the acoustic impedance profile? Where is your weakest link in the estimation process?

A. (David Caulfield) An important aspect of Hamilton's data is that it is regional in nature. If you are working in the Beaufort Sea you cannot use these data directly. Some calibration must be undertaken in order to arrive at local values. This is in fact what we have been doing. For a given site in the Beaufort Sea, of say 10-20 sq. miles, two or three cores would be taken for density estimates. This information could then be used with the seismic signatures from the profiling systems to give accurate impedance profiles. From the Beaufort Sea core data which I presented yesterday, 65% of the acoustic impedance measurements correlated within ±5%. The second point is that absorption data can be used to update density estimates. Our technique involves generating a synthetic seismogram using velocity and impedance data and comparing this with the actual signal. Density is changed to obtain the best possible effect. An absorption term is then added to the model to see if a better fit can be obtained. The weakest link in this process is the density information obtained from the core. Having continuous density information from say 20 cores in a particular area would improve the model and provide information as to spatial variability. Our model includes shear modulus but we do not have a good data base other than the one that we've collected over the last three years. Without core data, our model will not produce an acoustic impedance log.

COMMENT - STEVE BLASCO

You could make an assumption and generate a density log but your confidence in it would be zero.

COMMENT - DAVID CAULFIELD

That is correct. We will not give an impedance section without a core log in the area.

COMMENT - LARRY MAYER

I think Hamilton would agree that the correlation between acoustic and physical properties are not for regional areas. They are for areas where continual depositional processes exist. You can be in a very small area and yet have very different degrees of correlation. You can have a very large area and as long as the depositional processes are constant, the relationships should hold.

COMMENT - ROGER HUTCHINS

I want to correct a misimpression of an earlier remark. Yes you can get acoustic impedances from seismic data but you have to calibrate the seismic data depending on the complexity of your geological model. The modelling operation is an inversion process and you have to resolve the ambiguities in the inversion modelling in order to extract the impedance profiles. You have to log at intervals and the seismic data, once calibrated, can be used to fill in between the boreholes.

COMMENT - ALASDAIR McKAY

I would like to point out that all of these considerations about acoustic impedance profiles do depend on the assumption that the parameters within the layers are constant. If you allow them to vary you may have problems. This may or may not be important in general terms.

COMMENT - LARRY MAYER

I am really concerned with the geologic processes that are responsible for these changes. We can put some constraints on the resolution we need in many environments. For most of the deep sea, a profiling system need not have a resolution better than 10 cm because the average mixing depth, the area in which sediments are stirred, is about 10 cm. These deep sea measurements are made on materials such as volcanic ash layers that are geologically instantaneous events.

Q. (from floor) How closely do you sample a core? A 4 cm interval perhaps?

A. (Bill Roggensack) Generally, sampling is closest nearer the surface unless of course, you are able to anticipate a condition of depth that may be of interest from a design standpoint. If you have a good geophysical section it can indicate the presence of for example, the soft zone that Dr. Mitchell mentioned earlier, then you may wish to sample at a closer interval at depth. Typically, in a routine investigation, the semi-continuous sampling would be restricted to the uppermost 10-15 m, after which the sampling interval might drop down to once every 2-3 m, possibly as low as 5 m. Within a 5 m sampling interval the sample then would be at most half a metre which means only 10% of your section being sampled in detail.

COMMENT - LARRY MAYER

If indeed it is the fine scale layering that is creating the impedance contrasts, then sampling intervals on the order of 10-15 cm are of little use.

COMMENT - BILL ROGGENSACK

Unless in the 50 cm sample that you take you are able to identify the layering that you are trying to resolve with the geophysics. Another alternative is to move into some continuous probing like the CPT system we saw yesterday. But even here you are restricted in being able to pick up very thin layering because of the relatively large cone diameter.

COMMENT - DICK CAMPANELLA

Not really.

COMMENT - BILL ROGGENSACK

Okay I stand corrected. My understanding is that if the interlayering is of the order of 1 cm it is not likely to be detected.

COMMENT - DICK CAMPANELLA

In our system there is a thin piezometer element which picks up a dramatic change in water pressure as it is pushed through the soil. There is a great deal of research presently being undertaken to determine how thin a layer can be detected. For example, a Swedish group claim that they can pick up layers as thin as 2 mm.

COMMENT - BILL ROGGENSACK

That then requires continuous monitoring on each of the channels which would present problems under anything other than research conditions.

COMMENT - DICK CAMPANELLA

Yes it requires continuous monitoring.

COMMENT - LARRY MAYER

If we are going to use the borehole as our calibration point, a measurement described above would be tremendously useful because we would have a continuous profile. I was quite surprised on my one experience in the Beaufort Sea that there was no way of measuring sound velocity, even using laboratory methods. If indeed there is an interest on the part of the geotechnical community to have geophysics play a more useful role I think there has to be some involvement by the geotechnical engineer in terms of making measurements that can be useful for calibrating our equipment.

COMMENT - JIM HUNTER

We have what we call a tube wave which is an interface wave and can be used to estimate shear velocity indirectly. We are not very satisfied with the accuracy as the error bars are very large. When it comes to measuring the velocities I feel that even in unconsolidated water saturated materials there may be velocity dispersion but at the frequency used in engineering geophysics on land (10-500 Hz), I wonder about the validity of the velocity measurements made at 880 kHz on a sample. Denzil Taylor-Smith mentioned that we should be measuring velocities to 0.1% accuracy. That is a long way from where we are. Even 10% accuracy may be in the future, but is a 10% accuracy in velocity measurements worthwhile? It is a major step to go from a single channel to a multi-channel streamer in order to estimate velocities and is it really worth the cost?

COMMENT - ROGER HUTCHINS

Ask the people who are financing this kind of work.

COMMENT - SCOTT CHEADLE

The frequency at which the Biot viscous loss effectively predominates is around 1 kHz. The most rapid increase in attenuation and dispersion effects are in the 1 kHz to 10 kHz range. This is the bandwidth that I think is required for acoustic tools. If you wish to compare well or core log measurements taken at 10 kHz or 20 kHz with seismic sections that are shot in the 100 Hz range, these (Biot) effects are going to have to be incorporated into a model. Models like the one suggested by Pullan and Johnson have incorporated these effects and indicated that shallow saturated sediments are more susceptible with dispersion in the order of 100 m/s occurring over a 1 kHz to 10 kHz range. Over the same frequency range, attenuation increases by an order of magnitude. So the physics as described by the Biot theory is in effect a barrier between the seismic section and the logging tool. We have been discussing it up to now as if it were a problem. I think its a problem under the present technology but I think it can also be a solution. By looking at the rates of increase of attenuation over the 1 kHz to 10 kHz frequency range and by looking at dispersion over the same frequency range, you can obtain much information about porosity, not just grain size, but the condition of the pore space and some of these other physical parameters that I think both the geophysicist and geotechnical engineer are probably most interested in. Using some recent data we have plotted the porosity versus the frequency spread (dispersion) with interesting results. The resulting characteristic which shows a minimum in the 1-10 kHz region is similar in form to when the angle of internal friction is plotted against porosity.

COMMENT - FROM FLOOR

The Biot theory is complicated and as Paul Vidmar pointed out it is difficult to keep track of all the parameters involved particularly when you involve the dynamic aspect of the elastic constants as well as their static quantities. Someone mentioned a 10% accuracy in velocity measurement. It will have to get better than that if you want to be able to look up velocity dispersion. Measurement systems on logging tools will have to improve considerably before these effects can be exploited. Apart from the increase in attenuation, up to 5% of your energy could be converted into a wave that is virtually indetectable, this mode conversion is a phenomenom that has to be incorporated into the concept of impedance contrast and reflectivity time series.

COMMENT - MIKE KING

I would just like to address this problem of velocity dispersion. My results show evidence of velocity dispersion at seismic frequencies and at frequencies used in acoustic logging. Between the acoustic logging frequencies and those used for laboratory measurements dispersion is not as great. But there is evidence that between 30-50 Hz and 1,000 Hz dispersion exists.

COMMENT - LARRY MAYER

Do you have any idea of the amount of dispersion at 1 KHz?

COMMENT - MIKE KING

Certainly the 1% or 2% levels have been measured for sandstone and for harder rocks. I suspect that dispersion might be a little higher for sediments but not as much as 10%.

COMMENT - FROM FLOOR

That 10% figure is from a paper by Staal and he is referring specifically to the most unconsolidated saturated sediments. If you are trying to solve the high resolution problem in the top 10-40 m of the ocean bottom then care must be taken because the top 40 m is the exact area where these dispersion effects are most profound.

SUMMARY OF MORNING SESSION - LARRY MAYER

With the capabilities that we have been discussing, resolution in the order of tens of centimetres, and lateral resolution of tens of metres, I think we are doing a reasonable job at structural problems and at identifying faults, hazards, etc. The geophysical interpreters, geotechnical engineers and site survey personnel probably agree that there are some specific problems we cannot handle. Denzil Taylor-Smith mentioned the 4 cm clay layers at a depth of 40 m. There may be ways we can improve the situation, large receiving arrays, spatial stacking or maybe using shear waves. I think we all agree that there needs to be improvements in logging capabilities and better in situ testing programs. I think we have identified many of the factors that affect our ability to get quantitative seismic profiles and we probably believe that most of them are manageable. If we calibrate our sources quite carefully and assure that the sources are very repeatable, then if we design our experiments carefully with a knowledge of our capabilities and limitations, and specific objectives, we may be able to use geophysics to extrapolate the results from one borehole to the next. The question is, however, how far can we go in that direction?

