RICE UNIVERSITY

STUDY OF P WAVES THROUGH LAYERED AND FAULT GEOMETRIES, USING THE TWO-DIMENSIONAL MODEL TECHNIQUE

by

Jose G. Viveros

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARTS

Thesis Director's signature: [Signature]

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ABSTRACT

STUDY OF P WAVES THROUGH LAYERED AND FAULT GEOMETRIES, USING THE TWO-DIMENSIONAL MODEL TECHNIQUE

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The two dimensional seismic scale model technique was used to investigate high frequency wave propagation through fault and layered geometries. These structures were simulated, using one or more different elastic media. The reflection method was used considering longitudinal wave propagation and the experimental data obtained were then analyzed.

Several different cases were studied. In the layered cases, thin layers of wax were used between plexiglass sheets. These thin wax layers produce the necessary contrast of the acoustical impedances, so that reflections as well as transmitted energy could be produced.

Three fault geometries were also studied. These were obtained by varying the simulated fault plane between 70 and 110 degrees.

The frequency used throughout this experiment is about 630 times greater than that used in the field.
ACKNOWLEDGEMENTS

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I. INTRODUCTION

Purpose

This investigation was made in order to obtain objective knowledge of what happens when ultrasonic waves are propagated through two types of geological structures—layered strata and faulted strata.

The layered case involved three models horizontal Plexiglass layers separated by thin wax layers. The fault case involved nine models, three fault plane angles were used, each of which were studied with three different interfaces.

Experimental seismograms were obtained. The characteristic events indicated by the results were analyzed from two main points of view: Travel-time sections and amplitude-variation graphs. Overlapping of events, shadow zones in faults, phase changes, and partition of energy at boundaries were present in these experimental results.

Approach

The behavior of wave propagation of both longitudinal and transverse waves becomes more and more complicated as the geometry becomes more complex. It is necessary to know the reflection and transmission coefficients at all interfaces involved. However, in seismic modeling experiments, it is feasible to have only one type of elastic
wave traveling predominantly through the medium of the simulated geometry. It is very useful to find the reflection coefficient ratio, and the transmission coefficient ratio, which are function of the acoustical impedances (Ewing, Jardetsky, and Press, 1957). When there is a wave train reflected from an interface, the phase and amplitude depend on the acoustical ratio and on the wavelength, by the relaxation $h/\lambda$, where $h$ = sheet thickness and $\lambda$ = wavelength.
II. DESCRIPTION OF THE EQUIPMENT

The electronic equipment used in this study is shown in Figure 1. An adequate description is made by separating the model instrumentation into two parts. The first is referred to as the source system, and the second as the receiver system.

Source System

A General Radio Unit Pulse Generator, type 1217-B was used. This unit has a pulse rate frequency adjustable from 10 cps to 500 kc, with a pulse duration range adjustable from 0.1 used to 1 sec, delivering a unit pulse at approximately 35 volts. This unit pulse was amplified to approximately 200 volts and then was applied to the source transducer. In order to simulate a dynamite explosion, a disc-shaped transducer was used as a source. This transducer is a Glennite zirconate-lead titanate transducer with an external diameter of 1.27 cm, a thickness of 0.254 cm, and a resonant frequency of approximately 170 kc. The source transducer was placed into a hole made on the plexiglass sheet of the models (see Figure 1). The acoustical pulse is shown in Appendix II.

Receiver System

A small barium-titanate bar shaped transducer, 0.8 cm in length, 0.15875 cm in width and 0.07937 cm in
Figure 1. Wiring diagram (a), and Photograph (b) of the experimental setup.
in thickness, was used as the receiver. This receiver transducer was mounted in a long, insulator, free-moving copper tube; therefore, it was possible to situate the pick up on any part of the model surface. Once the signal is picked up, it is preamplified. Subsequently it is displayed on the oscilloscope.

The oscilloscope used was a type Tektronic 535 A with two plug-in preamplifiers: One a type CA with dual trace amplification from 0.05 to 20 volts/cm, with two channels, and rise time of 0.01 used. The second one is a type D, height gain from 1 millivolt/cm to 50 volts/cm, with two channels.

The signal was then photographed with an Oscillograph-record Polaroid Camera Dumont 2620 which is especially made to be used on the oscilloscope.

Elimination of Undesired Effects

Rayleigh Waves: Rayleigh waves are very small if the source is buried at a depth of approximately \(1/4\lambda\). They can also be reduced by setting plasticine on top of the model edge.

