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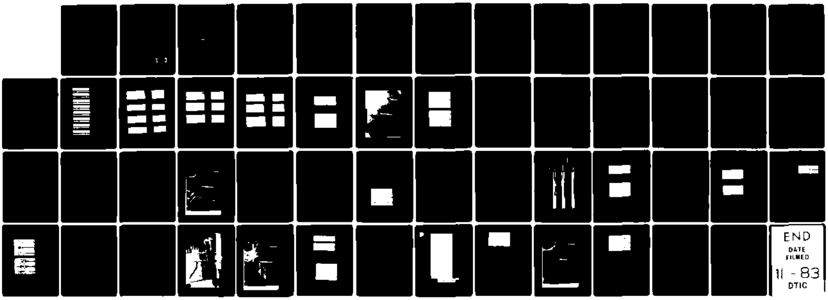

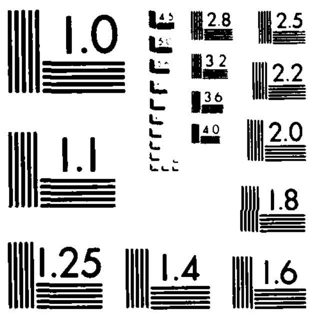

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DEVELOPMENT OF ULTRASONIC MODELING TECHNIQUES
FOR THE STUDY OF CRUSTAL INHOMOGENEITIES

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Cambridge, MA 02139

Final Report
1 June 1981 - 30 September 1982

August 1983

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The character of surface wave scattering at local distances depends strongly upon surface topography and local crustal structure. Ultrasonic methods were used to investigate the behavior of seismic waves propagating through scale models of topographic structures suspected of contributing to the scattering of seismic waves. Simple models, consisting of steps and rectangular-and triangular-shaped "mountains" of varying dimension, were used in an empirical analysis of scattering of surface waves. Realistic seismograms were generated (over)

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20. for a detailed scale model of the surface topography at Dry Valley Lake, Nevada. The addition of horizontal layers results in more complex seismograms, owing to dispersion and multiple reflections and conversions of the incident Rayleigh wave energy. Transmission of Rayleigh waves through the structure is improved with the addition of sedimentary layers. Finite difference methods were used to investigate the nature of the scattering produced by a scale rectangular "mountain". Upon encountering the "mountain", the incident Rayleigh wave becomes severely distorted, and the "mountain" re-radiates much of the incident energy in the form of body waves. The synthetic seismograms reveal a corresponding increase in the complexity of the transmitted signal. The finite difference method offers a valuable new approach to the interpretation of scattering phenomena.

INTRODUCTION

The following report represents a summary of the work that has been done in the past year in the study of seismic wave scattering. The joint CSDL/MIT efforts in this study have been separated into three areas of investigation. Two areas are within the realm of ultrasonic modeling. First, simple models are used for the empirical analysis of scattering and dispersion. Second, structural features found in the earth are carefully modeled, making it possible to generate realistic synthetic seismograms. The third area of interest is numerical modeling where important contributions have been made through finite difference calculations.

In the past year, the work on these three fronts has begun to coalesce. Insights have been gained concerning the propagation, dispersion, and scattering characteristics of surface waves passing through a medium with lateral and surface heterogeneities. The research has also received a clearly defined direction. In the future, numerical calculations and simple lab models will be used to quantitatively describe the scattering parameters for a broad class of different structural and topographic geometries. In conjunction with this, detailed models and complicated numerical simulations will allow geographic localities to be modeled in the lab. This will have important consequences concerning the determination of regional seismic safety.

A summary of past research in wave scattering, using analytic, numerical, and laboratory methods, is given below. Various analytic treatments of lateral heterogeneities have been given by Hudson and Knopoff (1964), Mal and Knopoff (1966), McGarr and Alsop (1967), and Gilbert and Knopoff (1960).

The finite difference method has been applied to scattering by Boore (1970), Alterman and Loewenthal (1972), Munasinghe and Farnell (1973), Fuyuki and Matsumoto (1980), and Boore *et al.* (1980).

Experimental modeling using specific geometries can be found in Knopoff and Gangi (1960), Martel *et al.* (1977), and Nathman (1980).

In this report, the contributions from experimental and numerical work will be summarized. We will outline the work that has been accomplished in each of the three areas of investigation that were discussed above. We will take a particular geometry (the case of a rectangular 'mountain' or 'valley') and show how it is treated in each area of research. Thus, we will demonstrate that the results from each area complement one another.

SIMPLE LABORATORY MODELS

Piezoelectric transducers are used as sources and receivers. A magnetostrictive material such as nickel is used as the medium. The case of steps (Figure 1) has received careful analysis. The seismogram of the receiving transducer can be digitized for subsequent decomposition of the waves. For example, reflection and transmission coefficients can be calculated making it possible to compare steps of different height. From the amplitude and phase spectra we can identify wave composition and dispersion characteristics. Some of the results can be found in Toksoz *et al.* (1981). Similar work has also been done by Gangi and Wesson (1978).

Scattering can be treated quantitatively with this model. Receivers can be placed as shown in Figure 2 with the resulting signals shown in Figure 3. The scattering characteristics of different shaped obstacles can thus be catalogued.

Varying the dimensions of rectangular 'mountains' is possible in this lab set-up. The results are shown in Figures 4 and 5. It is observed that the transmitted and reflected waves are sensitive to the geometry of the 'mountain'. However, detailed study of the differing wave components is not possible using this model alone. Comparing the reflections from rectangular and triangular 'mountains' (Figure 6), we can deduce that a larger fraction of the energy is converted into body waves at the corner for the rectangular 'mountain'.

ULTRASONIC MODELING

Much of the work at CSDL has been devoted to the fabrication of functional transducers and multilayered models. A detailed summary of this work has been given in the CSDL report by Chamuel (1982) which is included in this report as Appendix 1. The response of the piezoelectric transducers that have been developed is shown in Figure 7. An important characteristic of the shear wave transducer is shown in Figure 8: the capability of separating transverse and radial components.

The seismic properties of numerous composite materials have been tested in an effort to suitably model sedimentary layers. The interfaces between these materials have also been considered.

The transducers and modeling materials were applied to the three-dimensional model of Dry Lake Valley, Nevada (shown in Figure 9). This represents an extension of the simple rectangular 'valley'. The model was tested with and without sedimentary layers, thus making it possible to distinguish between the dispersive and scattering characteristics of layered media and topographical features. It was found that for the sedimentary-filled 'valley' the transmission of Rayleigh waves was greater than for the unfilled 'valley'. It is also useful to compare Rayleigh wave transmission through a flat region to that across an empty 'valley'. The 'valley' has the effect of reducing the signal by a factor of 10, attenuating higher frequency components, and creating an earlier body wave arrival.

It is possible to model the rectangular 'mountain' by placing two solid layers over a half-space. In Figure 10 the seismic properties of the model are given (with the solid layer parameters given in the first two rows). The seismograms generated by displacing the receiver away from the layered materials are also shown in Figure 10. The dispersive characteristics resulting from the layered media are observed in these traces. These traces can be compared to the seismograms in Figure 4 for the case of homogeneous layers. Reflection from layers and the formation of new modes result in the dominant features of Figure 10.

NUMERICAL MODELLING

The finite difference scheme with appropriate boundary conditions has been investigated. Some of the stability problems that are encountered are described in Ilan and Lowenthal (1976). The cases of steps and rectangular 'mountains' have been treated.

Figure 11 shows the input surface displacements. The Rayleigh wave scattering for the rectangular 'mountain' case is described. The geometry is shown in Figure 12. The top edge is a free surface with the other edge modeled as an absorbing boundary. For the specifics of the absorbing boundary conditions see Clayton and Engguist (1977). The finite difference scheme makes it possible to monitor the wave propagation over time. In Figures 13(a-i) vectors representing the particle displacement are plotted at each grid space for a particular time frame. The initial waveform is shown in Figure 13a. Many insights into wave conversion are gained from this simulation. We observe the resonance of the 'mountain'. Subsequently, the 'mountain' acts as a source for body waves. The seismograms for stations on the incident side of the 'mountain' are shown in Figure 14 with the seismograms from the transmitted side given in Figure 15. Analysis of the seismograms and 'snapshots' of Figure 13 gives us information on the wave composition in the near- and far-field.

The following observations can be made. In Figure 13c, the Rayleigh wave appears to track along the free surface. The first cycle of the Rayleigh wave has rotated. In Figure 13d the entire 'mountain' starts to resonate. A body wave is forming at the right corner of the 'mountain'. The surface wave itself appears to float across the inside of the 'mountain' just making contact with the other side. It is unclear if this energy would be considered a body wave or a surface wave when it crosses the interior of the 'mountain'. The 'mountain' continues to resonate as the energy trapped in the 'mountain' reverberates. In Figure 13f, a body wave has formed at the left corner of the 'mountain' while the transmitted surface continues to move away from the 'mountain'. The 'mountain' continues to resonate. In Figures 13(g-i), the Rayleigh wave leaves the grid and the 'mountain' finally damps out by radiating energy as body waves to the lower media.

Figure 14 shows seismograms 1-3 from the incident side of the 'mountain' as found in Figure 12. Seismogram 3 is closest to the 'mountain'. Complicated reflected phases can be seen along with the incident wave. Figure 14 also shows seismograms 4-8 on the transmitted side. The amplitudes gradually increase to a stationary value away from the 'mountain'. Also, the pulse compresses away from the step. In seismograms 7-8, a body wave is seen to form in front of the transmitted surface wave.

CONCLUSION

Ultrasonic methods applied to scale models of realistic earth structures and simple representative structures offer a powerful means of investigating scattering phenomena. In addition, the finite difference method provides a useful new approach to the interpretation of seismic wave scattering. For example, the interaction of a Rayleigh wave with a simple model 'mountain' is demonstrated with this method to be a complex process in which the Rayleigh wave excites oscillations of the 'mountain' as a unit. These oscillations decay by reradiation of body wave energy into the medium.

We now have the means to interpret ultrasonic seismograms using techniques similar to those used in terrestrial-scale seismology. The expected result is that laboratory modeling will receive a secure quantitative foundation, enabling correspondence between laboratory models and earth structure to be made with greater confidence in the future.

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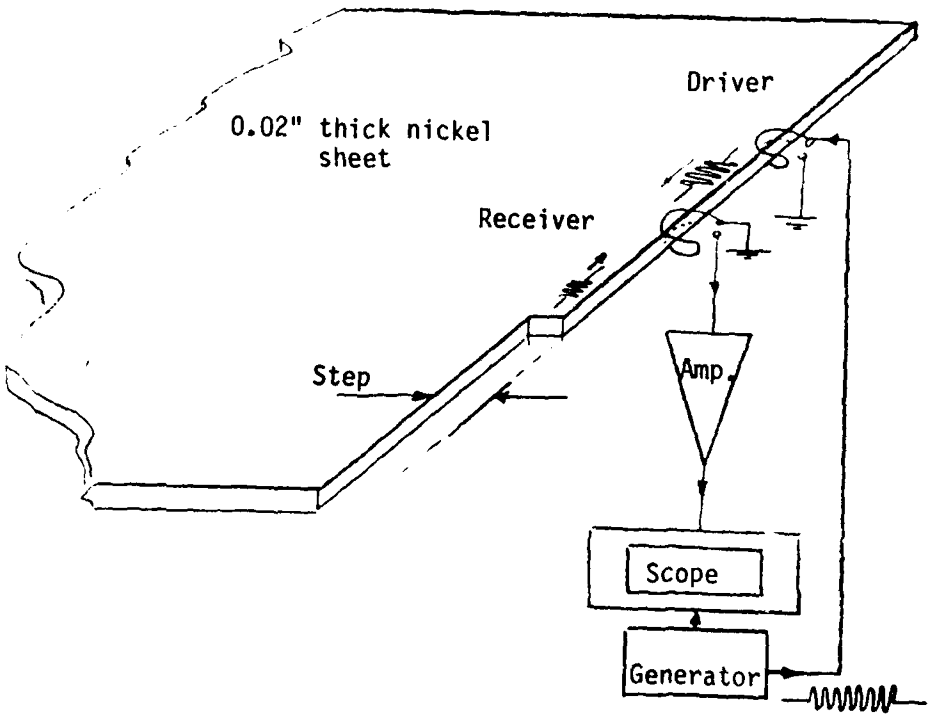


Figure 1. Laboratory set-up for two-dimensional step model.