DAY 2 AFTERNOON SESSION

INTRODUCTORY PRESENTATION BY MR. STEVE BLASCO

GEOLOGICAL SURVEY OF CANADA

This afternoon we hope to address the problems of associating acoustic properties with physical properties, to discuss which properties are of particular importance and to establish which direction we should be going. Dr. Richard Campanella of the University of British Columbia will chair this session.

DICK CAMPANELLA

To start off this afternoon's session Mr. Michael Jeffries of Gulf Petroleum, Calgary, has a presentation which will be useful in setting the scene for discussions later this afternoon.

MIKE JEFFRIES - GULF RESOURCES CANADA

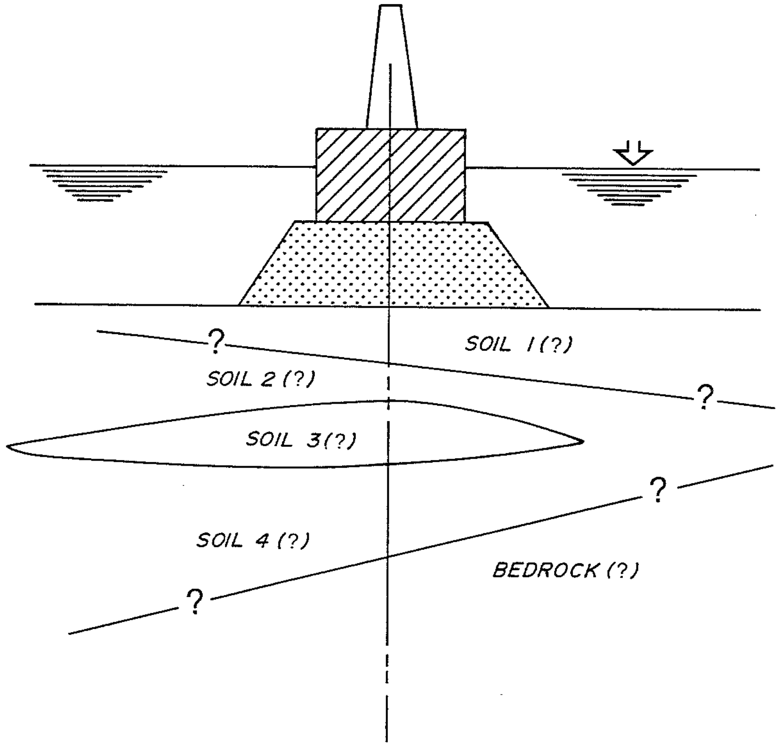
In the last day we have seen some interesting data and concepts with the general assumption that graphic records or colour enhancements are reasonably satisfactory for many engineering uses. I wish to state that I do not think this is so and I would like to support this statement with data from two Beaufort Sea sites. I would like to make the following points:

1. The problem is considerably more complex than is generally realized.
2. There are more variables in the problem than is generally accepted.

My discussions are aimed at high resolution seismics and my following remarks would be inappropriate if directed at vertical seismic profiling or cross hole surveys.

I would like to discuss the engineering situation from the point of view of a civil engineer attempting to provide a service to an oil company. Assume that the civil engineer is to position a platform which is to be stable under a variety of loading conditions. Three fundamental questions arise which so far at this Workshop have not been addressed. Referring to Figure 1, the questions we face as engineers are:

1. What is the configuration of the subsurface conditions?
2. Once the configuration or geometry is known, what are the properties of each zone?
3. What is the material that makes up each zone?

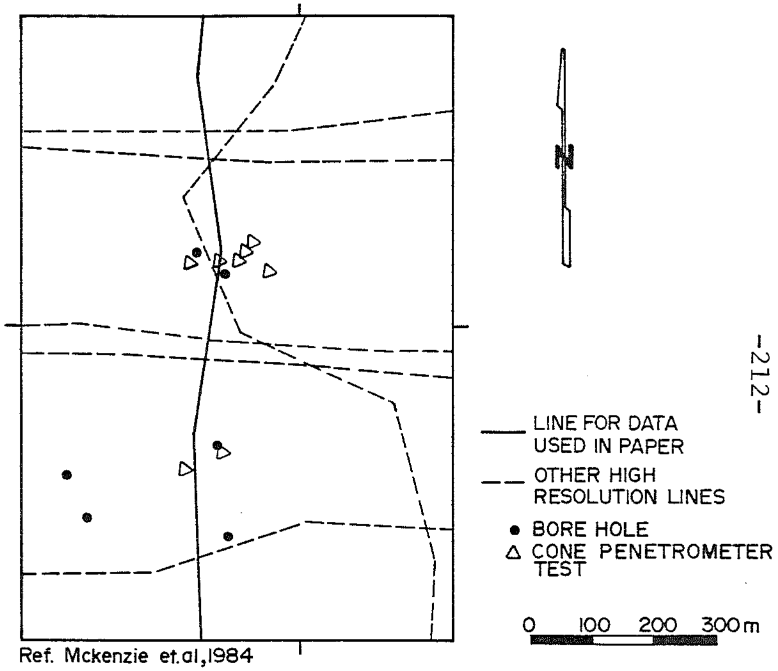


What is the configuration of the soil layers?

What materials comprise the soil layers?

What is the constitutive behaviour of each soil layer and what properties are associated with the constitive model?

Fig 1: Some fundamental considerations for for foundation engineering of offshore, caisson-type exploration platforms.



Ref. Mckenzie et.al,1984

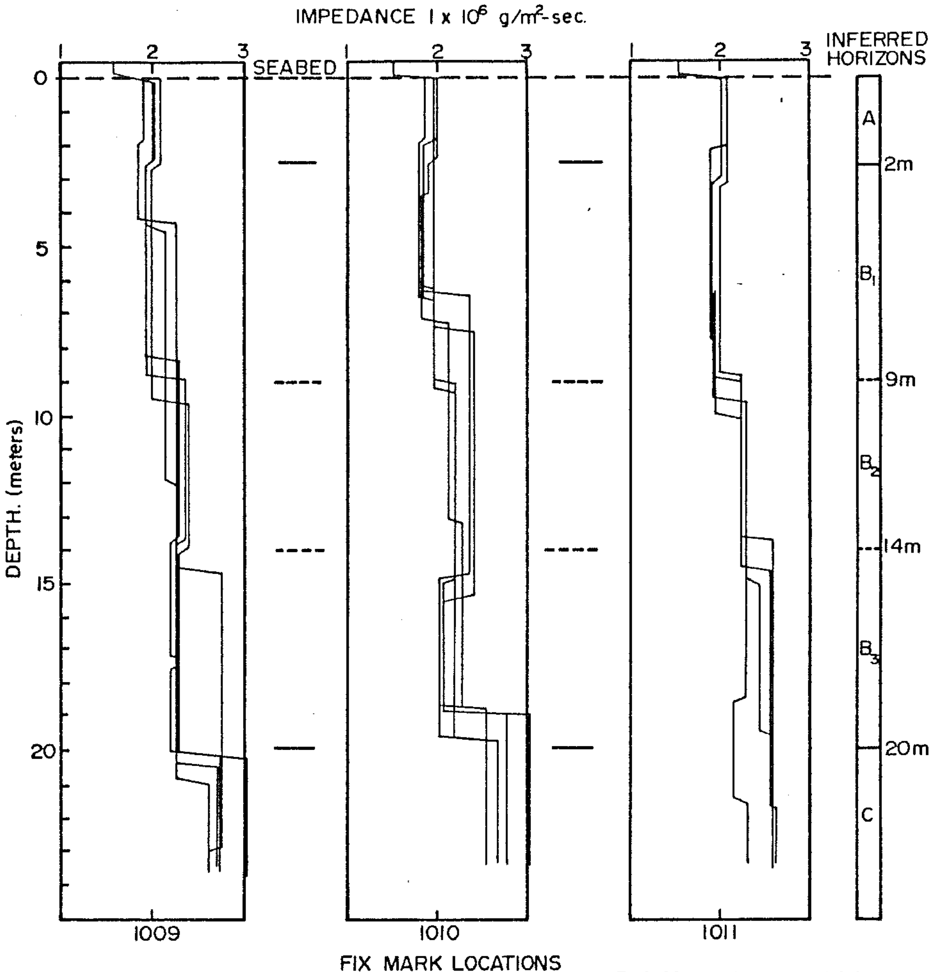
GEOTECHNICAL TEST LOCATIONS
AND SEISMIC LINE COVERAGE

Fig 2: Plan of correlation test site.

In trying to put forward my argument I will present data from a site composed of a clay material. In making this presentation I am going to advance the thesis that the acoustic core should not be used as a means of determining geotechnical properties but rather as a means of imaging subsurface conditions. I am going to suggest that these conditions are more complicated than has been previously thought to be the case. Specifically, I hope to show that the acoustic core technique detects sublayers whereas graphic records from seismic profiling present an incoherent phase or a transparent zone where reflectors exist. Finally, I am going to suggest that the appropriate ground truth for geophysics is not boreholes but rather the cone penetrometer test (CPT).