Side reflections: To prevent side reflected signals it is necessary to make the model of large dimensions and to cover the surfaces of both sides of the model with Polyvinyl chlorite tape.
Joints: It is necessary to obtain a material that will give good glue joints and still not modify the reflection coefficients between the joined materials on the basis of its characteristics, epoxy resin was used to glue the Plexiglass to the aluminum. In the layered models, thin wax layers were used as glue joints between Plexiglass sheets.

Damping: The damping was eliminated at the receiver transducer by mounting it in a copper rod of approximately 25 cm and by surrounding the upper three-fourths of the transducer with a thin piece of rubber.

Ringing: At the source the ringing effect is prevented by using frequencies which are below the ringing frequency of the source transducer. At the receiver, ringing is avoided by using frequencies below the ringing frequency as well as by using transducers with small dimensions.

Noise: The ambient noise is reduced by using cotton strips between the table and models. The electrical noise is prevented by using amplification levels with the lowest possible distortion.
III. GENERALITIES OF TWO-DIMENSIONAL SEISMIC MODELS

Scaling

Three factors are basic in relating the seismic models to field structures. These are:

- Dimension (L): \( L \) (original) = \( K_L \) \( L \) (model)
- Time (t): \( t \) (original) = \( K_t \) \( t \) (model)
- Mass (M): \( M \) (original) = \( K_M \) \( M \) (model)

Therefore, for convenience, the distance scale factor is assigned. The velocity scale factor may be determined from the materials used (Appendix I). It is clearly seen that the time scale factor, \( K_t \), may be easily specified. The elastic constants, stresses, and strains can be expressed in terms of these factors.

The frequency used here is about 22.2 kc which, in comparison with approximately 35 cycles/sec used in field seismograms, represents a factor of about 630. Consequently 1 meter in the models represents about 630 meters in the field.

Because the longitudinal velocity through a plexiglass sheet is about 2338 meters/sec (Appendix I), the wavelength is approximately

\[
\lambda = \frac{V}{f} = \frac{2338}{22200} \approx 10.5 \text{ cm}.
\]

Most materials used for the seismic model construction have Poisson's ratio values close to 0.33. These values are larger than those found for natural rocks (approximately 0.25). A pseudo-Poisson's ratio
may be calculated by the following equation:

\[ \sigma = \frac{0.5 - (\beta/V)^2}{1 - (\beta/V)^2} \]  

(1)

where \( V \) is the longitudinal plate velocity (which is smaller than the bulk velocity) and \( \beta \) is the shear velocity. These two velocities are given by the following equations (Oliver, Press, and Ewing, 1954):

\[ V = \frac{4\mu}{\rho(\lambda+2\mu)^{1/2}} \]  

(2)

\[ \beta = \frac{(\mu)}{\rho} \]  

(3)

Model Designs

With the above discussion it was then possible to design the models. Also it was feasible to choose the oscillograph time-range or horizontal scales. The optimum time range was 100 \( \mu \text{sec/cm} \). Model dimensions were determined knowing both the wave frequency and longitudinal velocity on the basis of which the wavelength is calculated. Thus, it was possible to determine the necessary interface depths in order to obtain separable reflections when two or more reflected interfaces are involved. A factor to take into account when working with a two-dimensional medium, is that the sheet thickness must be small in comparison with the wavelength.
Layered Models: These were constructed using plexiglass sheets 0.3175 and 0.1586 cm in thickness and 170 cm in length. The three model geometries involved in this study are shown in Figures 2, 3, and 4.

Fault Models: Figures 5, 6, and 7 show the dimensions for each of the fault plane models. For the three cases the surface layer consisted of plexiglass sheets 0.1586 cm thick. Each geometry was analyzed using three different interfaces—plexiglass-free air, plexiglass-aluminum, and plexiglass-wax.

Acoustical impedance ratios: The wave velocities experimentally determined are shown in Table 1. These velocities were obtained experimentally as shown in Appendix I.

**TABLE 1. Experimental elastic wave velocities**

<table>
<thead>
<tr>
<th>Material</th>
<th>$V_{m/sec}$</th>
<th>$S_{m/sec}$</th>
<th>$V_{R_{m/sec}}$</th>
<th>$\rho_{gr/cc}$</th>
<th>$\rho_{c_{gr/cc}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plexiglass</td>
<td>2338</td>
<td>1400</td>
<td>1250</td>
<td>1.22</td>
<td>0.25</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5450</td>
<td>3300</td>
<td>2960</td>
<td>2.77</td>
<td>0.26</td>
</tr>
<tr>
<td>Wax</td>
<td>1400</td>
<td>----</td>
<td>----</td>
<td>0.902</td>
<td>----</td>
</tr>
</tbody>
</table>

The acoustical impedances were then calculated, giving the following ratios:

Plexiglass: aluminum, 5.3 to 1
Plexiglass: wax, 2.78 to 1
Figure 2. Two layered model.