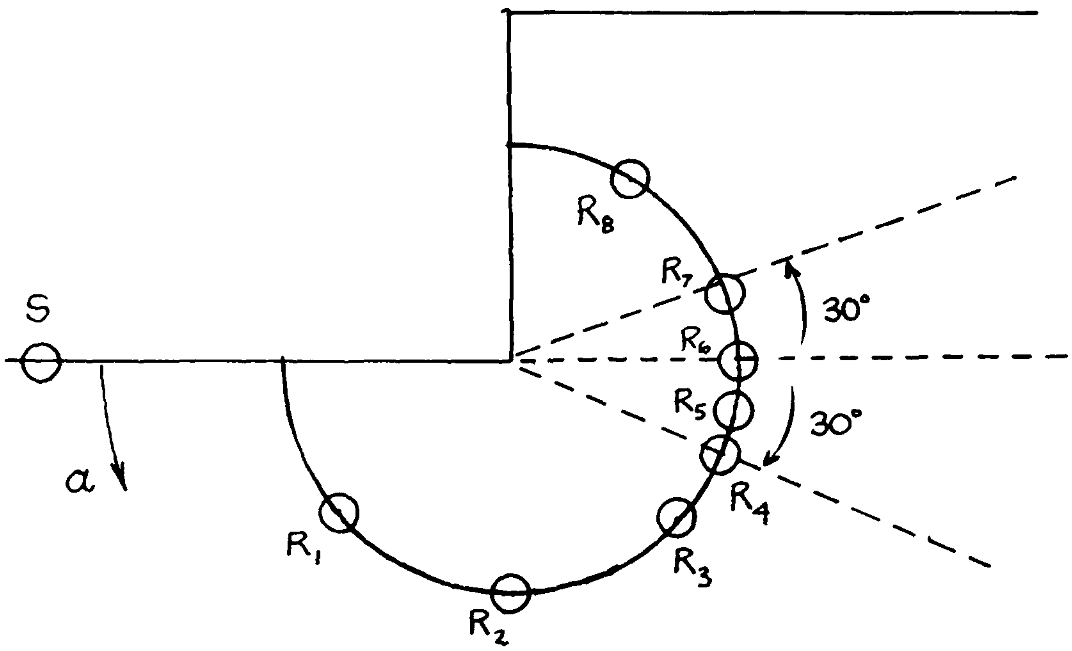
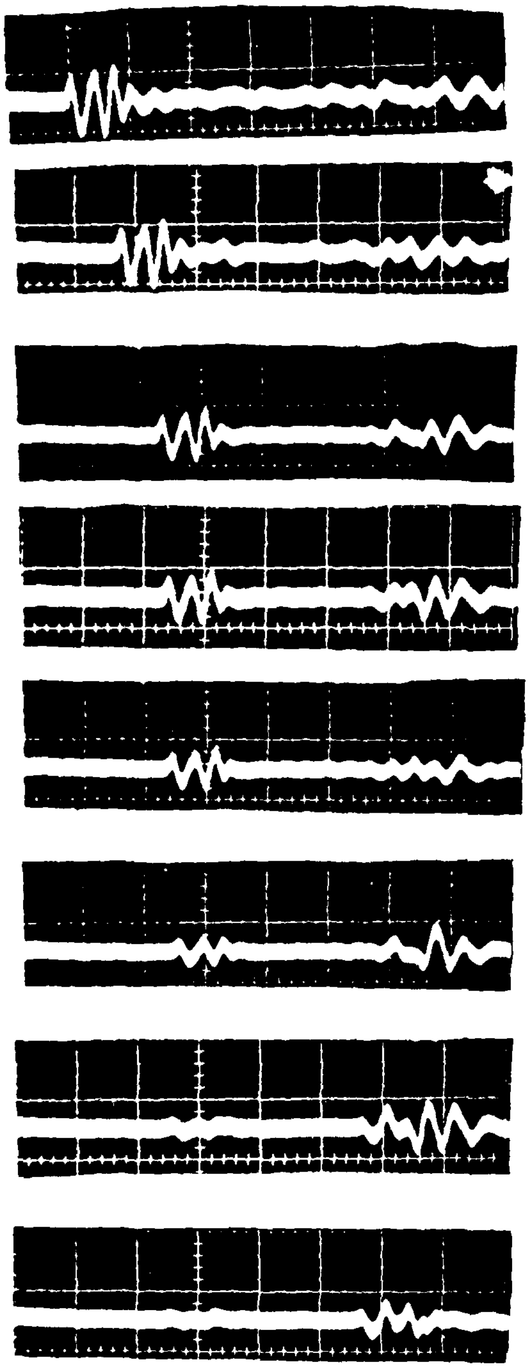


Figure 2. Receiver positions used to measure azimuthal scattering of step.



R_n	$\alpha°$	Distance (mm)
R_1	15°	165
R_2	90°	205
R_3	135°	237
R_4	150°	243
R_5	162.5°	247
R_6	180°	248
R_7	207°	245
R_8	237°	230

Figure 3. Seismograms corresponding to receiver positions shown in Figure 2.

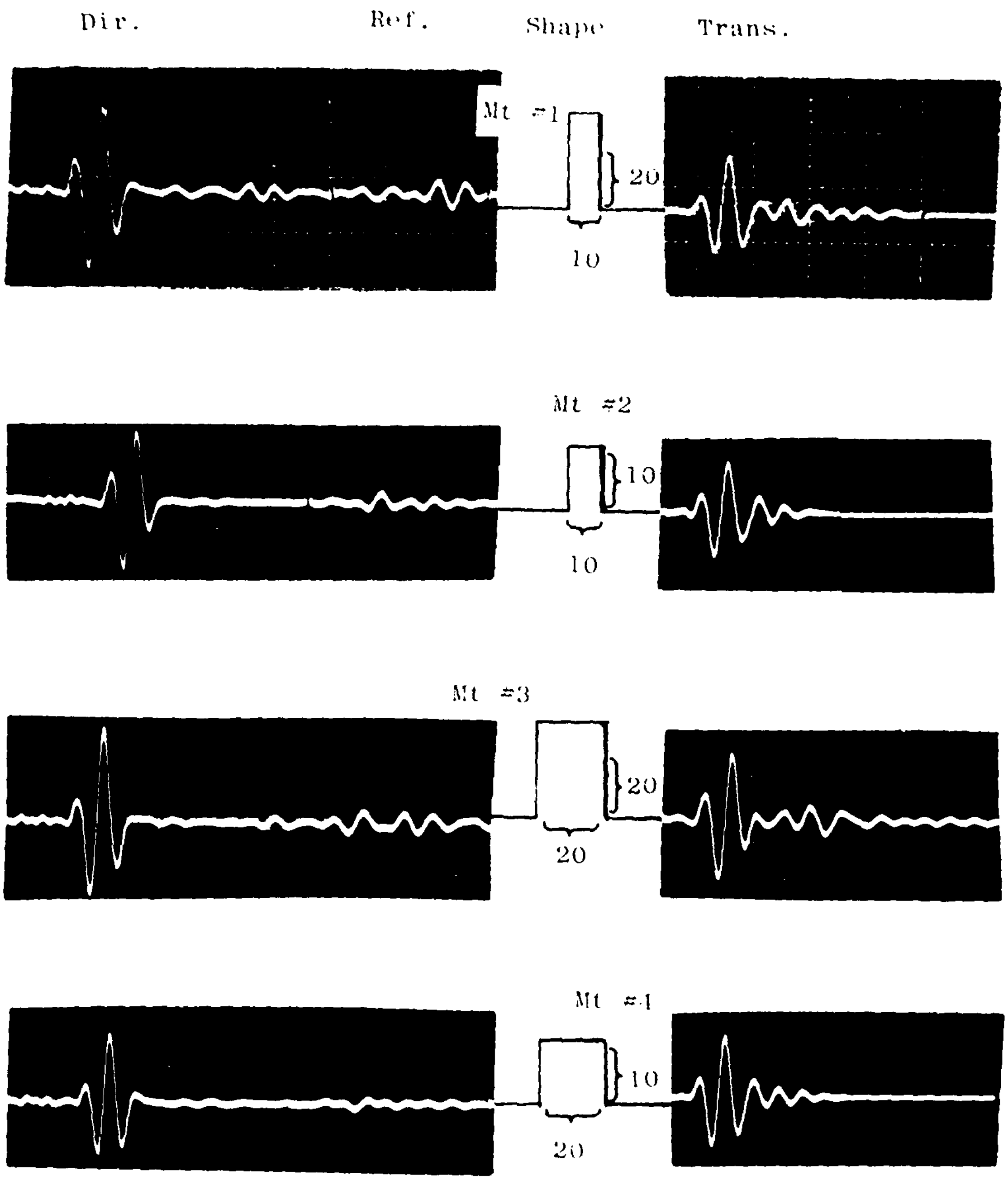


Figure 4. Seismograms of reflected and transmitted pulses for rectangular 'mountains' with different geometries.

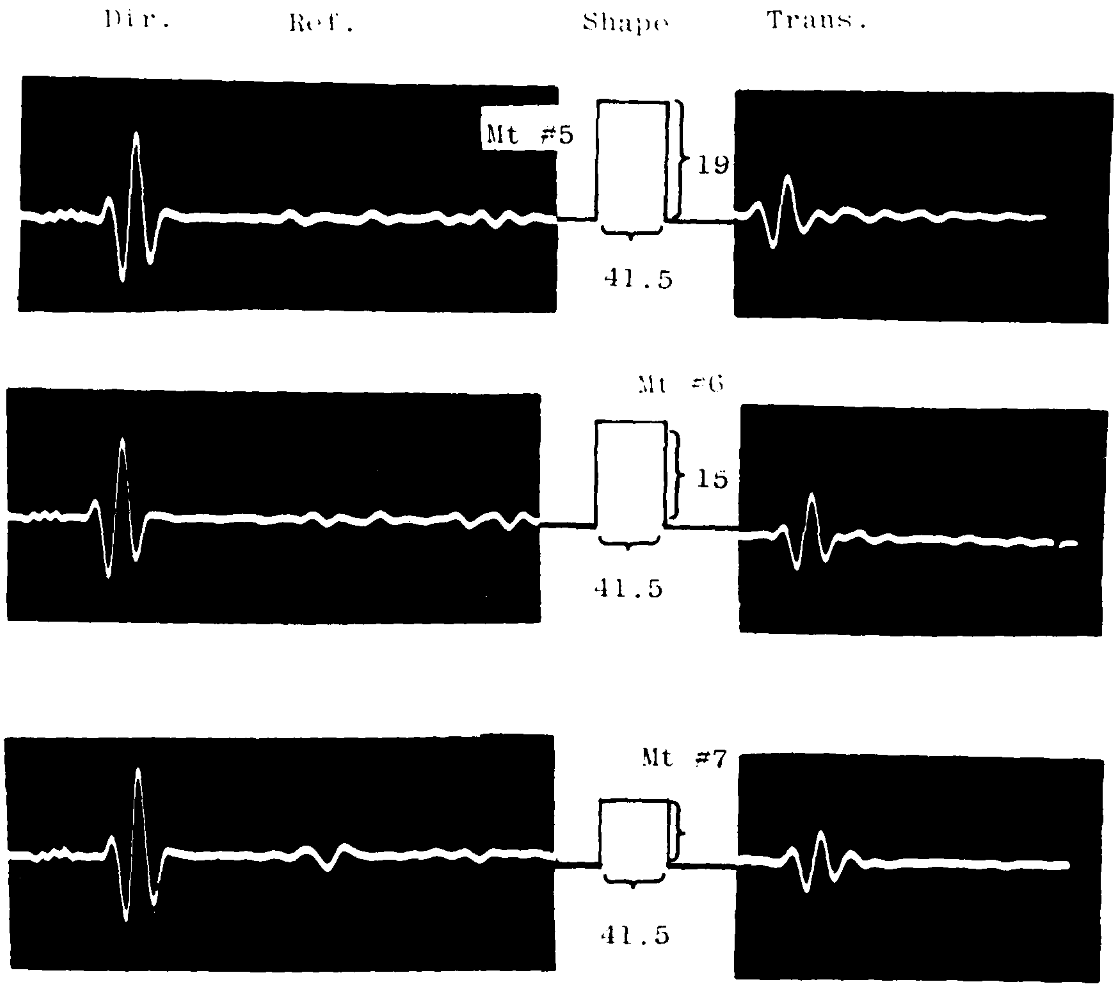


Figure 5. Seismograms of reflected and transmitted pulses for rectangular 'mountains' with different geometries.

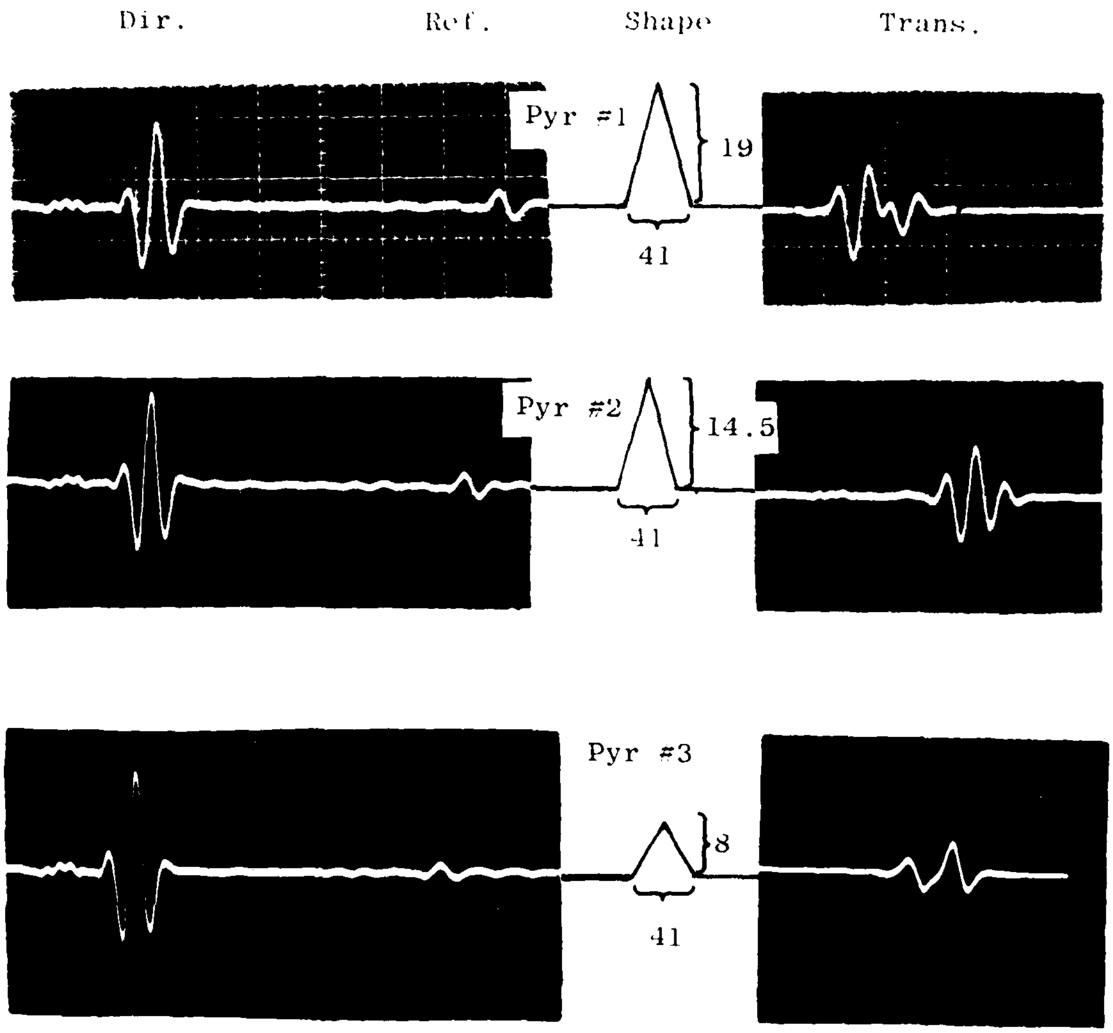


Figure 6. Seismograms of reflected and transmitted pulses for triangular 'mountains' with different geometries.