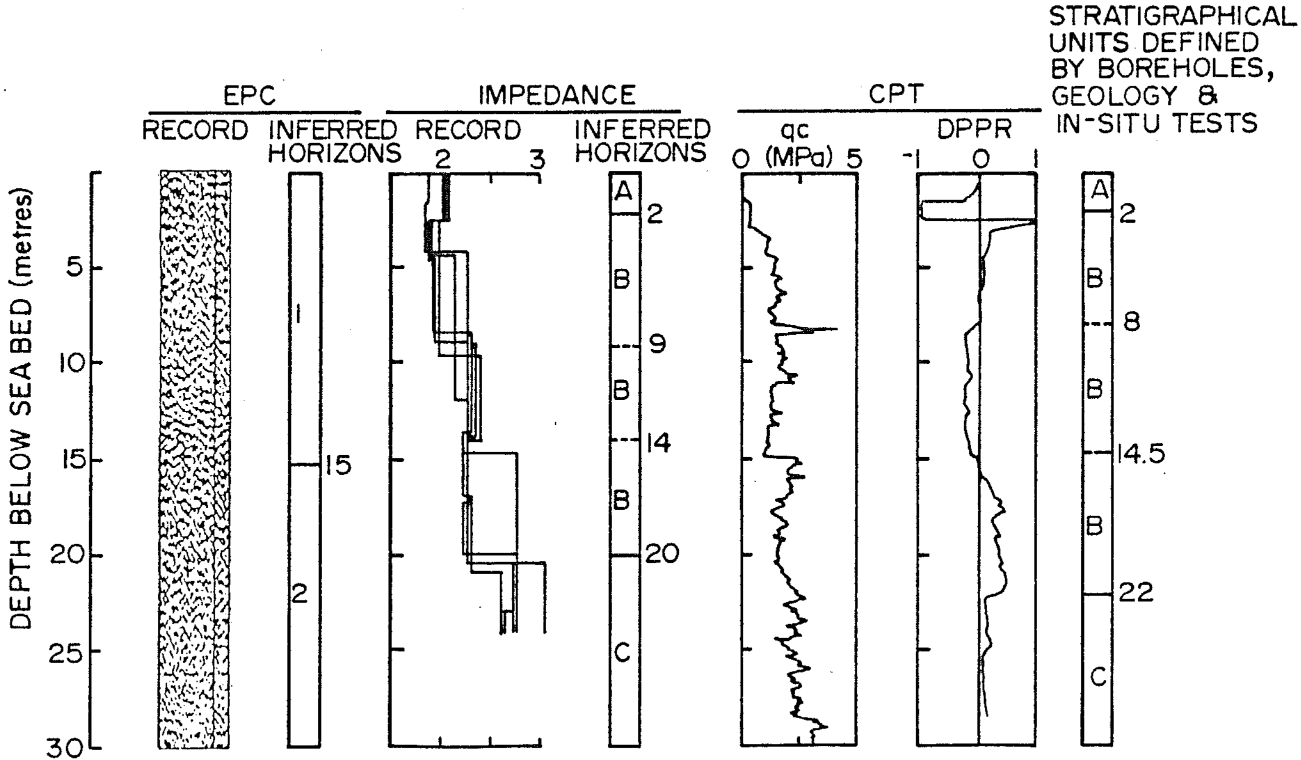
The following slides are from an OTC presentation by MacKenzie, Stirbys and Caulfield (Reference 1) relating to foundation work in the Beaufort Sea for the Gulf-Mobil Arctic Caisson. The data is from an area approximately 100 sq. metres in which CPT data and two borehole logs are available (Figure 2). The geophysical data was collected in 1981 and from it acoustic impedance profiles were calculated. The five shot points across the site resulted in five locations for calculation of acoustic impedance and five profiles. Between each profile we were able to detect a reasonable amount of consistency in five separate layers (Figure 3). Ground truthing was by CPT tests and analysis of the raw tip resistance and pore pressure data indicated a two layer stratigraphy. A second level of interpretation of the CPT data is required for the clay zones. This involves the dynamic pore pressure ratio which is the ratio of the excess pore pressure and the portion of the tip resistance attributable to plastic cavity expansion. This second level interpretation technique also enables the five layer sequence to be mapped across the site. Some layers are continuous and others seem to pinch out. The upper material is heavily modified due to the effects of ice. The simple and improved interpretations of both high resolution and geotechnical data are shown and contrasted in Figure 4.

Before considering sands it is necessary to mention that the inverse problem using in situ data is probably more significant than is generally accepted by geotechnical engineers. There is an inverse problem because in collecting the raw in situ data a deformation is imposed on the soil and the soil's response in terms of gross loading is measured. Other tools may impose a loading and measure a corresponding deformation. The important point is that in situ tools do not directly measure any particular soil parameter at all. Specifically, they measure a load or a change in geometry so that in order to provide a meaningful result a constitutive model has to be used. We may have to assume a failure mode and also accept a lack of uniqueness in the solution (in terms of soil parameters).



Ref: Mckenzie et.al.,1984

Figure 3 ACOUSTIC IMPEDANCE PROFILES



Ref. Mckenzie et. al.,1984

Figure 4 COMPARISON OF STRATIGRAPHIC UNITS DESCRIBED BY VARIOUS METHODS

In interpreting one type of in situ test, the CPT in sands, we use calibration charts obtained from laboratory measurements (see for example Reference (2)) and use cone resistance as an indication of stress and ultimately density. In extending the interpretation to moduli, we use the relationship:

$$K \propto \text{DENSITY} * \bar{I}_1^{\,n} \qquad -(1)$$

where: K = bulk modulus of soil

$$\bar{I}_1 = \frac{\bar{\sigma}_V + 2\bar{\sigma}_H}{3}$$

and: Density = f(qc)

qc = cone tip resistance

$\bar{\sigma}_V$ = vertical in situ, at rest effective stress

$\bar{\sigma}_H$ = horizontal in situ, at rest effective stress

n = exponent whose values typically range from 0.4 to 0.7

Figure 5 is an example of CPT data and resulting relative density section from a Beaufort Sea site consisting of a dense sand. For engineering purposes, it is insufficient to say that a layer is "sand" because of possible sublayers that can exist with large variations in density and in other properties. Although we have little data on sand it would appear that stress levels are related to the geological subunits. If the relationship between density and bulk modulus mentioned earlier (Equation 1) is used as a model for sand then holding the vertical overburden pressure and k_0 constant we find that the bulk modulus is approximately linearly proportional to density (Figure 6). This analysis can be extended to produce a sound velocity section which does seem to agree with the inferred seismic model described by Alasdair McKay earlier. The low velocity regions suggested in Figure 6 appear valid and I recall measuring the degree of saturation in tailings as an example of how low velocities can occur in sand.

The level of saturation controls a large portion of the materials' response to the first few cycles during cyclic loading. In particular, when slightly unsaturated, a material is very insensitive to stress increments which is an important consideration in earthquake hazard assessment. Figure 7 shows sound velocity data from tests on samples of Ottawa Sand to examine the influence of saturation (3). It is observed that even minor gas content (1/2% by volume) can have a marked effect on the sound velocity.

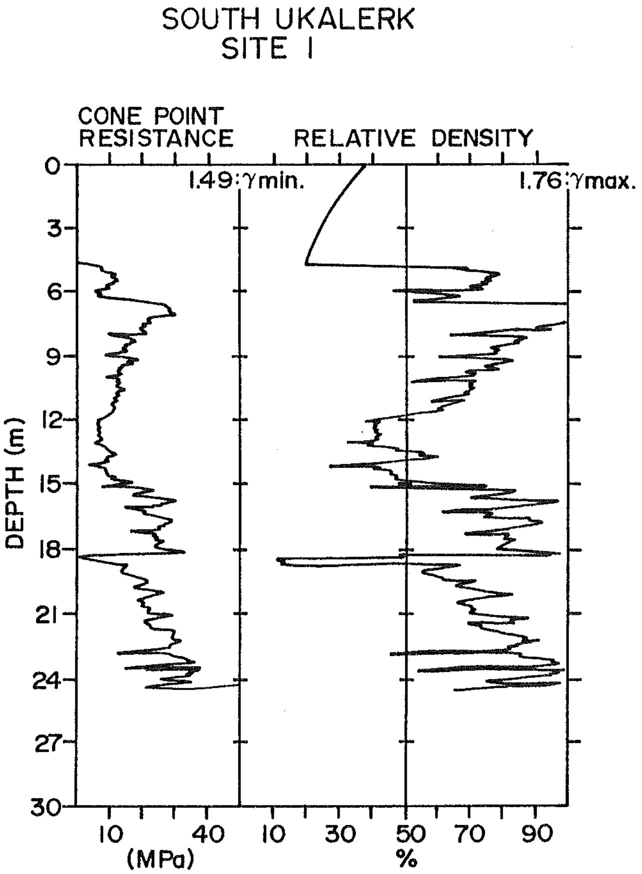
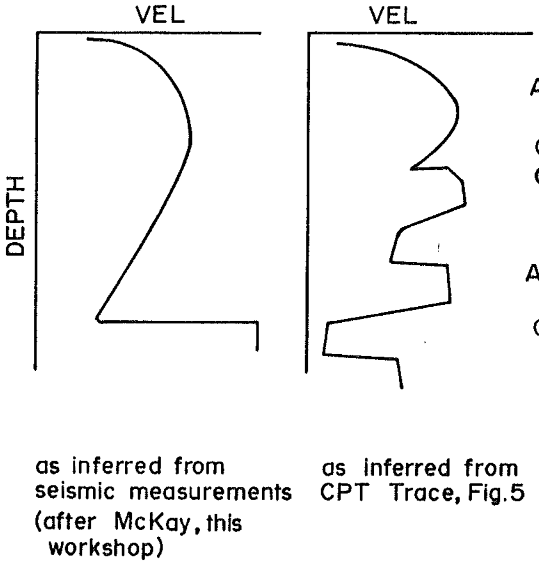


Fig. 5: CPT and relative density sections from a Beaufort Sea site.