<table>
<thead>
<tr>
<th>P.V.C. TAPE</th>
<th>Source</th>
<th>Receptors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plexiglass (a)</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plexiglass (b)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Three layered model.

<table>
<thead>
<tr>
<th>P.V.C. TAPE</th>
<th>Source</th>
<th>Receptors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plexiglass</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plexiglass</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plexiglass</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Four layered model

<table>
<thead>
<tr>
<th>P.V.C. TAPE</th>
<th>Source</th>
<th>Receptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>36cm</td>
<td>Plexiglass (a)</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31cm</td>
<td>Plexiglass (b)</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25cm</td>
<td>Plexiglass (c)</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25cm</td>
<td>Plexiglass (d)</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
<td></td>
</tr>
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</table>

Figure 4. Four layered model
Figure 5. Fault model with fault plane dip of 90°.
Figure 6. Fault model with fault plane dip of 110°.
Figure 7. Fault model with fault plane dip of 70°.
These acoustical impedance ratios assure reflection at the interfaces.

IV. RESULTS

Seismic records were obtained by moving the receiver transducer, 4 cm each time for the layered models and 5 cm each time for the fault models, from the source toward the left and right sides. In all models the upper plexiglass sheet contains the source in a hole approximately 2.5 cm from the surface, and centered from each side.

Summary of Results

Each seismogram shows specific characteristics on its events, in accord with the model geometry involved. Paths of the more common events are drawn on Figures 4, 5, 6, and 7. These events, indicated by the experimental results, are summarized below in two parts: first those related to layered studies and second those related to fault geometries. These experimental results are analyzed in detail in a later section.

Layered Models: Figures 8 through 16 show the seismograms obtained, as well as the time-distance and amplitude-variation graphs for the three layered models. Those events involved are: longitudinal and shear direct events, reflection $R_a$ coming from the interface marked "a", reflection $R_b$ coming from the interface marked "b",...
Model geometry

Source

<table>
<thead>
<tr>
<th>Plexiglass</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8in.Thick</td>
<td></td>
</tr>
<tr>
<td>wax</td>
<td></td>
</tr>
<tr>
<td>Plexiglass</td>
<td>b</td>
</tr>
<tr>
<td>1/8in.Thick</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Seismogram for two layered model.
Figure 9. Time-distance profile for two-layered model
Figure 10. Amplitude variation graph for two-layered model.
Figure 11. Seismogram for
Three layered model.
Figure 12. Time-distance profile for three-layered model.
Figure 13. Amplitude variation graph for three-layered model.
### Model geometry

<table>
<thead>
<tr>
<th>Source</th>
<th>Thickness</th>
<th>Wax Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plexiglass</td>
<td>1/8in. Thick</td>
<td>a</td>
</tr>
<tr>
<td>Plexiglass</td>
<td>1/8in. Thick</td>
<td>b</td>
</tr>
<tr>
<td>Plexiglass</td>
<td>1/16in. Thick</td>
<td>c</td>
</tr>
<tr>
<td>Plexiglass</td>
<td>1/16in. Thick</td>
<td>d</td>
</tr>
</tbody>
</table>

**Figure 14.** Seismogram for four layered model.
Figure 15. Time-distance profile for four-layered model.
Figure 16. Amplitude variation graph for four-layered model
reflection $R_c$ coming from the interface marked "c" except in the case of the two-layered model, reflection $R_d$ coming from the interface marked "d" on the four layered model only, the event identified as compressional to shear converted ($R_a(ps)$ coming from "a", and the multiple reflected event $R_{am}$.

Fault Models: Figures 17 through 46 show the seismograms as well as the travel-time profiles, and the amplitude-variation graphs for the three fault models. Those events involved are: longitudinal and shear direct events which do not appear on all seismograms because delay time was used, reflection $R_a$ coming from the upthrown side of fault or interface marked "a", reflection $R_b$ coming from the downthrown side of fault or interface marked "b", reflection $R_c$ which comes from the bottom interface marked "c", compressional to shear converted event $R_a(ps)$ coming from "a", multiple reflection $R_{am}$ which is reflected two times from the interface marked "a", diffraction $D_a$ coming from the upper corner event $D_b$ coming from the lower corner marked $D_2$. 