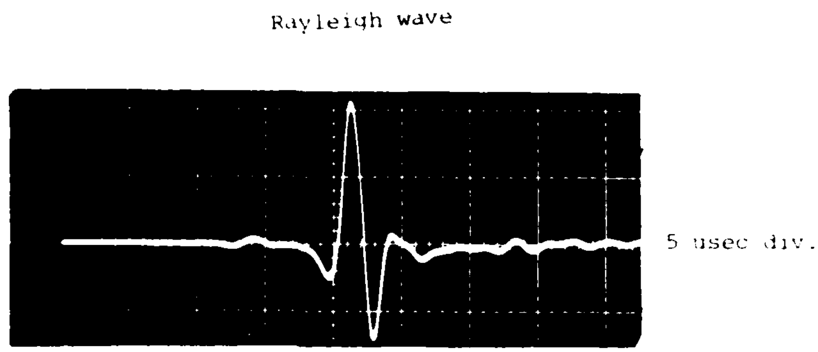


Figure 7. Response of compressional transducers separated by 5 cm. (from Chamuel, 1982).

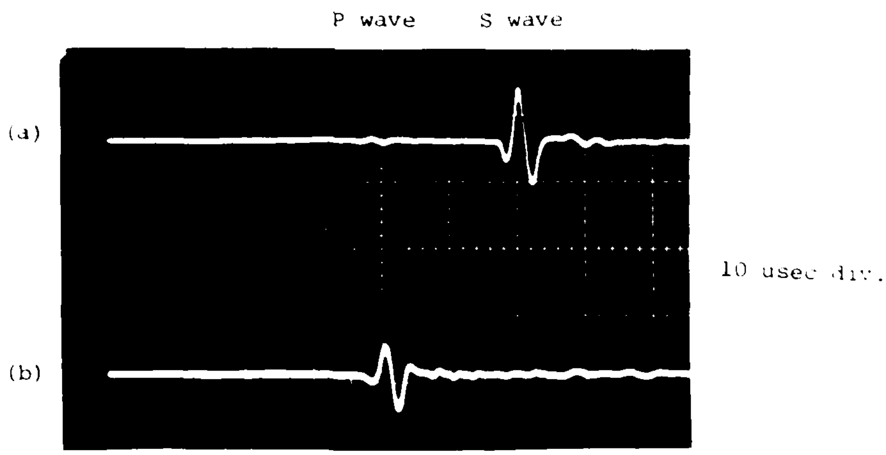
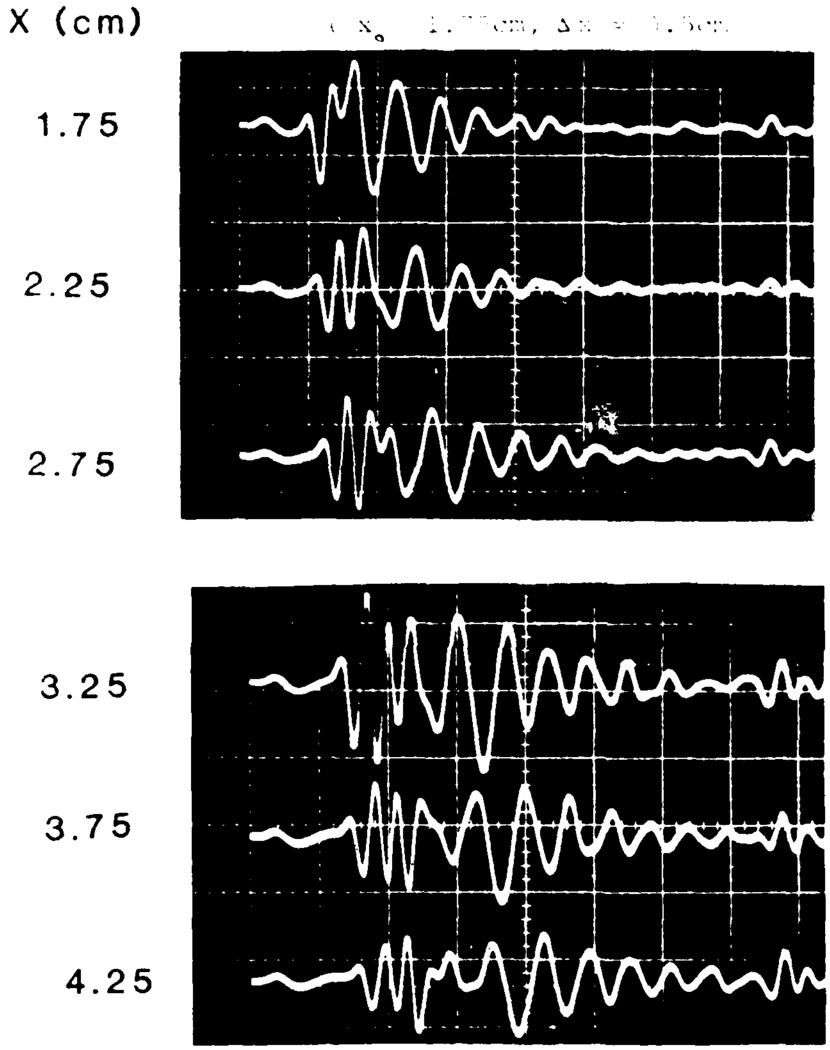


Figure 8. Seismograms demonstrating the result of rotating the shear wave transducer by 90 degrees (from Chamuel, 1982).


The Charles Stark Draper Laboratory, Inc.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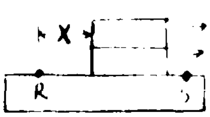
4.25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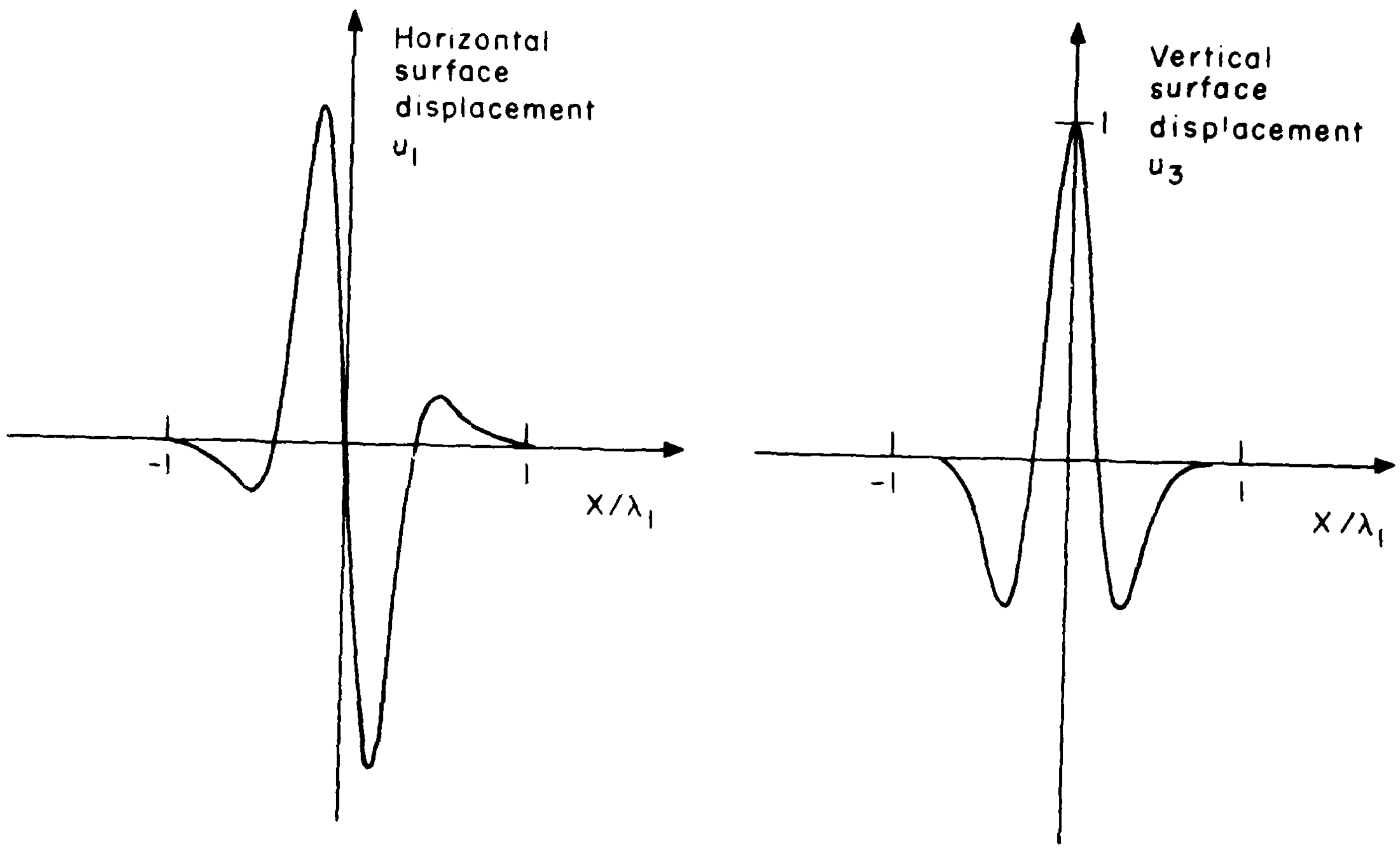

Fig 11 : Waveforms representing the input pulse for the finite difference model.

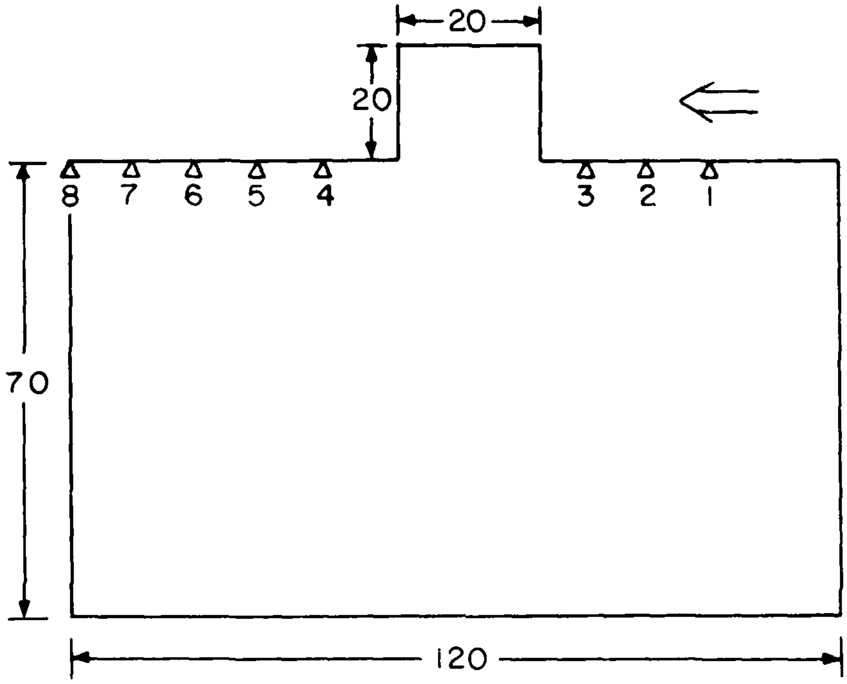

Fig. 12: Area of interest for finite difference model.
Receiver locations are also shown.