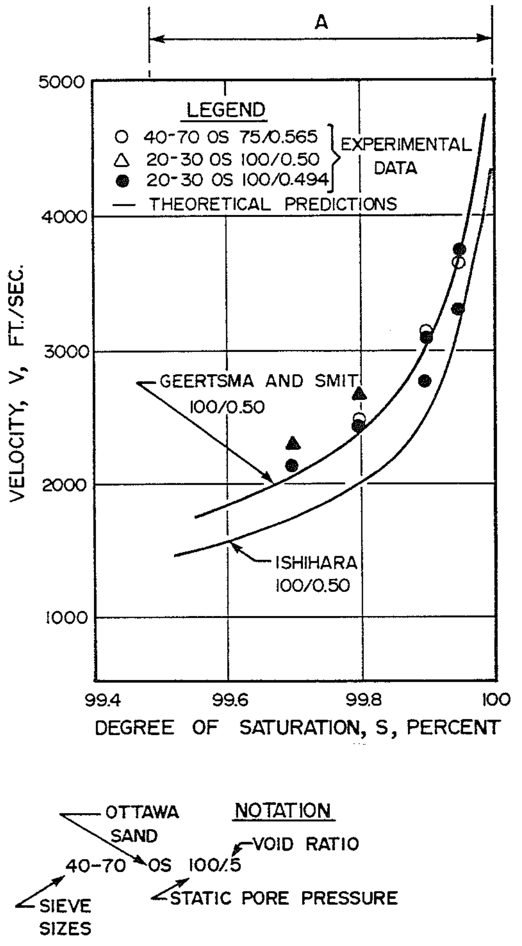
as inferred from seismic measurements (after McKay, this workshop)

as inferred from CPT Trace, Fig.5

AT CONSTANT DENSITY &
OVERBURDEN
G = 80 UNITS FOR K_0=.5
G = 130 UNITS FOR K_0=2
⇒ HORIZONTAL STRESS
IMPORTANT

AT CONSTANT DENSITY &
OVERBURDEN
G = M + DENSITY
⇒ DENSITY (SAND ONLY)
IMPORTANT

Fig 6: Inferred sound velocity profiles.



NOTE: TEST DATA FROM ALLEN et al (1980)

DISTANCE A REPRESENTS ONLY 1/2% GAS CONCENTRATION.

Fig. 7: Sound velocity data from Ottawa sand samples.

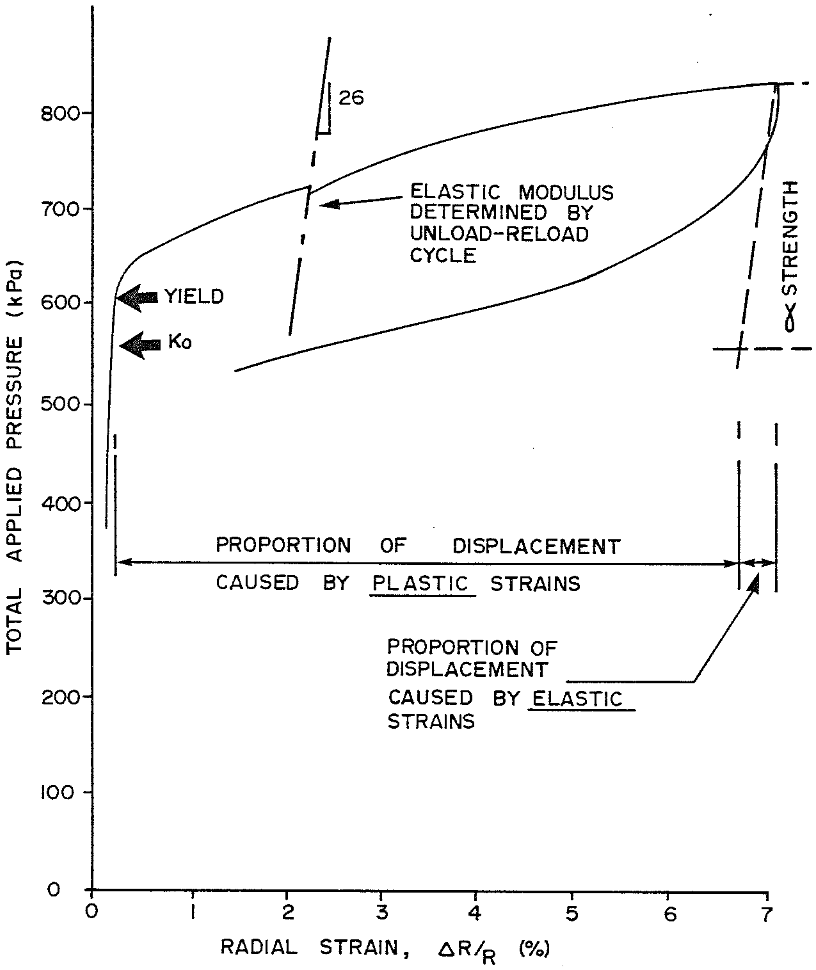


Fig. 8: Examples of self-bored pressuremeter data to show relative importance of elastic and plastic strains on soil behaviour.

The object of this presentation is to suggest that the three-dimensional geometry of soil layers at a site is the basic requirement from a geophysical survey, whereas so far, we are only able to infer certain parameters. As far as constitutive models are concerned, the basic requirement are the properties of the individual layers. This means finding which constitutive model is appropriate for a particular layer and then determining which soil parameters should be used in the model. What is common in geotechnical engineering is to use a stress-strain relationship to obtain estimates of G_{max}. This process is absurd since it implies only one stress-strain relationship for a particular soil with no allowance for how the load is applied. It is important to recognize that a soil is a multiphase material that displays yield surfaces outside which stress-strain relationships show plastic behaviour and are not ideally recoverable. Moduli are only appropriate in elastic material and quite inappropriate for plastic behaviour. In plastic regions, hardening, softening and plastic flow parameters must be considered. These parameters are governed by the geometry of the particular loading situation. The importance of elasticity and plasticity in soils can be demonstrated by a pressuremeter test which involves a tool inserted into an undisturbed region of soil.

During self-bored pressuremeter testing, a membrane is pressurized against the undisturbed soil and displacement measured as pressure is increased. If the soil is in an elastic condition the radial stress will decrease smoothly with distance and the hoop stress will also decrease but the difference between the two stresses will remain constant. This allows a direct measurement of the shear modulus. As stress is increased further, the soil eventually reaches a yield condition resulting in work hardening. Figure 8 shows data from a pressuremeter test. The soil behaviour is almost entirely due to plastic behaviour. This shows that in any technique which attempts to describe multiphase material the models must be mathematically consistent with the observed facts. This implies that a mathematically consistant approach would have to apply Biot's theory to high resolution seismic data.

I am aware of two solutions to Biot's theory which are expressed in terms of conventional soil parameters. One is due to Geertsma and Smit (4) and the other due to Ishihara (5). What I require of Biot's theory concerns what can be measured in terms of geotechnical parameters and what are the implications of the lossy elastic theory of wave propagation? Figure 7 compares measurements of sound velocity against degree of saturation for Ottawa sand.

TABLE 1
MATERIAL PARAMETERS IN BIOT'S EQUATION

FIRST ORDER	SECOND ORDER
Skeletal Bulk Modulus	Soil Particle Modulus Porosity
Skeletal Shear Modulus	Viscosity of Pore Fluid
Pore Fluid Modulus	Permeability Specific Gravity of Fluid Specific Gravity of Soil Particles

In principle the Biot solution contains nine material unknowns (Table 1), but in fact only three of these prime unknowns need to be considered. Thus three independent measurements may allow useful soil properties to be inferred. There are other variables such as frequency and wave amplitude, etc. and material parameters such as grain size. With all these variables the question that is raised is " Why is Biot used?". One answer to that question is that we wish to be mathematically consistent and Biot will allow us to go from actual soil behaviour to an equivalent lossy elastic situation. It allows us to involve partial saturation and to develop parameters for use in a lossy elastic model which can then be used in three-dimensional imaging. Biot also allows us to look at the second mode wave conversion where we have a loss of energy which involves the reflection coefficient.

In summary, I have raised the following ideas:

- As an engineer, I would like a good 3-D image of my site's stratigraphy as the basic product of geophysics.
- Ground truthing of high resolution data is best carried out by the cone penetration test.
- While elastic moduli of the soils affect the acoustic velocity, the dramatic affect of slight amounts of gas should not be ignored.
- The best approach is to use geotechnical data (including moduli) to allow equivalent lossy-elastic parameters to be developed by means of Biot's equation.
- Properly derived, equivalent lossy-elastic parameters will allow a good 3-D image of a site to be developed from high resolution seismic data.
- Elastic parameters are essentially irrelevant to most foundation engineering; plastic soil parameters are what matter. Seismic techniques necessarily are concerned with elastic parameters.

QUESTIONS

Q. (from floor) In your discussion on Biot's theory you violate one of his assumptions of elastic wave propagation that the density of the different material be in the same range.

A. (Mike Jeffries) When I discuss the gas in the pore space I am assuming between 1/2 and 1% by volume. This amount has little effect on the density of the pore fluid. The Biot model has been found to work.