Model geometry

Source

Plexiglass
1/16in. Thick

Figure 17. Seismogram for fault plane dip of 90°.
Figure 18. Time-distance profile for fault plane dip of 90°, Plexiglass-free air interface.
Figure 19. Amplitude variation graph for fault plane dip of $90^\circ$, Plexiglass-free air, interface.
Figure 20. Seismogram for fault plane dip of 90°.
Figure 21. Time-distance profile for fault plane dip of 90°, Plexiglass-aluminum interface.
Figure 22. Amplitude variation graph for fault plane dip of 90°, Plexiglass-aluminum interface.
Model geometry

Source

Plexiglass
1/16in. Thick

Plexiglass D2
1/16in. Thick

Figure 23. Seismogram for fault plane dip of 90°.
Figure 24. Time-distance profile for fault plane dip of $90^\circ$, Plexiglass-wax interface.
Figure 25. Amplitude variation graph for fault plane dip of 90°, Plexiglass-wax interface.
Model geometry

Source

Plexiglass
1/16in.Thick

Figure 26. Seismogram for fault plane dip of 110°.
Figure 27. Time-distance profile for fault plane dip of 110°, Plexiglass-free air interface.
Figure 28. Amplitude variation graph for fault plane dip of 110°, Plexiglass-free air interface.
Model geometry

Source

Plexiglass
1/16in. Thick

Aluminum

Figure 29. Seismogram for fault plane dip of 110°.
Figure 30. Time-distance profile for fault plane dip of 110°. Plexiglass-aluminum interface.
Figure 31. Amplitude variation graph for fault plane dip of 110°, Plexiglass-aluminum interface.
Figure 32. Seismogram for fault plane dip of $110^\circ$. 
Figure 33. Time-distance profile for fault plane dip of $110^\circ$, Plexiglass-aluminum interface.
Figure 34. Amplitude variation graph for fault plane dip of 110°, plexiglass-aluminum interface.
Model geometry

Source

- Plexiglass 1/16in.Thick

- Wax a D1

- Plexiglass D2 1/16in.Thick b
c

Figure 35. Seismic record for fault plane dip of 110°.
Figure 36. Time-distance profile for fault plane dip of 110°, Plexiglass-wax interface.
Figure 37. Amplitude variation graph for fault plane dip of 110°, Plexiglass-wax interface.
Model geometry

Source

Plexiglass
1/16in. Thick

a

D1

D2

b

Figure 38. Seismogram for fault plane dip of 70°.
Figure 39. Time-distance profile for fault plane dip of 70°, Plexiglass-free air interface.
Figure 4D. Amplitude variation graph for fault plane dip of 70°, Plexiglass-free air interface.

Figure 40. Amplitude variation graph for fault plane dip of 70°, Plexiglass-free air interface.
Model geometry

Source

Plexiglass
1/16in. Thick

Aluminum

Figure 41. Seismogram for fault plane dip of 70°.
Figure 42. Time-distance profile for fault plane dip of 70°, Plexiglass-aluminum interface.
Figure 43. Amplitude variation graph for fault plane dip of 70°, Plexiglass-Aluminum interface.
Model geometry

Source

Flexiglass
1/16in. Thick
wax

Flexiglass
1/16in. Thick

Figure 44. Seismogram for fault plane dip of 70°.
Figure 45. Time-distance profile for fault plane dip of 70°, Plexiglass-wax interface.
Figure 46. Amplitude variation graph for fault plane of 70°. Plexiglass-wax interface.
V. ANALYSIS OF RESULTS

In both the layered and fault cases, the amplitude variation does not decrease smoothly but has a zigzag variation. However, in order to analyze the amplitude variations of the events and relate them to each model, it is possible to consider a main amplitude variation in a general sense. This principal amplitude variation may be considered as an average curve. The zigzag variations will be taken into consideration in the section entitled Secondary Amplitude Variation.

The amplitudes were measured by taking peak to peak readings. The overlapping of signals other than reflections and diffraction is evident. Side, converted multiple, and ghost reflections are also present. Phase changes are evident in the reflected and diffracted events when a P wave passes from a high acoustical impedance medium to a low acoustical impedance medium.

Those events, summarized above, are analyzed in this section for each model geometry. These analysis are made on the basis of both time-distance profiles and average amplitude variation graphs. The layered cases are considered, and then the fault cases. In order to have a cross check, experimental and calculated values were obtained. Time paths were calculated using the following equations:

Reflections:  \[ t = \frac{2}{V} \left( h^2 + (x/2)^2 \right)^{1/2} \]  .............. (4)
Diffractions: \[ t = \left[ \left( h^2 + X_1 \right)^2 + \left( (X = X_1)^2 + h^2 \right)^{\frac{1}{2}} \right]/V \ldots (5) \]

\( X_1 \) = horizontal distance from source point to upper edge of the fault plane.