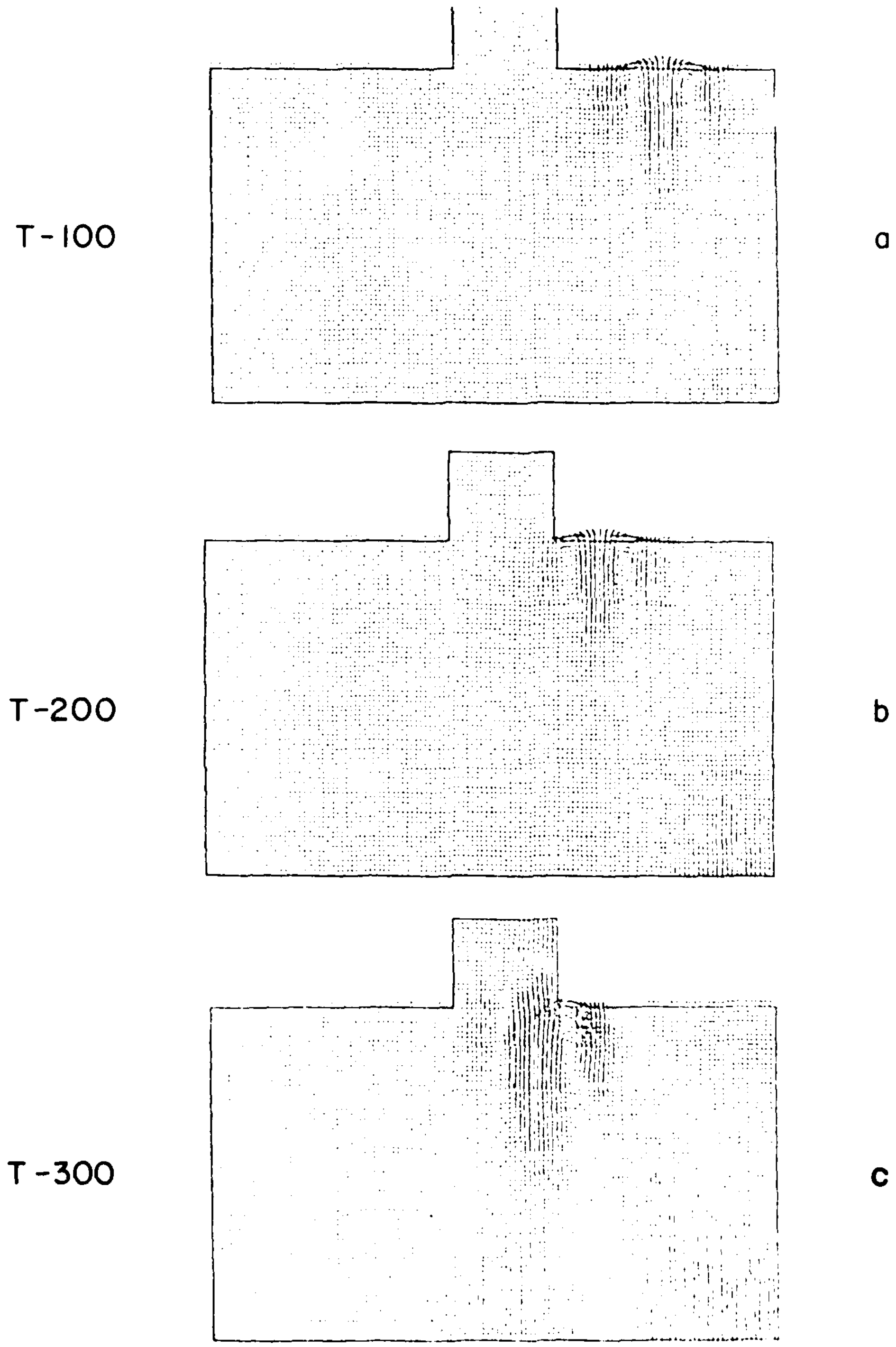

Fig. 13: Time sequence depicting the scattering of a surface wave for the rectangular 'moutain' case.

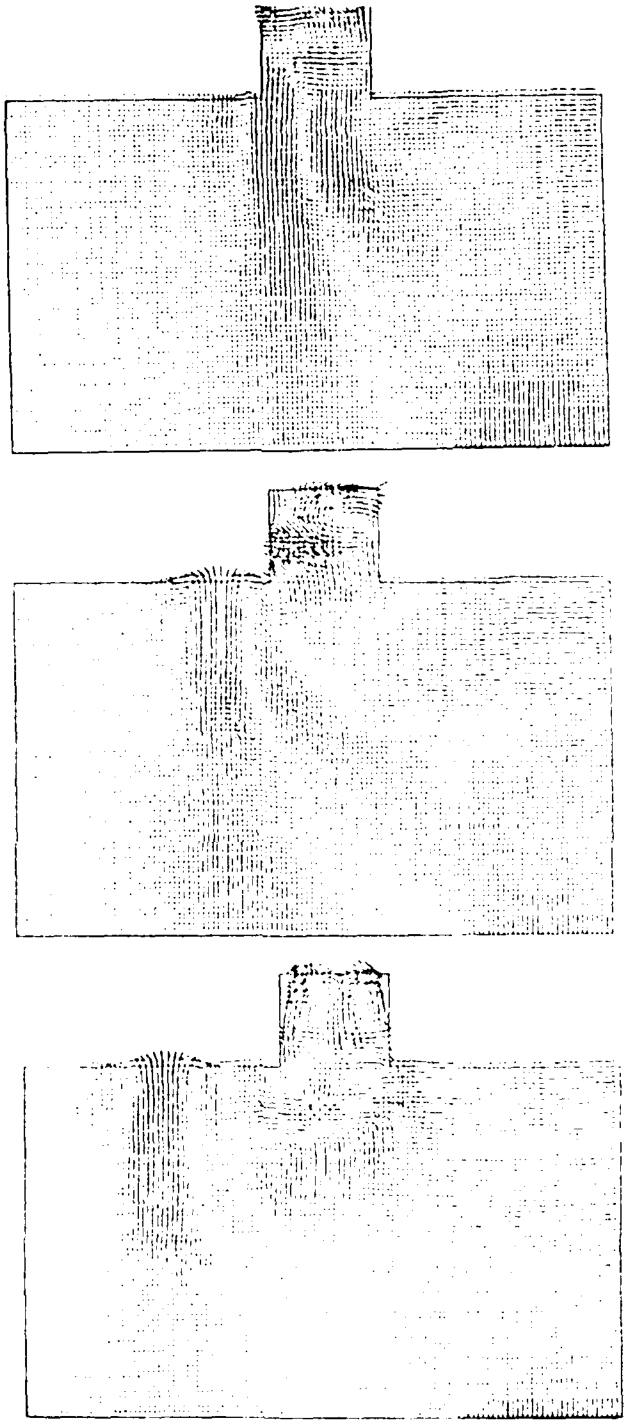

Fig. 13: Time sequence depicting the scattering of a surface wave for the rectangular 'mountain' case.

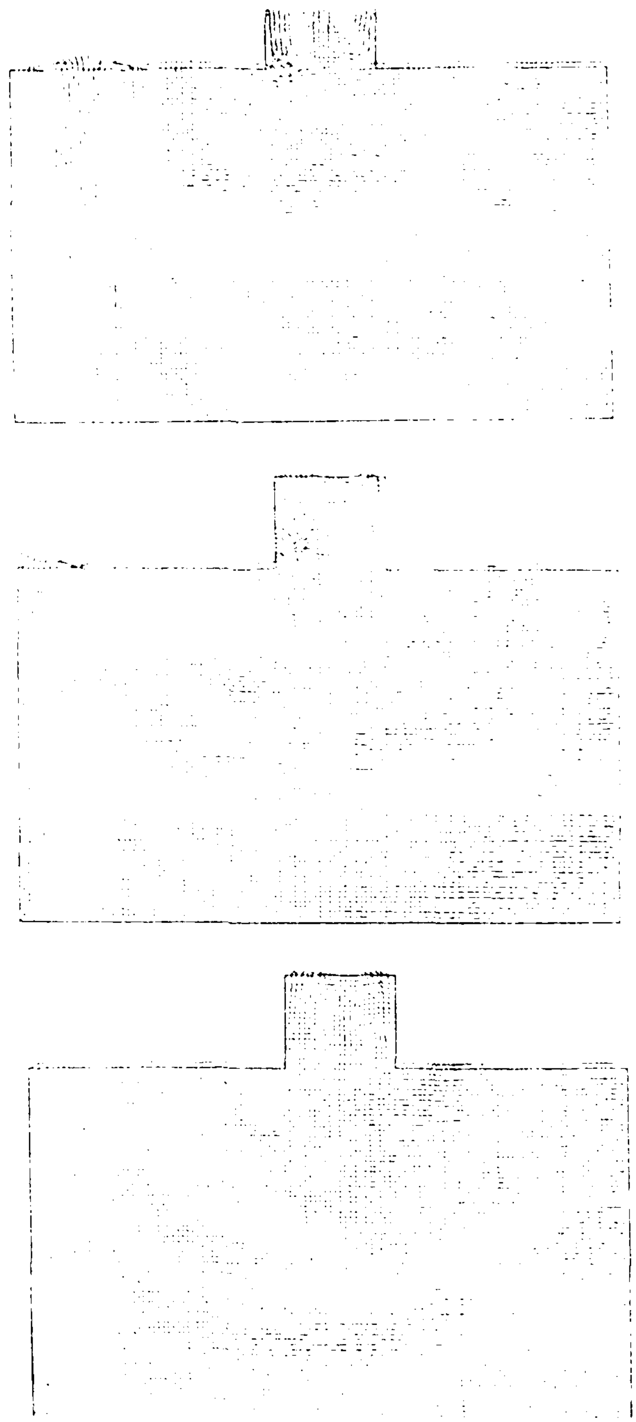

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Fig.13: Time sequence depicting the scattering of a surface wave for the rectangular 'mountain' case.

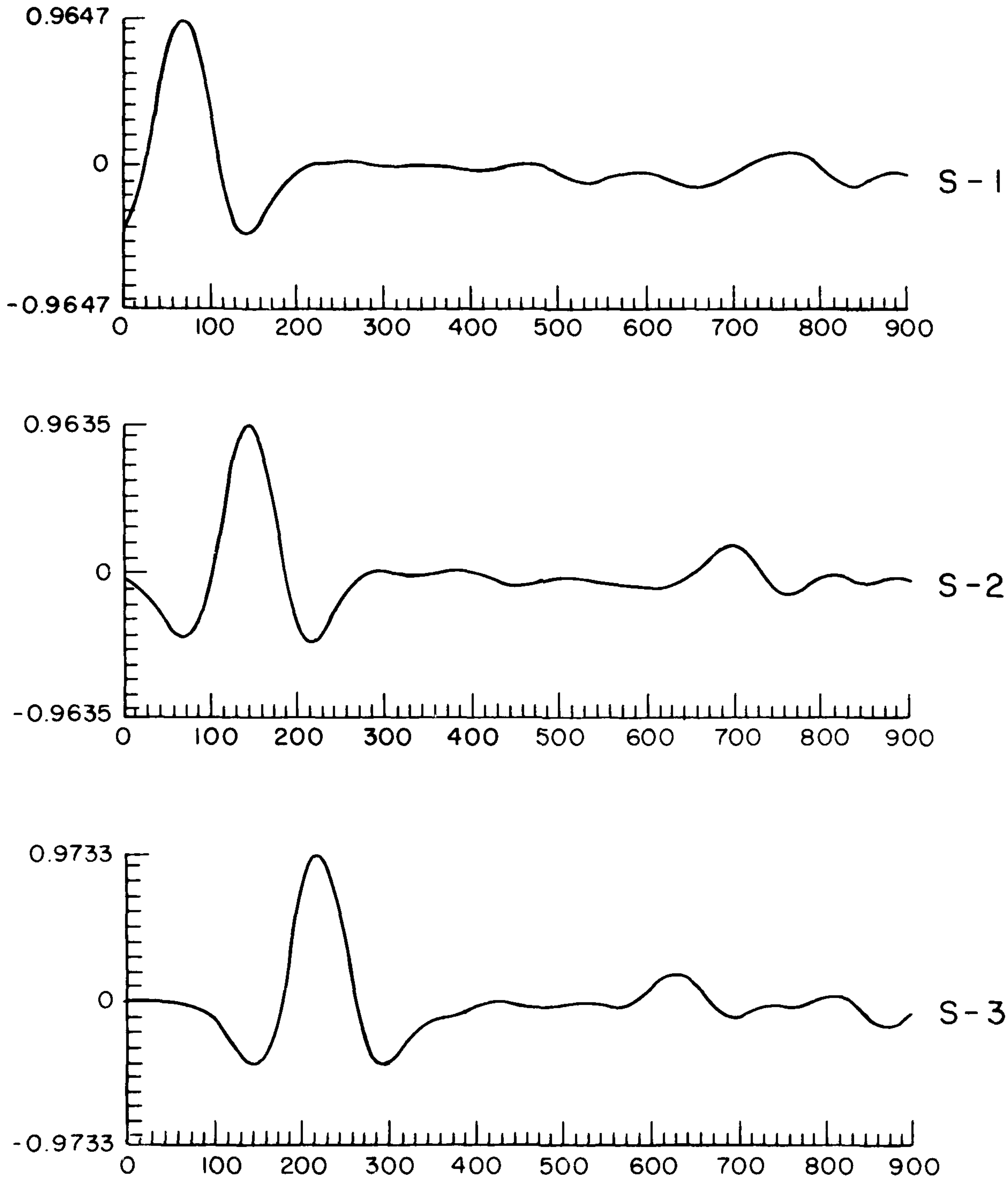


Fig. 14 : Seismograms corresponding to the receiver locations shown in Fig. 12 .