A. (from floor) Other people have found Biot to work also. Dominico has presented papers.

A. (Mike Jeffries) Dominico is the other case in the literature. However, I am concerned about his experimental techniques. Specifically, he didn't differentiate between total and effective pressure. He also proposes that velocity decreases with an increase in modulus which is opposite to the relationship recognized by Geertsma and Smit.

Q. (Denzil Taylor-Smith) You mentioned several parameters which are required to solve the variance equation. I do not think that Ishihara's solution of Biot is as good as that of Geertsma and Smit. One of the problems is that of mass coupling which you did not mention. How did you in fact measure mass coupling?

A. (Mike Jeffries) I did not measure mass coupling at all. I am a consumer of results. I use Geertsma and Smit's results and fit them to laboratory data for my materials.

Q. (Denzil Taylor-Smith) Your mass coupling will vary according to the material you are using. You cannot use Geertsma and Smit's solution without including a mass coupling factor for your material.

A. (Mike Jeffries) The Biot theory would be appropriate for my sands which cover half my acreage. I would have to do more experiments to prove that it would work or not in clay and whether mass coupling should be involved. The Biot theory worked well for the Ottawa sand in the laboratory and this sand is very close to those present in the Beaufort Sea.

Q. (Roger Hutchins) What do you mean when you say it works?

A. (Mike Jeffries) That the predicted velocity using geotechnically measured parameters matches the acoustic velocity measured in the laboratory.

Q. (Roger Hutchins) I presume you wish to know how a soil is going to behave under stress. How can you take a measurement of material that is not under stress and extrapolate it through several orders of magnitude in order to predict its performance for foundation design?

Q. (Mike Jeffries) Do you mean in terms of my laboratory tests?

A. (Roger Hutchins) The behaviour of this material under stress is clearly different from how it behaves under static conditions present during your experiments.

A. (Mike Jeffries) Many of our loadings are quasi-static so the use of the term dynamic is not really true for many rates of strain experienced in engineering. The problem with in situ testing is the inverse boundary value problem which requires a constitutive model for interpretation. Laboratory testing allows stress elements to be evaluated but in doing so disturbance of the sample must take place. I would suggest that the appropriate approach would be to use laboratory testing to infer constitutive parameters or constitutive model which we then use to interpret the in situ data. This becomes a circle because you need the in situ data in order to construct the appropriate laboratory test program. My main requirement from the geophysics is a three-dimensional image of the site. I do not think the parameters resulting from interpretation of geophysical data have much use to me as an engineer. However, the three-dimensional image is very valuable in defining sublayers which could be acoustically transparent on graphic records.

Q. (Denzil Taylor-Smith) As far as the soil properties are concerned, I presume you are making pressure meter measurements down a borehole?

A. (Mike Jeffries) We push the pressure meter down which takes the soil inside it.

Q. (Denzil Taylor-Smith) You mean you are using a self-boring pressuremeter down to 40 metres?

A. (Mike Jeffries) We went down 35 m using a self-boring pressuremeter.

Q. (Denzil Taylor-Smith) It must cost a lot of money?

A. (Mike Jeffries) No, it did not. The measurements were made in 12 hours of shift time.

Q. (Denzil Taylor-Smith) If you are making measurements down a borehole what volume of material is effectively being sampled?

A. (Mike Jeffries) Relatively small. The radius of influence of the pressuremeter we used is probably about 300 mm or so.

Q. (Denzil Taylor-Smith) So you are going to infer your design for large structure like a gravity platform on the basis of how many volumes of material?

A. (Mike Jeffries) You raise a question of lateral variability. We have conducted CPT measurements over distances in the order of kilometres and we have found that even without making any allowance for the geological subunit within a physiographic region (say for a few kilometres), as long as the major reflector is more or less at the same level we observe a variability of about + or -5%. I may not know what my constitutive model is but this does tell me that the soil is remarkably consistent in terms of shear strength over large geographic distances. I do not rely on one test alone, I do several tests. We aim to get a three-dimensional image using CPT tests and once we know what the layers consist of and knowing what the layers are consistent laterally then we only have to insert the pressure meter where appropriate.

Q. (Denzil Taylor-Smith) I agree with the above but my point is why do you believe the pressuremeter information and not any information that is observed from a geophysical observation?

A. (Mike Jeffries) I don't disbelieve it. I say for example the geophysical shear modulus will match the modulus obtained from the pressure meter almost exactly.

Q. (Denzil Taylor-Smith) Therefore you are extrapolating from a small point over a large distance whereas the geophysicist is taking measurements over a large area and giving you a much better estimate.

A. I think I am being misunderstood. There are nine parameters in the Biot equation and even with mass coupling you cannot have a unique solution with a limited number of measurements. I am suggesting that some of the parameters are equal and others vary quite a bit but that I can't make an accurate guess.

Q. (Denzil Taylor-Smith) My point is that you can get a better estimate from the geophysics before you make any in situ measurement.

A. (Mike Jeffries) If you want good estimates from geophysical data then I think you have to use vertical seismic profiling. Please remember that my initial concern was targeted at high resolution surveys. The answer to my problem may be vertical seismic profiling because we can go directly from both shear modulus and bulk modulus. VSP work is very convenient down a borehole since it can be done with little additional cost. We then have a well conditioned situation for estimating both parameters and for three-dimensional imaging.

COMMENT - ROGER HUTCHINS

I agree with what you're saying.

COMMENT - DENZIL TAYLOR-SMITH

Okay. I agree also.

COMMENT - ROGER HUTCHINS

It is a difficult kind of exercise involving two disciplines in order to refine parameters for use in acoustic models. If you have acquired a good three-dimensional image you have to have a relatively simple geological structure and many sample points. The cost goes up by the number of samples.

COMMENT - MIKE JEFFRIES

That is accepted but what I am trying to suggest is that rather than worrying about all the variables in the geophysics, we attack the variables through the geotechnical direction and address the problems in the reverse order. It is very important to emphasize that the impedance logs (see D. Caulfield's presentation) were iterative solutions where we took an approximate density value for an area from two core logs and ran many solutions until the error was very small. Each solution took approximately half an hour on a computer.

COMMENT - ROGER HUTCHINS

One other point I will disagree with you on, is in estimating mean grain size from acoustic measurements. I do not believe that this is futile.

COMMENT - FROM FLOOR

I'll agree to that.

COMMENT - FROM FLOOR (Roger Hutchins)?

It depends on the acoustic measurements. From the measurements we are making we are getting good correlation. I am philosophically troubled with the "Us and Them" attitude that has entered the discussion. It is "we". We are trying to solve a problem and the problem is just as diverse for the geotechnical matters. There is as much a black art in the data you have presented.

COMMENT - FROM FLOOR (probably Mike Jeffries)

Yes, there is.

COMMENT - FROM FLOOR (probably Roger Hutchins)

Certainly the interpretation from the cone penetrometer or pressuremeter is much the same. You change some parameter and measure a force or a displacement. From there on you have to live with the data.

COMMENT - MIKE JEFFRIES

But it is an inverse boundary value problem which requires a constitutive model and you should perhaps model the in situ tests as a check on the interpretation. This is why laboratory tests are necessary for the constitutive model. Once you have an unambiguous constitutive model the boundary value problem can be solved.

COMMENT - FROM FLOOR

I wish to clarify a point that Mike Jeffries made concerning the cone penetrometer tests. When describing the relative density measurements he showed the correlation terms but neglected to mention that there were two other sets of correlation curves which vary with the compressability of the material. These correlation curves were determined in chamber tests on a very uniform, clean sand and unless in situ material has similar characteristics the correlations could be grossly in error. With a fine sand the results can be way out of line. We have as much a "black art" involved in our interpretation as the geophysicists and I believe we have to equally as careful.

COMMENT - FROM FLOOR

I see geophysics as a science which differs from the view taken by civil and geotechnical engineers. In fact the theories of the soil mechanics experts are so complex that we cannot expect geophysicists to appreciate them and I do not wish to change my activities in order to learn them. This problem is in an area which must be addressed by teams. It must involve geophysicists working alongside soil technicians.

COMMENT - FROM FLOOR

There is a need to plan ahead and have people that are going to be collecting information understand how much information may eventually interact before a program is executed. As Roger Hutchins mentioned earlier, this kind of coordination is very difficult to undertake particularly in the present economic climate where we are all responding to a situation that is basically forcing quality further and further downward every day. From my viewpoint that is a comment that has a major impact on where we can go as a team, whether we are a conceptual team or a real team.

COMMENT - ROGER HUTCHINS

I do not think you can separate economics out. The expertise is clearly in this room and elsewhere. The successful problems that have been solved in this country have been done by teams. The problem has been well defined for example in the Beaufort Sea Study Groups. If the problem could be well defined whether it be a Pacific clay problem or the sand lens problem, I think teams can be put together. I think there are means of doing that and maybe such a suggestion represents an important addition to the agenda.

COMMENT - JIM MITCHELL

I think we have forgotten a very important member of the team and that is the geologist. A philosophy I have is that if you know what is there and where the boundaries lie then you are along the way to solving your problem. You will be further ahead if you know the geology therefore you should have at least a three member team which includes a geologist, a geophysicist and a geotechnical engineer.

COMMENT - ROGER HUTCHINS

There is a large difference between the geophysicist who has a broad training in a variety of rock properties and one with training in acoustics. I think you have to add an acoustician because you have a measurement problem.

COMMENT - JIM MITCHELL

I would like to know from a geologist if there is a good chance that the material in the Beaufort Sea has been acted on by a glacier and for how many years. These are the kinds of things that we should learn.

COMMENT - STEVE BLASCO

Basically, it is the geologist that is the driving force behind the Beaufort Sea work. There is quite a cohesive group working on Beaufort Sea problems which has been driven from the geologic end. However, we haven't really considered geology in this Workshop. Nevertheless, the geology is a very important component but at this point in time we are dealing with quantitative geology which is geotechnical engineering and geology (geophysics? Ed.) and we have included the acoustician too. Thus the geologist basically provides the concept.

COMMENT - MIKE JEFFRIES

May I add that the k_0 data fits the geologic model but it is not as simple as overburden pressure. You have to recognize the influence that a transgressive environment has on the clay sites. We have seen k_0 in excess of 2 in so-called normally consolidated clays, i.e., clays that have not been exposed to historical increases in overburden pressure than presently exists.

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OVERVIEW OF WORKSHOP

Dick Campanella

With the time that is left I would like to take a simplistic view of the proceedings in order that the civil engineers amongst us may see in a general way where some of the geophysical applications can help us and to present to the geophysicists some of our major concerns and problems. Not being too familiar with geophysical measurements, I would summarize that acoustics are used to measure stratigraphy and topography, and obtain bulk density from the compressional wave speed. The following table lists what I see as the role of acoustics in engineering studies.

ENGINEERING PROPERTIES - ROLE OF ACOUSTICS

Acoustics —— Compressional (p) waves —— Topography
Stratigraphy
Impedance -
Bulk Modulus

Seismics —— p & s (shear) waves —— As above plus
Shear modulus
Bulk modulus -
Sediment type
Relative Density
Density

ENGINEERS REQUIREMENTS - PROJECT DEPENDENT

Stratigraphy —— Layering —— Changing properties
Density —— Only to calculate overburden stress
Strength (sands & clays) —— f(stress and stress history)
Information —— Shear Modulus, G
Constrained Modulus, 1/mv
In Situ Stress —— Horizontal stress
Permeability —— Ground water and seepage

COMMENT - ROGER HUTCHINS

Actually, reflectivity is a measure of acoustic impedance which is a product of the bulk density and sound speed. However, sound speed can be determined independently. The sound speed is a help in determining your topography and stratigraphy.

COMMENT - DICK CAMPANELLA

Exactly. The end product for the user is the stratigraphy, topography and the density.

Q. (Roger Hutchins) What about bulk modulus?

Q. (Dick Campanella) Can we get bulk modulus from compressional (p) waves?

A. (Roger Hutchins) You need to have both the shear wave velocity and the compressional wave velocity.

COMMENT - DICK CAMPANELLA

I am attempting to differentiate between one technique and the other and if we need both p and s wave measurements simultaneously or can we get by with just one? My understanding is that you cannot derive bulk modulus from the acoustic data but if you can get a good correlation between the impedance and bulk density then by using correlation methods a prediction of bulk modulus can be made.

COMMENT - LARRY MAYER

I think that in order to make the list valid, you should only have stratigraphy, topography and impedance. We do not have a direct measurement of density. We have a measure of a density/velocity product.

COMMENT - DICK CAMPANELLA

As an engineer, none of our equations require impedance but bulk density is certainly useful.

COMMENT - FROM FLOOR

It appears that you cannot get bulk density without either deriving it or assuming some value.

COMMENT - STEVE BLASCO

The stratigraphy, topography and impedance are direct outputs but bulk density has to be derived from these so that measurements of bulk density are one step removed.

COMMENT - ROGER HUTCHINS

It is not quite true to say that stratigraphy is a direct output because calibration is required if it is to be reduced to spatial distance. The only thing that acoustic measurements will give are time, amplitude and phase.

Q. (Dick Campanella) What I would like to ask the floor now is, can we put a degree of confidence in the three measurements?

A. (from floor) We would do best with topography.

COMMENT - ROGER HUTCHINS

Sure, because it's a direct measurement. But on land, topography is not simple.

COMMENT - LARRY MAYER

We have more problems with stratigraphy because of the resolution problem. The broader the bandwidth of the system, the closer we get to a true stratigraphy.

COMMENT - ROGER HUTCHINS

Arranging the acoustic measurements in order is risky unless you know exactly your source function.

COMMENT - DAVID CAULFIELD

All the above assume that there is good engineering quality control on the entire seismic system, otherwise measurements are meaningless numbers.

Q. (Dick Campanella) Let us assume that the best equipment is available. Can we get both p and s wave information at seismic frequencies?

Q. (from floor) Why do we not define the difference between acoustics and seismics?

A. (Steve Blasco) The terms are used by this group interchangeably. Basically we are dealing with seismic stratigraphy. When we talk about stratigraphy, we generally use it in terms of the seismic response.

ADDITIONAL COMMENT

I wish to add that acoustics is up to 20 kHz whereas seismic energy does not generally exceed 500 Hz.

COMMENT - STEVE BLASCO

That is true but it is not generally adhered to.

COMMENT - DICK CAMPANELLA

Presumably when we generate p waves, we also generate shear waves. Presumably this should lead to properties relating more to shear wave velocity. Is it fair to say then that we can now get the bulk modulus as well as the shear modulus? This also raises the question of which of the two modulii is more useful to the geotechnical engineer? It is clear that the overall stratigraphic picture is extremely important to all designers as it helps to define where potential problems lie, but are the acoustic properties what the geotechnical engineers require. The list shows some engineering properties that are required for design. Stratigraphic information, layering and changes in the properties through different layers, discontinuities and other anomalies are definitely required although density which is required for overburden stress can often be estimated, or alternatively, obtained by sampling. Density is of minor importance when it comes to material strength especially with clays.

COMMENT - JIM MITCHELL

I think that to ignore the fact that parameters like density, relative density, grain size distribution and plasticity, etc., can't be used as correlating parameters is to overlook important factors in engineering.

COMMENT - DICK CAMPANELLA

I am speaking only in general terms. If only the density of a material was given, you would know little about a material. If you were told that the material was clay, from a grain size analysis point of view, you would require further information such as its plasticity or more importantly what its stress history has been and its depositional history. These parameters are considerably more important than density. Grain size in sands is more important because it affects the packing configuration, but as Jim Justice mentioned earlier, knowing the sand grain size only informs you that you are dealing with a sand.

Q. (Roger Hutchins) Why then is grain size in the list?

A. (Dick Campanella) Grain size is included because engineers identify stratigraphy by describing a material as sand or clay or some other material.

COMMENT - ROGER HUTCHINS

I don't think the seismic experts can give you grain size. If he does then the results should be treated with caution.

COMMENT - LARRY MAYER

We saw a graph yesterday that showed acoustic impedance versus grain size.

COMMENT - DAVID CAULFIELD

That graph came from historical work of Hamilton and Brezlau who were trying to establish if acoustic impedance was directly dependent on geology or a function of the geology.

COMMENT - ROGER HUTCHINS

Very much depends on the depositional environment or processes, so I think it should not be on the list.

COMMENT - FROM FLOOR

Maybe we should use the word lithology.

COMMENT - ROGER HUTCHINS

You could include porosity.

COMMENT - FROM FLOOR

Hamilton will freely admit that grain size does not correlate well with other properties. He has used grain size to satisfy Navy requirements when typical values are requested.

COMMENT - DENZIL TAYLOR-SMITH

I think the problem is based on the fact that if you have high velocities, you have low porosity and the low porosity sediments are usually sands. That's the basic relationship and if you can get a velocity/porosity relationship you can get a velocity grain size relationship. This is not as good as the porosity/velocity relationship but it shows that you have high velocities in sand and low velocities in clays.

COMMENT - FROM FLOOR

Hamilton has used grain size because grain size information is available.

COMMENT - LARRY MAYER

Hamilton's graph of acoustic impedance versus grain size shows an overall correlation, but, for a particular depositional environment, the correlation is very poor.

COMMENT - ROGER HUTCHINS

From the Navy's point of view, what is required is how the geology affects the acoustics. Our objective is to determine the geology by looking at the acoustics. To estimate the acoustics from the geology can be accomplished with more confidence than *vice versa*.

Q. (Larry Mayer) Can we use acoustics to define the type of sediment and how in fact do we define sediment type? Is it not defined on the basis of grain size?

COMMENT - FROM FLOOR

There are certain classes of problems that can be associated with certain classes of materials.

COMMENT - JIM MITCHELL

If my problem happens to be a seepage problem I know I am dealing with sand, and in spite of what has been said, grain size would tell me much about the permeability.

COMMENT - FROM FLOOR

Very often there is a difference in acoustic reflectivity when you pass from a shell to a clean sand and coarse grain material will have a higher reflectivity than both. Yet they would have approximately the same sound velocity.

COMMENT - LARRY MAYER

Yesterday I presented an impedance profile measured from a deep sea core and I indicated how a synthetic seismogram could be generated. The conclusion was that reflections did not necessarily represent discrete layers in the sediment but often could be interference composites. This implies that if you change the frequency and shape of the outgoing pulse you will also change the resulting echoes. It is obvious that if you are going to study real layering of sediments, it is absolutely necessary to meet the resolution requirements.

COMMENT - ROGER HUTCHINS

If you have a precise knowledge of your source function you can upgrade stratigraphy.

COMMENT - LARRY MAYER

You can deconvolve it if you have the bandwidth.

Q. (Dick Campanella) Have we eliminated grain size?

COMMENT - FROM FLOOR

Sediment type could be added to the properties on the list.