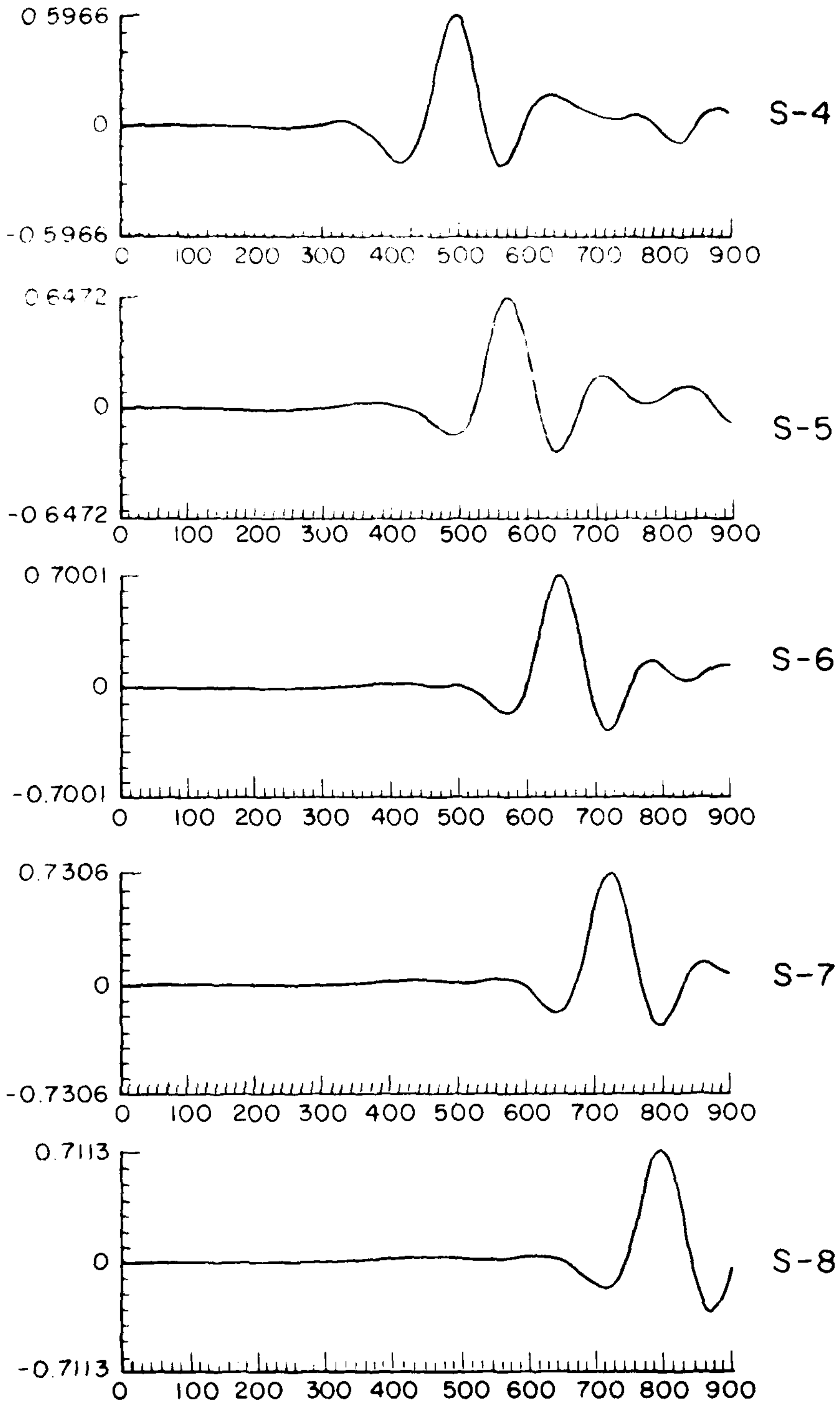


Fig. 14: Seismograms corresponding to the receiver locations shown in Fig. 13.

APPENDIX

THREE DIMENSIONAL SEISMIC ULTRASONIC MODELING
PART I : TECHNIQUES AND EXPERIMENTAL RESULTS

Jacques R. Chamuel
The Charles Stark Draper Laboratory, Inc.

INTRODUCTION

The seismic vulnerability of ground facilities such as nuclear power plants and military installations depends on ground motion duration and amplitudes. It is essential to understand and be able to predict these ground motions generated by earthquakes and explosions.

Real three dimensional seismic problems are practically beyond the state of the art of theoretical formulation and numerical analysis. In general, seismic problems are too costly to be solved with reasonable speed and accuracy with numerical techniques. Furthermore, empirical determination by field measurements of the effects of the earth structure on the ground motion caused by large events (nuclear explosions) are not practical.

In 1979, Jacques Chamuel (CSDL) demonstrated the potential feasibility of three dimensional seismic ultrasonic modeling by using a carved limestone block filled with wax composite materials. The limestone block was a free sample provided by C.S. Precourt & Sons, Co., Sudbury. Prof. Nafi Toksoz (MIT) [1,2,5,6,7] and Prof. Howard Schifflett [3] (Long Beach State College, CA) participated as consultants to implement Chamuel's proposed seismic ultrasonic modeling techniques to develop a quantitative model of Dry Lake Valley, Nevada.

THREE-DIMENSIONAL SEISMIC ULTRASONIC MODELING TECHNIQUES

A. Modeling Materials

In past work, the Charles Stark Draper Laboratory, Inc. developed a carved scaled model of Dry Lake Valley region, Nevada. A photograph of the unfilled model (scale 1:250,000) is shown in figure 1. The actual dimensions of the model are 38x28x21 cm.

Bedford limestone was chosen to model the rocks. Under the current AFGL contract, CSDL has developed necessary modeling materials to fill the valleys of the carved model. The preliminary materials developed under the BMO task were not suitable for modeling the top earth layers having a Rayleigh velocity between 450 and 700 m/sec.

Our approach to the modeling materials problem has been to look for materials that can provide us with a wide range of velocities and densities, and at the same time are easy to handle and replace. Epoxies in general create toxic fumes and cannot be removed easily from the carved model for modification or replacement. We decided to pursue the wax-base modeling materials since they are in many respects practical for preliminary three-dimensional modeling.

Figure 2 shows the simplified layered structure of Dry Lake Valley and the preliminary modeling materials used. Table 1 summarizes the measured properties of the seismic ultrasonic modeling materials. In our simplified model, the valley was filled with two parallel layers. The top layer was modeled using paraffin wax mixed with vaseline and aluminum powder. The middle layer material consisted of Carnauba wax and silica powder. A 2% (by weight) amount of beeswax was added to the middle layer material to reduce the shear wave velocity. As can be seen from Figure 2, we were able to match the modeling material properties to the actual earth properties. The top layer thickness was 1.7 mm, and the middle layer filled the gap between the bottom surface of the top layer and the limestone block. Away from the deepest spot of the valley, the thickness of the middle layer was 2.3 mm.

Although the described modeling materials have many advantages, including processing in a relatively short period of time, the elastic properties of these composite waxes are highly dependent on temperature. We made preliminary tests to determine their velocities temperature dependence. The Rayleigh wave velocity of surface waves propagating along the edge of modeling materials plates was monitored at different temperatures. For the soft top layer material (vaseline-paraffin-aluminum compound) Rayleigh velocities were determined to be 690 and 463 m/sec at 65 and 85 degrees Fahrenheit, respectively. The middle layer material is much less sensitive to room temperature variations. The

Figure 2. Preliminary modeling materials used to match seismic properties of Dry Lake Valley.

Modeling Material	Depth m	Density g/cm^3	Bulk Compressional m/sec	Shear velocity m/sec	
Al powder + Paraffin + vaseline	400	1.7-1.9	1.00 - 2.00	0.45 - 1.00	
	(1.7mm)	(1.77)	(1656)	(682)	model
Silica + carnauba + 2% beeswax	1000	2.0	2750	1600	
	(2.3mm)	(2.02)	(2580)	(1615)	model
Limestone	3000	2.20	4000	2300	
	(21cm)	(2.20)	(4100)	(2330 - 2500+carnauba)	model
↓	↓	2.65	5500	3180	

Table 1. Measured Properties of Seismic Ultrasonic Modeling Materials

	Material	Density (g/cm^3)	Bulk Compressional velocity (km/sec)	Rayleigh Velocity (km/sec)	shear velocity (km/sec)
1.	Paraffin wax	0.83	2.15	0.677	-
2.	Carnauba wax	0.99	2.60	0.947	-
3.	Aluminum	2.70	6.4	-	3.13
4.	Limestone	2.2	4.10	2.124 (+carnauba 2.380) *	2.35
5.	Top layer material (40 mesh Al powder + 45% vaseline + 55% paraffin wax*)	1.77	1.656	0.645	-
6.	Middle layer material (Carnauba wax + 2% beeswax + S-151 silica powder)	2.02	2.583	1.469	-
7.	Silica	2.35	5.97		3.76

* Prof. N. Toksoz pointed out the effects of soaking the limestone with the carnauba wax on changing the Rayleigh velocity.

hard carnauba wax dominate the Rayleigh velocity to a great extent; the Rayleigh wave velocity decreased by 2.9% from 65°F to 81°F. The middle layer material velocity was 1538 m/sec at 76.5°F.

The effects of temperature on a layered simple model are illustrated in Figure 3. The model is made of two parallel layers on a large limestone block. The top layer was 69 mil thick, and the middle layer was 91 mil thick. Again we used the same materials described above for the layers. The effects of raising the temperature of the model on the dispersion and attenuation of the received signal may be observed from the wave trains of Figure 3. Raising the temperature softens the top layer material and decreases it velocities. The time of arrival of the high frequency components would vary accordingly. It is clear that a temperature controlled environment is needed to achieve accurate modeling with the soft wax modelling materials.

We are currently evaluating alternative modeling materials for the layered valleys. We were able to reduce the Rayleigh wave velocity of Stycast epoxy resins by adding plasticizers.

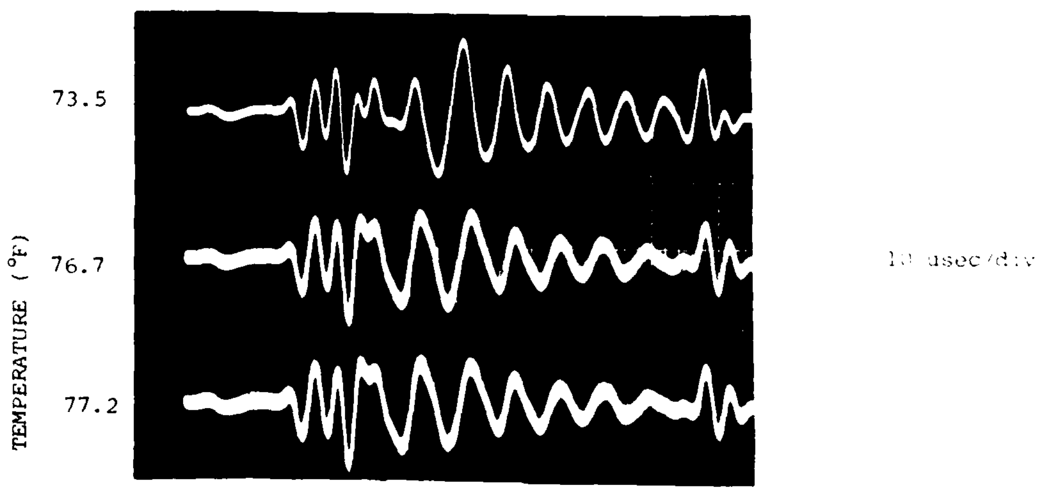


Figure 3. Effects of model temperature on Rayleigh wave propagation in a two-layer over half-space model.

B. Fabrication of Multilayered Models

In order to fabricate multilayer models, we used ultrasonic waves to determine the solidification temperatures of the wax-base modeling materials. Ultrasonic wave reflection information obtained from waves travelling in a magnetrostrictive rod, immersed in the modeling material, was plotted as the modeling material temperature decreased. The resulting plots of the middle layer and the top layer materials are shown in Figure 4. As the waxes solidified, the wave reflections decreased, since the solidified wax attenuated the travelling waves. Both temperature and reflection measurements were recorded as the material was allowed to cool. The solidification temperature of the top and bottom layer materials were 95 and 175 degrees Fahrenheit. The mixtures remained liquid down to 162 and 220 degrees respectively. We could safely fabricate a double layer model without disturbing the bottom layer by remelting.

C. Transducers

Two compressional and one shear wave piezoelectric transducers were developed during the course of the study. The piezoelectric elements were PZT-5 having a 4.7mm diameter and a 2 MHz equivalent thickness. Lead was used to damp the reflections of the elastic waves from the boundary of the piezoelectric elements opposite the sensing surface. A stainless steel cylinder was machined to house the PZT transducers. A photograph of the three transducers is shown in Figure 1. The sensing surface was covered with an epoxy composite material to protect the transducer. The diameter of the sensing area was reduced to about 3 mm by machining the tip of the epoxy. The response of the two compressional transducers, when placed 5 cm apart along the edge of a 1 mm thick aluminum sheet, can be seen in Figure 2 (time scale 5 usec/div). The compressional wave arrived at 11 usec and the Rayleigh wave at about 18 usec.