COMMENT - ROGER HUTCHINS

Change in sediment type could be added since you may not know what it is but you may know that it has changed in character.

COMMENT - FROM FLOOR

From a geophysicist's standpoint, when you are mapping stratigraphy, the first thing to do is to obtain regional control and map those reflectors which are considered to be real. If you have cores, you would ascribe some general lithology to them and identify seismic units such as a, b, c, because of their laterial continuity. In this way you would arrive at a gross stratigraphic model which would indicate gross lithology.

COMMENT - ROGER HUTCHINS

You are alluding to variability which can be measured?

Q. (Dick Campanella) This introduces the concept of relative density. Can changes in the material within a sequence be detected? In other words, if a material is sand, can it safely be said that it is denser in one area than another?

A. (Roger Hutchins) Yes.

COMMENT - DENZIL TAYLOR-SMITH

You can get a different velocity for a different packing relationship on the same material and you can also get a different velocity relationship on a different material. The variability measured as velocity changes may not necessarily be due to relative density changes. As presented yesterday by Peter Simpkin, if you have a sample of sand collected at a site where in situ sound velocity data are available then an in situ value of relative density can be obtained.

COMMENT - PETER SIMPKIN

The concept described yesterday involved measuring sound velocity on a sand sample over the complete range of relative density values (and porosity). With the resulting characteristic curve, in situ measurement of sound velocity could then be used to estimate an in situ relative density value.

COMMENT - MIKE JEFFERIES

The data I presented earlier was for the same sand. It was uniform in terms of grain size and silt content over the upper 15 m - 20 m. There appeared to be four sub-units in terms of density. Each sub-unit appeared to have a separate horizontal stress which would affect the stiffness as much as the porosity differences would. If you measure sound speed you cannot work backwards and infer porosity without an independent measurement of stress.

Q. (from floor) Are porosity and density one of the same thing?

A. (David Caulfield) For a fully saturated marine sediment, the answer is yes, with the exception where gas deposits exist as demonstrated by Mike Jefferies.

COMMENT - DICK CAMPANELLA

I would like to move on from the relative density question down to engineering parameters that are used in design because I believe that significant information is obtainable from shear wave velocity measurements. From what I have observed, shear wave velocity may give an estimate of shear modulus and shear modulus is sensitive to in situ stress. So in fact, we may have another indicator of stiffness through a measurement of the shear modulus. Therefore, what is the potential for categorizing shear wave velocities in different sediments? Is this easily done?

COMMENT - ROGER HUTCHINS

I think it requires contact with the interface.

Q. (Dick Campanella) With detectors right on the sea bottom?

A. (Roger Hutchins) I think a three-component seismometer would do that.

Q. (Dick Campanella) Can you pick up sufficient information to give shear wave velocities in the layers?

A. (Denzil Taylor-Smith) It can be done on land but whether it can be done on the seafloor is a different problem.

COMMENT - FROM FLOOR

It is possible to do it on the seafloor, but unless a horizontal shear wave is generated, you will not measure horizontal shear wave velocities. You will have vertical shear and converted shear wave energy however.

Q. (Dick Campanella) Is there a technique to determine shear wave velocity for vertical particle motion as opposed to horizontal particle motion in order to estimate the in situ stress ratio or the K_o measurement? Such information would be extremely useful.

A. (from floor) Such a measurement would have to be done in the borehole and not by imaging using normal horizontal seismic procedures. Perhaps a downhole vertical seismic profile would be of value, but direct downhole measurement may be preferable.

COMMENT - DICK CAMPANELLA

It is conceivable that with triaxial seismic detectors on the seafloor such information may be obtained without resulting to borehole measurements?

COMMENT - ROGER HUTCHINS

I think you need borehole measurements.

COMMENT - PHIL STAAL

Our work at the Defence Research Establishment has tended to involve interface waves. We haven't produced horizontal or vertical shear waves.

COMMENT - JIM HUNTER

I believe that using an array of shear wave detectors on the seafloor would produce the same uncertainties as refraction measurements on land. Also, I suspect that large wavelengths would be necessary in order to propagate any distance with a resulting loss of resolution.

COMMENT - JIM MATTHEWS

We conducted an experiment last fall using diver-deployed three-component geophones and compressional and shear wave sources. The source was essentially a hammered plank and although there are many problems the procedure has considerable potential. We collected cores and made laboratory measurements together with compressional and shear wave velocities and also investigated anisotropy. The data was collected over about 50 m and although it is shallow data the results are quite consistent. One of the major problems is identifying the arrivals. They can be very complex but the concept should be pursued because I cannot see how any great value can be gained from compressional wave measurements. I am interested in shear propagation because of the range of magnitudes in the shear wave velocity. The velocities we have measured for natural clays are around 6-7 m/sec whereas in sands velocities exceed 100 m/sec.

COMMENT - DICK CAMPANELLA

My interest in shear wave velocity is more of a physical nature because the shear wave energy is transmitted through the skeletal structure of the material whereas the compressional wave travels through the medium.

COMMENT - JIM MATTHEWS

I was interested in your data display yesterday, not only in terms of the velocity itself, but in the velocity gradient. The sands showed a shear wave velocity gradient of 20 seconds^{-1}. This would not be obtainable in clay, but shear wave velocities in hard clay and a sand may overlap.

COMMENT - DICK CAMPANELLA

We have found that in many cases, we can characterize a shear stress versus shear strain curve with a knowledge of the maximum value of the shear modulus. If then we had a value of the ultimate shear strength, which for example in a clay would be obtained through a vane shear test, then we know that the curve can be approximated by a hyperbolic relationship. The resulting stress/strain curve for the material can then be projected to very large strains.

COMMENT - JIM MATTHEWS

Personally I do not see a great future in shear attenuation. Compared with what we have heard in the last two days, shear attenuation is a "black art".

COMMENT - DENZIL TAYLOR-SMITH

I do not agree with the last statement. If you are involved in a seismic risk assessment problem, then you need to know a damping figure. Where will this be obtained?

COMMENT - JIM MATTHEWS

I am not saying that shear wave attenuation is not needed. We have made laboratory measurements of shear wave attenuation and find that changing the transducer coupling pressure on the sample by 1 gram/sq. cm will change signal amplitude by 20-30 dB.

COMMENT - DENZIL TAYLOR-SMITH

I agree that in situ measurement of shear wave attenuation is difficult, but you could do an analysis similar to that described by Peter Simpkin for compressional wave measurements and obtain a value for damping (for a particular packing density) by using a resonant column test. You could measure the change in shear wave velocity throughout the range of packings and eventually obtain a value equivalent to the in situ measurement.

Q. (Roger Hutchins to Denzil Taylor-Smith) What happened to your acoustic probes? Weren't you measuring shear wave velocities several years ago?

A. (Denzil Taylor-Smith) Yes, we still are. We have a probe which goes on the seafloor.

Q. (Roger Hutchins) Does this work?

A. (Denzil Taylor-Smith) Yes.

COMMENT - LARRY MAYER

We may want to discuss if attenuation measurements can play an important role in support of parameters which seem to be showing promise (as estimators of the geotechnical condition).

COMMENT - FROM FLOOR

Shear wave damping is required for some of the dynamic studies. I know of one technique that has been used where three detectors were positioned at different distances from a source. The source was operated at three different energy levels with a result that three different levels of shear strain at three different distances were obtained. This results in the shear modulus dependency on the strain and also gives the damping parameters.

COMMENT - JIM MATTHEWS

I would support the last speaker if the degree of coupling could be guaranteed. However, a fraction of a layer of water between the probe and the sediment will produce great variability in the results. I will accept what has been said providing coupling is identical for each shot. However, a very thin layer of water between the probe and sediments will produce meaningless results.

COMMENT - MIKE JEFFERIES

I would like to suggest that my answer to Larry Mayer's question concerning our interest in attenuation is "yes" but not for the reasons discussed previously. As I mentioned earlier, in the Geertsma and Smit solution to the Biot equation, there are three major variables which means that three independent field measurements must be made. On a particular field project with which I was involved, our aim was to measure the saturation of tailings. We measured the p and s wave velocity but failed to make a third measurement. Thus with two measurements and three independent variables we were not able to conclude the work. We did learn however, that although attenuation may not be a well conditioned problem it may provide a chance at measuring saturation.

COMMENT - LARRY MAYER

I think also there may be more hope in terms of using attenuation to identify a sediment type as we defined earlier.

COMMENT - MIKE JEFFERIES

I have to say "yes and no". Using those Biot equations, a small degree of partial saturation will actually dominate the sediment's contribution to damping. The gas content totally dominates the entire equation in terms of velocity and damping. So I think it may be a good measure of gas content, but unless perfect saturation can be assumed, which I doubt very much, then I don't think attenuation can be used to identify sediment type.

COMMENT - JIM MATTHEWS

In investigating the Biot theory, we have made laboratory shear wave attenuation measurements at 18 frequencies between 1 kHz and 20 kHz in three different sand materials. We inverted a Biot and Stoll model and held the frame moduli constant. Although, we did not get a perfect fit to the model, our values did appear reasonable.

COMMENT - DICK CAMPANELLA

One point that I wanted to make on measurement of the shear wave velocity is the importance of reproduceability and accuracy since in estimating the bulk modulus, the shear wave velocity is raised to the power of 2.

There was mention made of constrained modulus which is a parameter that relates compression to the effective stress in a material. I personally think that this parameter cannot be obtained from a compressional wave measurement. I seek comments from the panel.