The directivity of the shear transducer was tested by placing the shear transducer perpendicular to the plane of the sheet and orienting it first radially, then transversely to the wave propagation direction. The source was

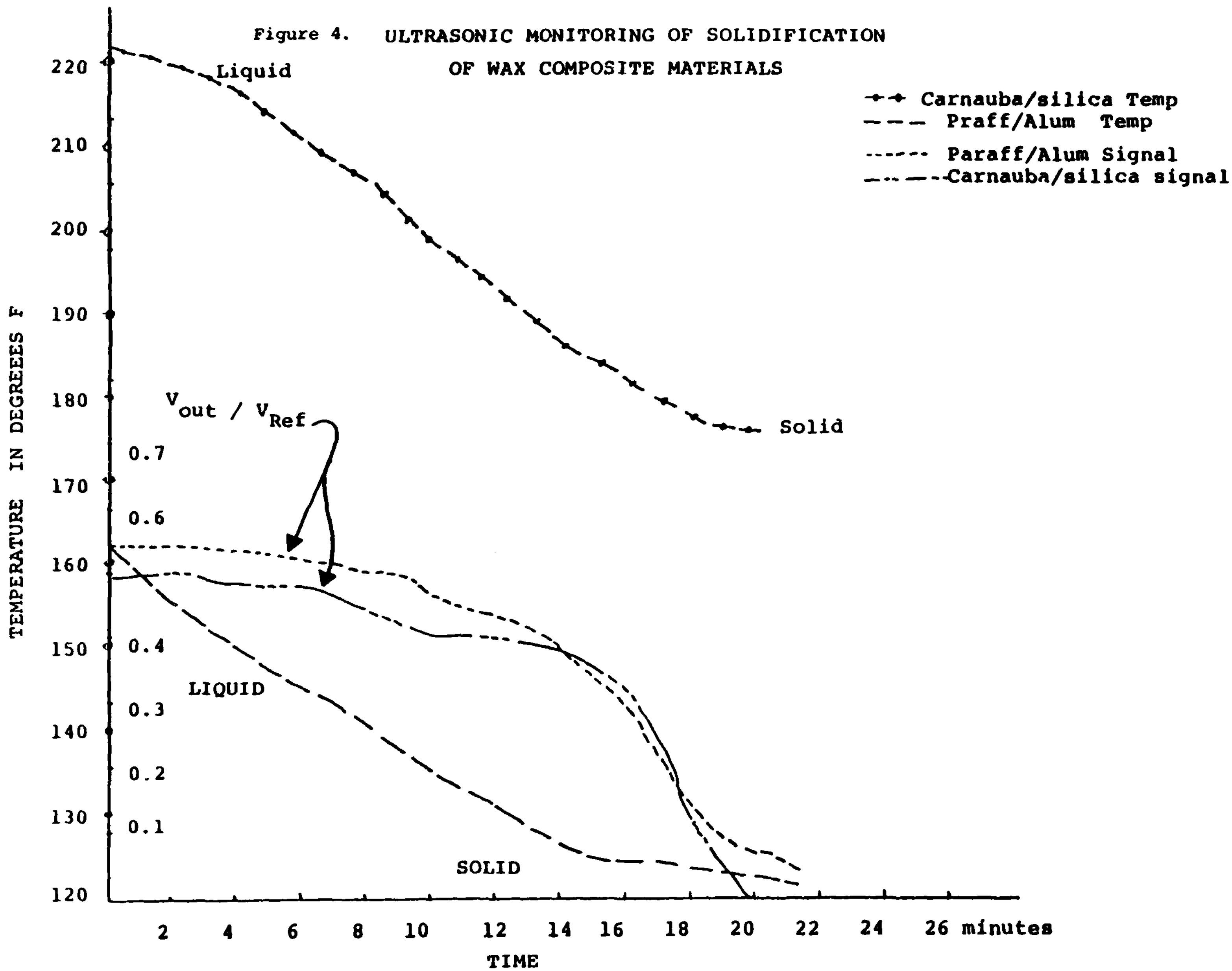


Figure 4. ULTRASONIC MONITORING OF SOLIDIFICATION OF WAX COMPOSITE MATERIALS

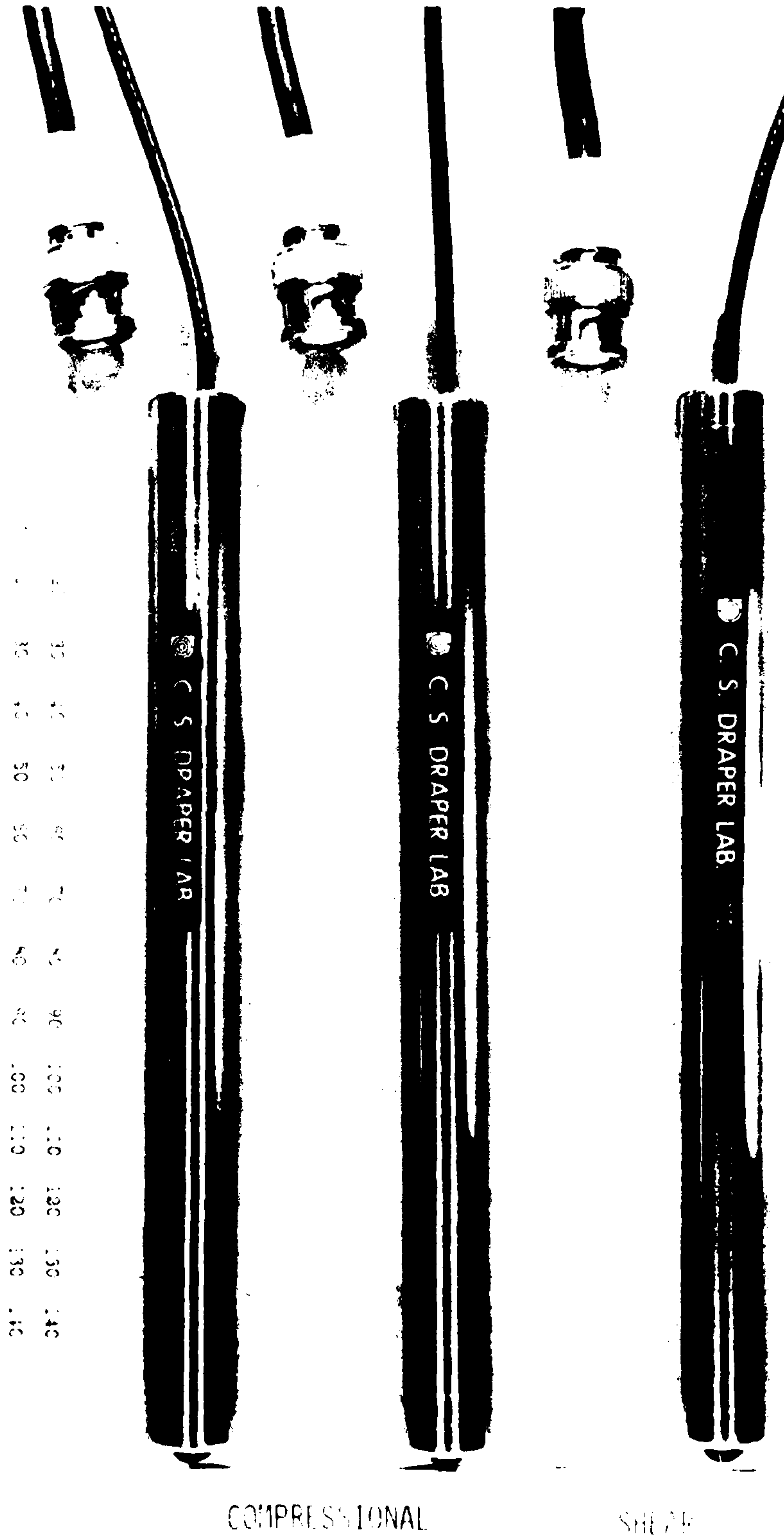


Figure [illegible]. Photograph of [illegible]

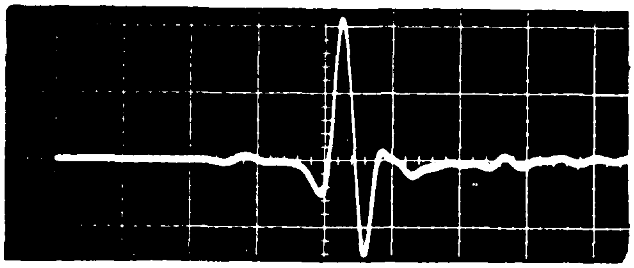


Figure 6. Response of CSDL compressional wave transducers placed [illegible] cm apart along the edge of an Al sheet.

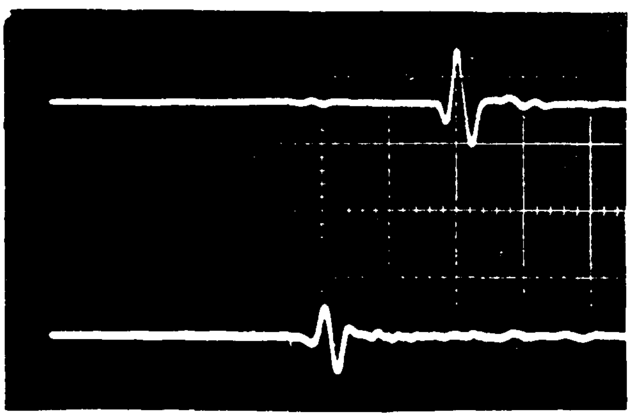


Figure 7. Relative directional response of CSDL shear wave transducer (a) transverse component, (b) radial component.

a compressional transducer placed at the edge of the sheet. The relative transverse and radial directional response of the shear transducer is shown in Figure 7 . These transducers were used to study the Rayleigh wave scattering from two and three dimensional models as described in the report.

RAYLEIGH WAVE SCATTERING FROM VERTICAL DISCONTINUITIES

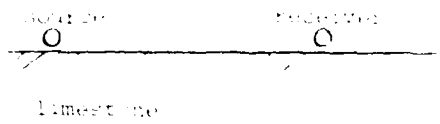
Rayleigh waves propagating on the surface of the earth are greatly affected by the presence of topographical discontinuities. As a follow on to our studies on the effects of topography on Rayleigh wave scattering, we measured from the three dimensional Dry Lake Valley model the transmitted wave propagating across the valley without sediment. Figure 8 shows the outline of the valley drawn at its center (scale 1:1). The received signal, Figure 8(b), is compared with another signal received from a half-space, Figure 8(a) keeping the same horizontal distance (4 cm) between the source and receiver. The reflections and scattering from the valley decreased the Rayleigh wave by almost a factor of ten. From Figure 8, one can notice the reduction of the high frequency components, the delay in the Rayleigh wave arrival, and the appearance of an early arrival wave caused by conversion of body waves into surface waves.

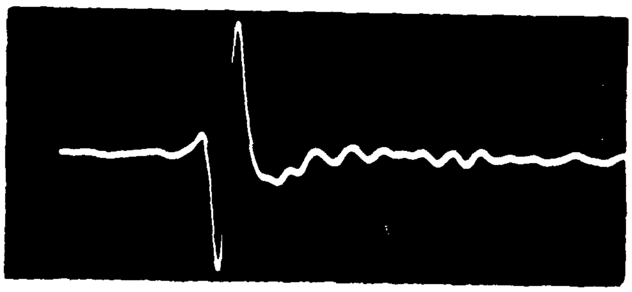
Figure 9 shows the transmitted waves obtained from a two dimensional limestone model consisting of a simple rectangular cut having the same width as Figure 8 Valley, and a depth of 7.5 mm (simplified model of Valley). The transmitted signal also consists of an early arrival wave followed by the Rayleigh Wave. A comparison of Figure 9 with Figure 8(b) indicates that the lack of the multiple steps in the approximate model resulted in a larger transmission of the high frequency converted body waves, and at the same time resulted in a reduction of the high frequency components of the Rayleigh Wave. It would be interesting to compare these experimental results with a theoretical model based on the superposition of steps.

(SCALE: 1:260,000)

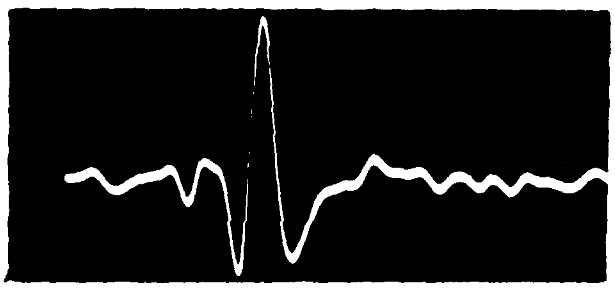
10usec/div

x= 4cm

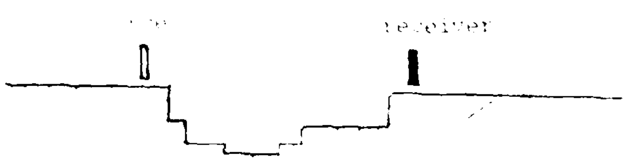




Solid half-space
5.0volts/div.



Across empty valley
0.5volt/div.



TOPOGRAPHY

10 usec/div.

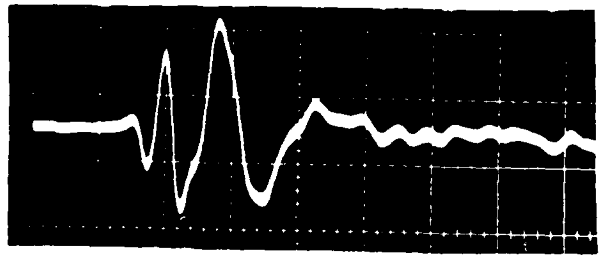


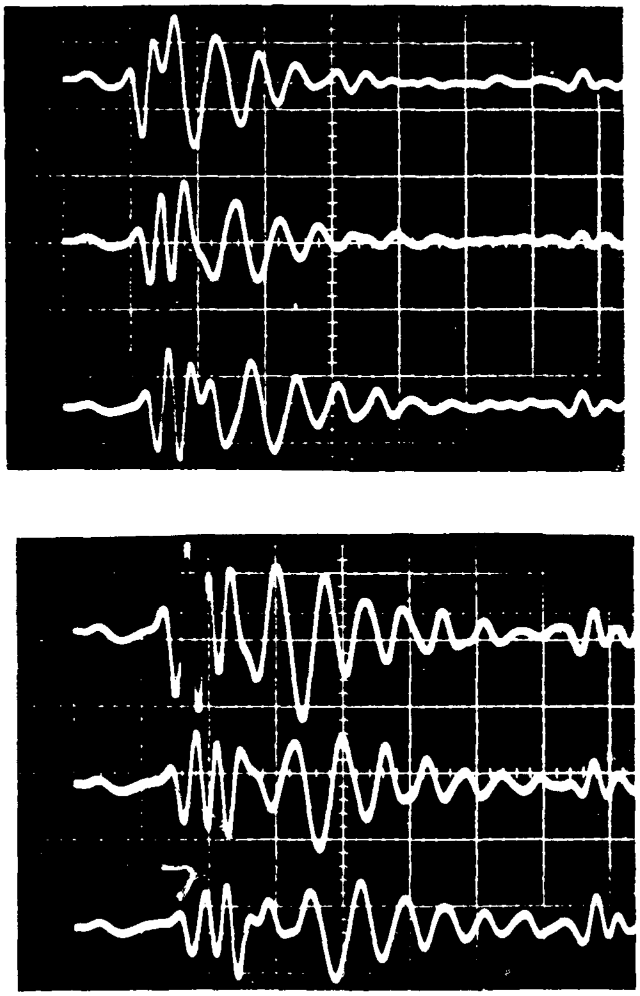
Figure 9. Rayleigh wave transmission across a simplified 2-D model of Dry Lake Valley center (no sediments) .

RAYLEIGH WAVE DISPERSION FROM DOUBLE SOLID LAYERS OVER HALF-SPACE

A double layer model was fabricated and tested to evaluate our seismic ultrasonic modeling technique. A 2.3 mm thick layer composed of the carnauba wax mixture was deposited on a limestone block. A second layer was added on top of the carnauba mixture layer. The top layer was 1.6 mm thick and consisted of the vaseline paraffin mixture. Compressional piezoelectric transducers were used to generate and detect the elastic waves in the double layer model. Initially, the receiver was 1.75 cm away from the source, then it was displaced in 0.5 cm intervals. The received signal was photographically recorded from the oscilloscope. Figure 10 shows the family of signals recorded from the experimental model. The elastic parameters of the layers are given in Figure 10. The group velocity experimental points were calculated and plotted in Figure 11 as function of frequency. The theoretical group and phase velocities will be included in the MIT final report. Our preliminary analysis indicates that we have a satisfactory modeling technique.

[illegible] Rayleigh wave dispersion [illegible] layer on half-space

(x_0 = 1.75cm, Δx = [illegible]



density	compressional	shear	thickness
1.78	[illegible]	[illegible]	1.6mm
2.03	[illegible]	1615	2.4mm
2.2	4100	[illegible]	12.5cm
g/cm^3	m/sec	m/sec	

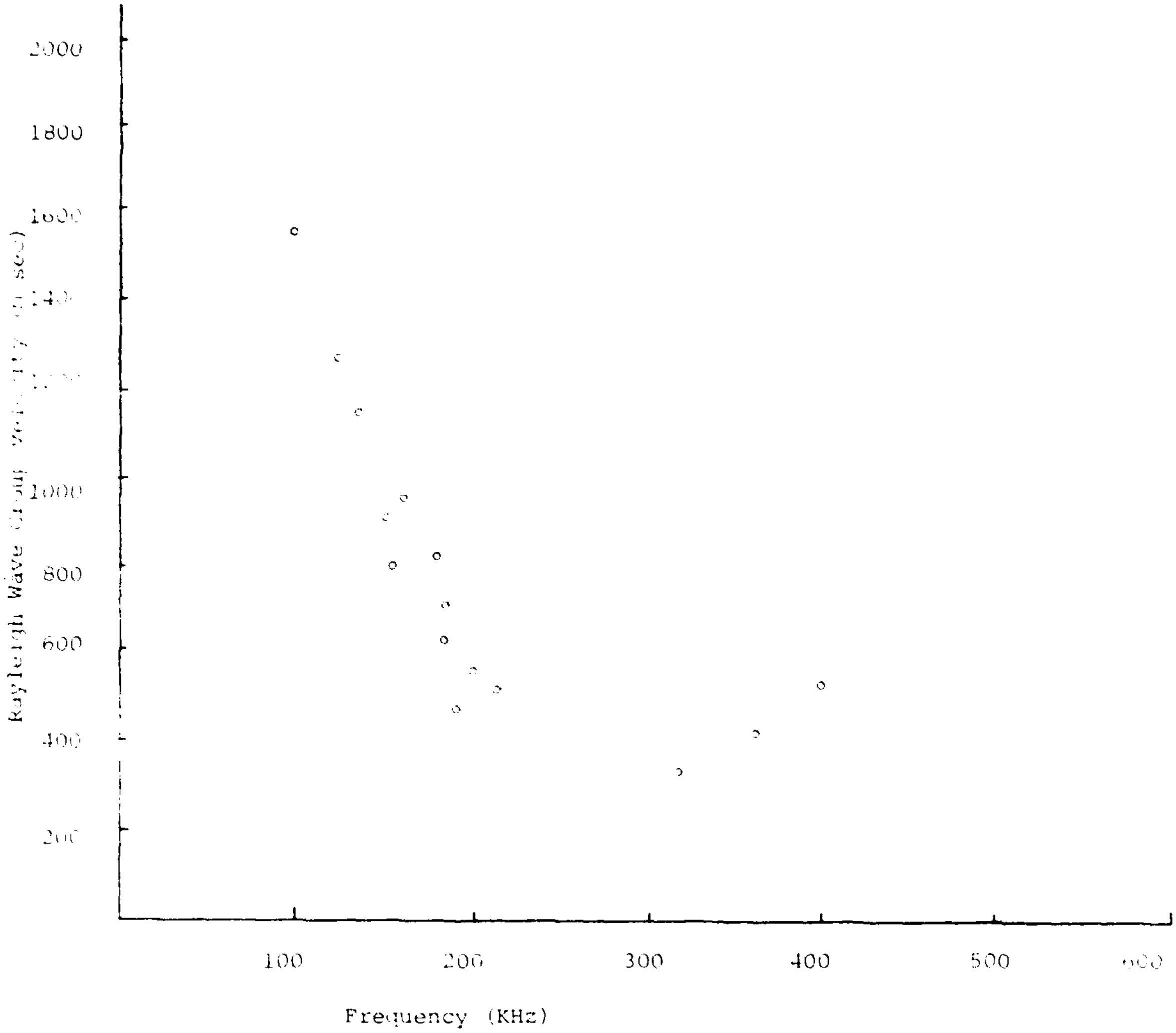


Figure 11. Calculated group velocity from two layers on half space model experimental data.

RAYLEIGH WAVE SCATTERING from FILLED THREE DIMENSIONAL DRY LAKE VALLEY MODEL

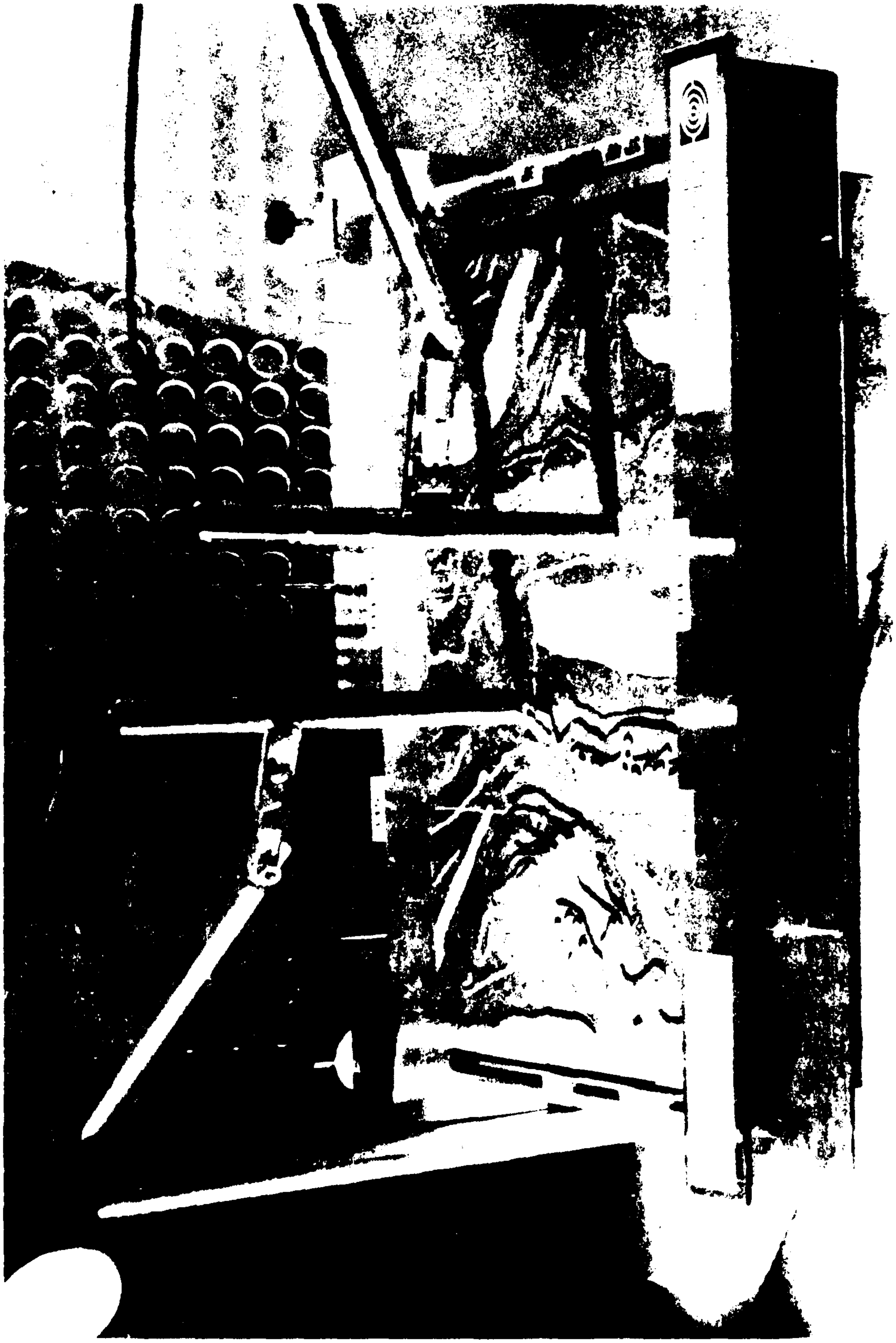
The unfilled Dry Lake Valley model (Figure 1) was filled with two parallel layers of sediments. The top layer is 69 mil thick composed of vaseline, paraffin wax, and aluminum powder. The second layer has different dimensions depending on the depths of the valley. The average thickness of the second layer is about 2.3 mm. We used carnauba wax, beeswax, and silica powder to model the second layer.

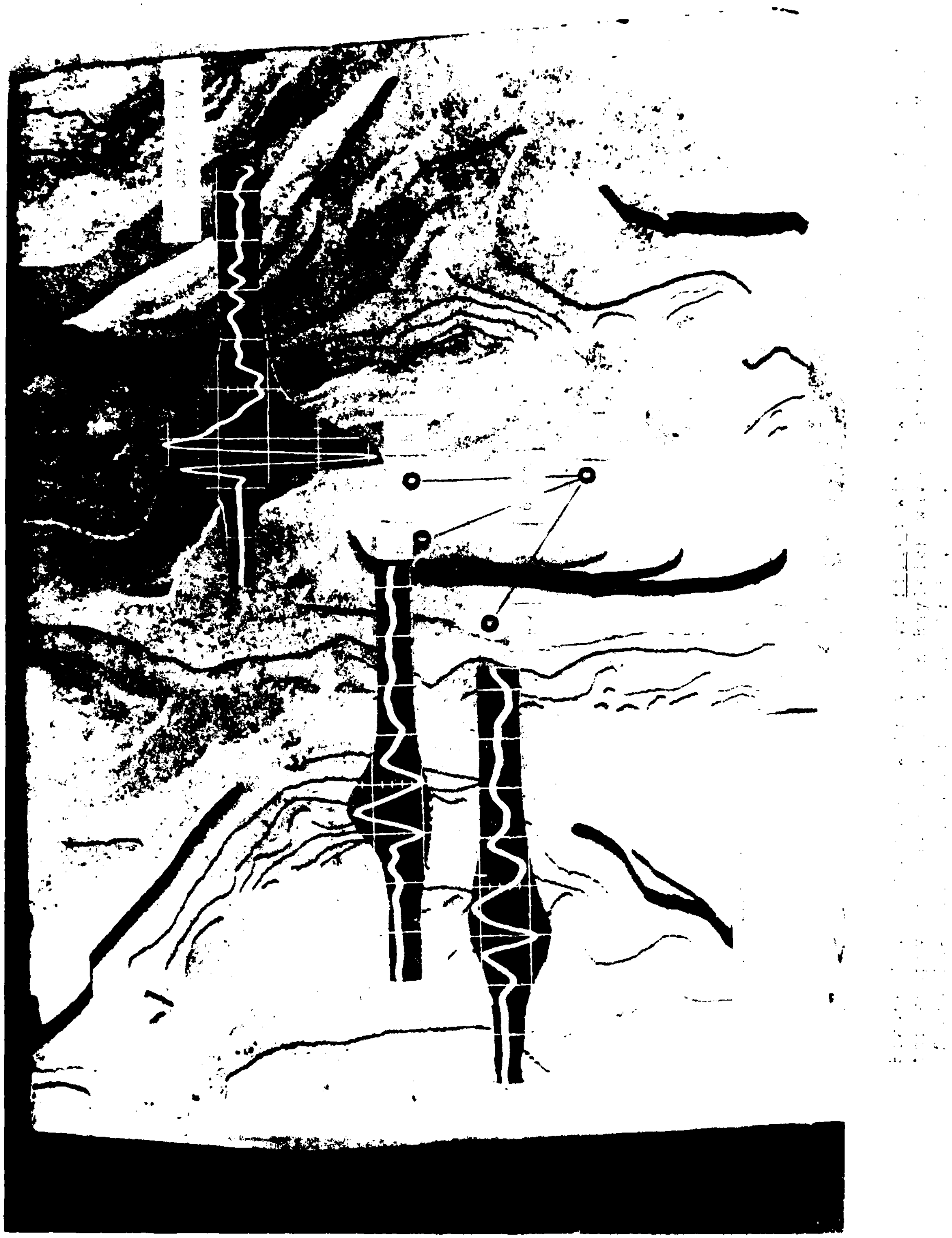
The elastic properties of these modeling materials are identical to the double layer over half space model described in the previous section.