COMMENT - DENZIL TAYLOR-SMITH

I think it is possible with a good measurement of the p wave velocity but a further parameter, the void ratio at the in situ condition, is also required.

COMMENT - DICK CAMPANELLA

I was skeptical of such a process.

COMMENT - DENZIL TAYLOR-SMITH

The important point is that a good measurement of velocity is required.

COMMENT - DICK CAMPANELLA

The last point I wanted to address was permeability, ground water and seepage conditions. I would like to consider if acoustics can play a role in measuring these types of parameters. Another requirement would be for information about the water in the formations.

Q. (From Floor) What kind of water movement are you talking about?

A. (Dick Campanella) Very slow pressure gradients.

COMMENT - DENZIL TAYLOR-SMITH

I think the problem is that there are so many definitions of permeability. This morning Mike Jefferies discussed the Geertsma and Smit analysis of Biot which results in what is called velocity at zero frequency. The velocity at zero frequency is virtually the velocity for a very low permeability material. So if an in situ velocity measurement on clay is made the result would be similar to the Geertsma and Smit solution at zero frequency. If you then increase the size scale or the permeability scale differences between the calculated zero frequency velocity and the velocity that could be measured would be observed. So the difference between the zero frequency velocity and the actual velocity is a function of the permeability. But again, the reliability of this method depends on how well in situ velocity can be measured. For instance, if the velocity difference is 100 m/sec and the in-situ velocity cannot be measured to better than 100 m/sec there is little point in continuing the analysis. Theoretically, it can be done and some people have been successful in the laboratory, but I am not sure if it's being done on the seafloor.

COMMENT - MIKE JEFFERIES

In principle, it is possible, but great precision is needed. Particularly, in frequency. It is a very ill-conditioned problem since permeability is a second or third order parameter for the Geertsma and Smit solution. Just one bubble of air in a litre of sand will render results useless.

COMMENT - DENZIL TAYLOR-SMITH

Permeability measurement would be a problem whichever way it was attempted. Geophysics will give an estimate within an order of magnitude.

COMMENT - JIM MATTHEWS

Compressional wave attenuation will distinguish between a clean sand and one with a very small amount of clay. Only a small amount of clay is needed to decrease permeability in terms of the Biot theory. The attenuation of a synthetic sample of clean sand is very large.

COMMENT - DICK CAMPANELLA

There are two other problems that concern permeability. One is the tremendous range of values that can exist and the other is whether a pressure gradient exists. If a pressure gradient does not exist then no matter what the permeability is there will be no fluid flow. Another possibility is that a clay layer will retard and hold back fluid and when excavated will cause many problems. These problem areas are mentioned to provide food for thought when interpreting acoustic information.

Q. (Dick Campanella) Are there any other comments that the panel and guests would like to make before bringing this session to a conclusion?

COMMENT - FROM FLOOR

Our discussions so far have addressed whether or not geophysics can give us a measure of certain properties such as permeability and strength parameters. It is probably fairly safe to say that if you have a certain material, it must have certain physical properties and I think it would be interesting to ask the question, whether or not we would be able to infer the material type by measuring certain physical properties and then knowing the material type to infer other properties, the engineering properties. Electrical properties in particular have not been mentioned and these are fairly easy to measure.

COMMENT - DAVID CAULFIELD

We all realize that grain size itself is not a unique function, but once you have identified a given characteristic, then you have the start of a classification scheme.

COMMENT - FROM FLOOR

That is a good point. The grain size in itself is not a unique characteristic, but is combined with the geological parameters such as the shape of the pores or the type of porosity. There are three types of porosity that can be defined. There is intergranular porosity and then connective porosity where you have narrow channels with the grains fairly close together and then microporosity which is associated with clay platelets. If you know the types of porosity and the clay content then you may ultimately be able to relate physical properties to geological properties and then to engineering properties. Not only in the field, but also under laboratory conditions.

COMMENT - DENZIL TAYLOR-SMITH

We have avoided electrical measurements because this is basically an acoustical/geotechnical workshop but electrical measurements are an important part of geophysical site investigation. Electrical resistivity, or formation factor, is much more sensitive to changes in porosity than seismic p wave velocity. It is also little effected by gas entrainment. I believe there is a good case for merging electrical measurements into the acoustic data in order to measure in situ void ratio without going to field measurements.

COMMENT - PETER SIMPKIN

The important point about resistivity measurement is that it is a volume rather than a line of sight measurement.

COMMENT - MIKE JEFFERIES

I would like to suggest we go one stage further from pure resistivity and the volume inference to formation factor and the sand grain arrangement. All the work that is presently being conducted on sands suggests that grain arrangement is extremely important during the initial part of the loading curve and that's frequently the portion of the loading curve that structures are designed to operate at. We should try and consider that resistivity be introduced into routine site investigations since once a borehole is drilled resistivity is a fairly easy measurement to make.

COMMENT - JIM MITCHELL

Yesterday Ken Baldwin clearly showed that a material could have the same absolute density but different seismic wave velocities, different resistances to liquefaction, and different formation factors.

COMMENT - FROM FLOOR

Resistivity is extremely important when doing modelling. A seismic section can be used to extrapolate from a drilled well. If resistivity data had been collected in the well the water content is available and gamma (nuclear) measurements will indicate sand or shells. All these data are linked and the quality of the data is determined by the quality of the measurement. But not only is measurement important, engineering and sometimes geophysics can be seen as an exact science whereas geology is an experimental science. The best model will involve running a seismic line over a well that has been logged.

SUMMARY OF THE DAY'S PROCEEDINGS

Denzil Taylor-Smith

In yesterday's presentation and today's discussions we have been exposed to a wide range of problems including propagation over long distances and the relationship between acoustics and geotechnical quantities. I believe that what is required is a merging of problems and techniques in order to find some solutions. Looking at the requirements for the future:

NEEDS

1. **Instrumentation to create and detect shear wave reflections and refractions on ocean floor. Parameters required: shear wave velocity and damping.**

2. **Further development of cone penetrometer to include compressional wave, shear wave and resistivity devices.**

3. **Same as (2) for self-boring pressuremeter and/or dilatometer.**

4. **Computer solutions to Biot's theory to get fundamental information - permeability, compressibility. (This requires assessing p-wave velocities over wide range of frequencies - 0 Hz - 100 kHz say).**

5. **Instrumentation - resonant column modification - to give G_{max} variation with strain level and strain rate.**

6. **Assessment of quantities on sites where building performance data available.**

There are many people working on shear waves and what must be considered as a priority is to obtain some accurate <u>in situ</u> measurements of shear wave velocities, and perhaps attenuations, as well as making compressional wave measurements. But what is lacking at the moment is a good analysis of the production of shear waves and an analysis of the data that shear waves produce. What can be done in this direction is to generate and measure shear waves on the seafloor in a refraction mode. But the refraction mode does not accommodate velocity inversions with depth as would be encountered, for example, with the clay problems that were mentioned yesterday and discussed today. In order to study the effects of velocity inversion, we need some form of study of the reflection processes involving shear waves. Also we need to know whether horizontal shear or vertical shear waves are being produced and propagated. One possible experiment could be similar in nature to that described by Jim Hunter but involving shear waves rather than p waves. Such an experiment may give shear wave velocity variations with depth.

In terms of creating an element of respectability with the engineering community the geophysicist must develop close associations and become more involved in measurements during site investigations. As was mentioned yesterday, cone penetrometers and pressuremeters could be modified to carry geophysical measuring systems so that geophysical information can be obtained from the same zone as the engineering parameters.

Leading to Biot's theory, and the concerns raised by Mike Jefferies that various solutions to Biot's equation exist. What is required is a study of the various solutions to see if the variations in the parameters can be measured under laboratory conditions. In my studies of the Biot equations which involve a modification of the Geertsma and Smit approach, one of the major problems is that a large variation in the results is obtained when the mass coupling factor is changed. Mass coupling is of particular importance when attempting to extract permeability information from velocity measurements. It was pointed out yesterday that we should consider the basic physics of the material and ask the question "What are the quantities we need to measure"? And although Biot's approach is useful for the sort of materials that make up the seafloor, it may not be the correct analysis. There may be others that are as yet unknown. We do need to study the fundamental problem and analyse the variables that we are measuring. If we are looking at velocity variations, then these should be measured over a wide range of frequencies. Other areas for instrumentation development include measurement of the confining stress and in obtaining G_{max} from shear wave data.

The resonant column technique has been used extensively in earthquake dynamics but has not been used in problems concerning the seafloor. There is a need to use the resonant column to measure the effects of confining stress, the different strain levels, and the rate of strain within a material. The resonant column also allows estimates of Young's modulus using compressional and shear wave data. We have attempted to compare measurements made in the field to measurements made in the lab using the resonant column method. Although this work is at an early stage, there seems to be a resonable agreement between the values of G_{max} as given by a pulse technique in the field to the values of G_{max} made using the resonant column method.

In attempting to be realistic the geophysicist has to say that quantities that are being measured relate to the stresses involved in actual building construction. For this we need to have historical data so that the performance of a building could be assessed and differences between the original design estimate measured. There must be vast quantities of such data in archives which could be researched to provide a valuable insight into building performance. Over the last two days, we have discussed problems that need solutions and perhaps in a couple of years, we should meet again and see how far we have progressed. The important aspect of such gatherings as this is that it allows all of us to appreciate each other's problems. This is certainly a healthy situation.