A photograph of the filled three dimensional model with the transducers is shown in Figure 12.

Preliminary Rayleigh wave measurements have been made using this model to determine the effects of topography on Rayleigh wave scattering and dispersion. Figure 13 shows the relative signals obtained as the Rayleigh wave path crossed a flat region (R_1) or a valley, (R_2 and R_3). The time scale setting was 10 μsec/div. Transmission across the valley crested dispersion, made conversion, and attenuations.

We noticed that filling the valleys increased the ground motion duration and amplitude. Figure 14 shows the effects of filling a valley from a two dimensional limestone model. Figure 15(a) shows the effects of the sediments on the transmission across the three dimensional Dry Lake Valley. The received signal is much larger than Figure 8(b) where the valley was empty (absolute amplitude information is questionable). We damped the Rayleigh wave of Figure 15(a) by pressing by hand on the sediment surface. Figure 15(b) shows the received signal with the damped Rayleigh wave. The transmission across the filled valley in Figure 13 (R_3) is almost 1/4 of Figure 13 (R_1) signal, however, in the empty valley of Figure 8(b) the ratio:transmission across a valley/transmission across a flat region was about 1/10 in our model.





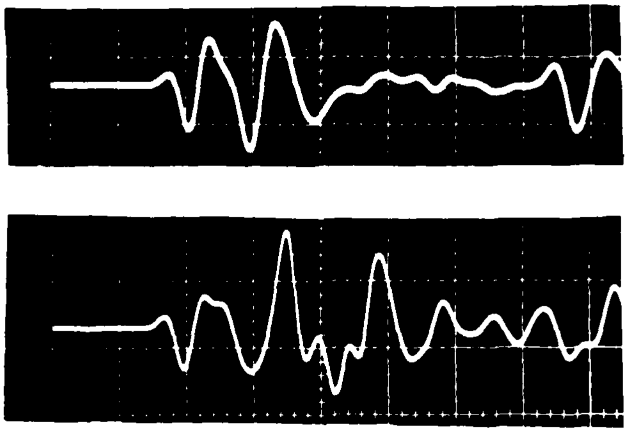


Figure 14. Rayleigh wave transmission across unfilled (top) and filled (bottom) two dimensional limestone model of Dry Lake Valley center line. Used paraffin and aluminum as sediment.

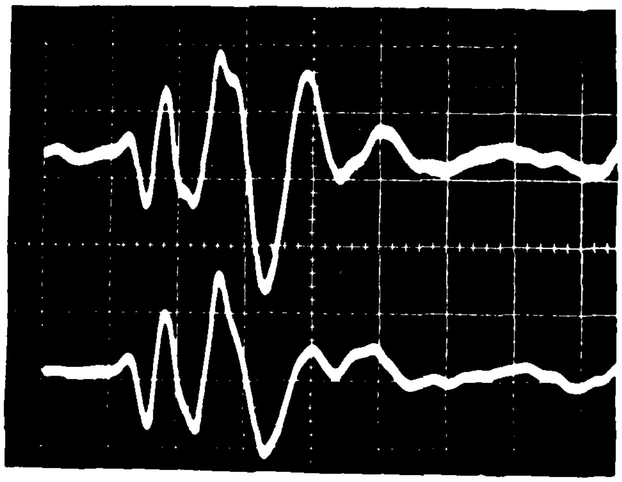


Figure 15. Rayleigh wave transmission across the width of Dry Lake Valley model with transducers outside of valley (x=4cm).

A set of measurements were taken from the filled Dry Lake Valley to study Rayleigh wave dispersion. The source was located in the valley near its north end. The receiver was displaced 1 cm at a time towards the south. The initial distance between the transducers was 2 cm. Figure 16 shows the dispersion results. The time scale was 10 usec/div. At 8 cm, an additional waveform with a 20 usec/div setting was recorded. The high frequency signals observed at about 110 usec are the reflections of the P waves from the bottom surface of the large limestone block.

We used the shear wave transducer to measure the radial and transverse components of the dispersed waves. Figure (17) was taken from the Dry Lake Valley model. The rejection of the Rayleigh Wave is observed when the shear receiver transducer was oriented transversely.

RECIPROCITY

Rayleigh waves reflection coefficient is much larger for a downstep topographical surface discontinuity than for an upstep case. Intuitively, one may think that interchanging source and receiver positions would give different transmission for an upstep versus a downstep case. The author was curious to test the reciprocity theorem on the three dimensional model in view of conversion of surface to body waves and body waves to surface waves. A source was placed at "S" on the surface of the filled valley as shown in Figure 19. A receiver was placed at "R". The received signal is displayed in Figure 20(a). The electrical leads of the transducers were interchanged so the original source is now used as a receiver. The received signal for the interchanged case is shown in Figure 20(b). The same experiment was repeated without moving the oscilloscope trace. Figure 20(c) shows the superposition of the two signals. A close look at Figure 20 signals reveals that Figure 20(b) is slightly smaller than 20(a). This is due to the different electrical impedances of the transducers. The experiment was repeated on a half-space (limestone block) giving the same ratio. From these results we conclude that the Reciprocity theorem holds for conversion of surface and body waves.

In the real earth, the presence of nonlinearities would tend to modify the problem.

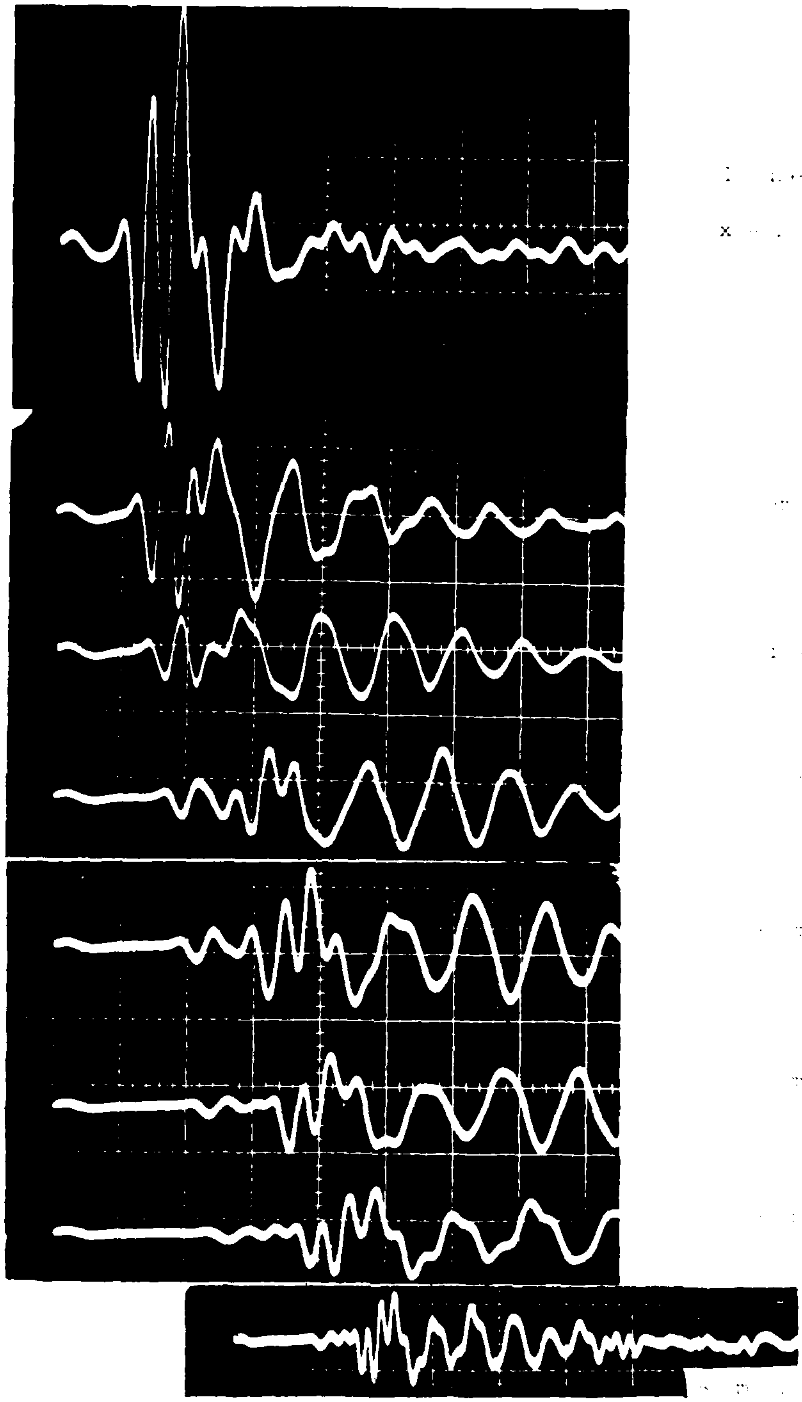


Figure [illegible]. Effects of valley sediments on Rayleigh wave [illegible] from [illegible] model of Dry Lake Valley, Nevada with [illegible] near its [illegible] end. Receiver was [illegible] [illegible]

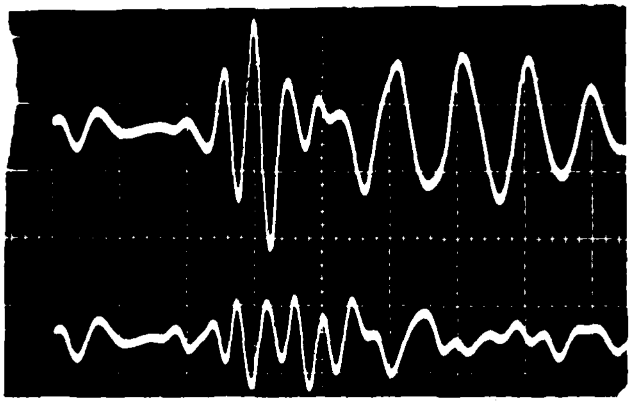


Figure 17. Radial and transverse components measured from three-dimensional model with source and receiver located on Dry Lake Valley (x=5cm).

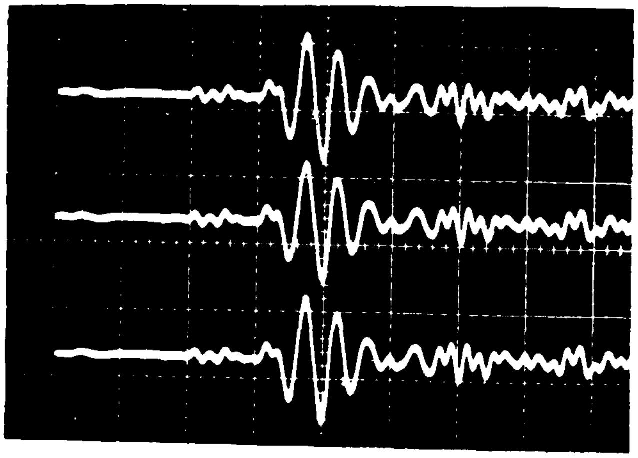


Figure 19 . Reciprocity test results: (a) source-receiver, (b) receiver-source , (c) source-receiver superimposed on receiver-source . Data taken from 3-D model of Dry lake Valley. Transducers locations shown in figure 18.

SUMMARY AND CONCLUSIONS

The Charles Stark Draper Laboratory has continued the development of three-dimensional seismic ultrasonic modeling techniques for Air Force applications. New broadband piezoelectric compressional and shear transducers were developed. New modeling materials suitable for modeling top earth layers were introduced. A preliminary three-dimensional model of Dry Lake Valley, Nevada region with sediment filled valleys was constructed. Experimental results showing the effects of layers and topographical features on Rayleigh wave attenuation, dispersion, and scattering were presented. We planned and conducted experiments demonstrating receiving identical signals when source and receiver locations are interchanged for Rayleigh wave transmission across complex topographical features.

The main conclusions to be drawn from the CSDL efforts are:

1. Filling the model valleys with sediments increased the Rayleigh wave transmission across the valley.

2. The wax-base modeling materials are suitable for fabrication of multilayered models. Temperature controlled models would be required for quantitative studies.

3. Rayleigh wave transmission across an empty valley (Dry Lake Valley) decreased the signal by almost a factor of ten, reduced the high frequency content, and created an early arrival wave caused by body waves.

4. The presence of multiple steps in the valley underneath the sediments drastically reduces the high frequency content of the early arrival transmitted wave.

5. ~~deling the valley with one major slot having vertical boundaries (no sediments) increased the transmission of the high frequency converted body waves, and at the same time resulted in a reduction of the high frequency components of the transmitted Rayleigh wave.

6. We discovered that reciprocity holds for conversion of body waves to surface waves and also for conversion of surface waves to body waves resulting from Rayleigh wave transmission across topographical features.

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