Amplitude values which are obtained in millivolts/cm were normalized to relative values in db by using the relation: \[ \text{db} = 20 \log \frac{V_1}{V_2} \], where \( V_2 = 5 \) millivolts, and \( V_1 \) are the amplitude readings.

The time-distance curves resulting from equations 4 and 5 are hyperbols with their axis of symmetry along the line \( X = 0 \). This axis is drawn on all the time-distance curves in Figures 9, 12, and 15. It is also evident from those equations that the curvatures of the hyperbols change with depth. These theoretical results check very well with the experimental results obtained in this investigation. The time-distance profiles were a very good tool for locating the various events.

Layered Models

Figures 9, 12, and 15 show the travel-time profiles, and the average amplitude-variation graphs are shown on Figures 10, 13, and 16 for the three layered models.

Time-distance profiles: Longitudinal to shear converted events are very well defined except for the third case (Figure 15) where delay time was used. Reflections \( R_a \) and \( R_b \) are well-defined for the three layered cases, \( R_a \) with a \( \Delta t \approx 60 \mu \text{sec} \) and \( R_b \) with a \( \Delta t \approx 48 \mu \text{sec} \).
Reflection $R_c$ is present for the second and third cases and shows a $\Delta t \approx 40$ μsec. Reflection $R_d$ is only weakly present for the third case showing a $\Delta t \approx 30$ μsec. Reflection $R_{a(p)}$ is present in the three geometries with a $\Delta t \approx 65$ μsec. The multiple reflection $R_{am}$ is present in the first case, however it is not well-defined in the seismogram for the two last cases. It is evident that the time-distance curves vary in their curvature ratios in accordance with the interface depths.

Amplitude-variation graphs: In order to have a general idea of how the amplitude values change when the wax layer width is varied, two two-layered model were used. The wax layer was about 1.0 cm one model and 0.4 cm in the other. The amplitude variation graphs for each of these are shown in Figure 10. The two graphs are consistent in shape but the values are lower for the smaller wax layer. The greater amplitude values in the left graph can be explained as follows:

The top wax layer reflection is reinforced with the bottom thin layer reflection.

For the three cases, the reelection $R_a$ shows a decreasing amplitude as the detectors are farther from the source, and the average amplitude is more or less symmetrical with respect to the source point. The amplitude range values are similar for the three cases. The amplitude values for the first case vary from about 18.1 to 10 db, for the second from 17 to 12 db and for the third from about 18 to 12 db.
Reflection \( R_d \) is present as a small average amplitude decreasing with distance from the source and is more or less symmetrical for the three different geometries. Those amplitude values decrease from about 13.9 to 12.1 db in the first case, from 13 to 12 db in the second, and from 13.6 to 12 db in the third.

The reflection \( R_c \), which is only possible in the second and third geometries, has a decreasing amplitudes varies from 17 to 14 db for the second case, and from 12 to 6 db for the third. These values are different because, in the second case this reflection is coming from a Plexiglass-free air interface, while for the third case it is coming from a Plexiglass-wax interface.

The reflections \( R_d \) is present only in the third model. The record is more complex because more interfaces are involved.

Both reflections \( R_{a(ps)} \) and \( R_{am} \) appears, but do not have a definite variation in their amplitudes. This may be caused by overlappings with other signals generated at the different interfaces.

Fault Models

Figures 18 through 45 show the travel-time profiles, and Figures 19 to 46 the average relative-amplitude variation graphs, for the various fault models.

Time-distance profiles: The longitudinal and shear direct events are very well defined except when the delay time was used. Thus, these events do not appear on those
seismograms, however the calculated values are shown on their respective travel-time profiles.

Reflection $R_a$ is very well defined for all the fault models. This event has a consistent $\Delta T = 75\mu\text{sec}$ for all cases. Because of the geometry when the fault plane dip at $70^\circ$ this event appears only on detectors number 6 to 24.

Reflection $R_b$ is also present for all the fault geometries. It has $\Delta T = 50\ \mu\text{sec}$ for the nine fault models. For a fault plane dip of $70^\circ$ this event is picked up from detectors number 1 to 7, path calculations show that this event is diffracted from corner $D_1$ and then reflected from interface "a".

Reflection $R_c$ is present for all models except when the Plexiglass-free air interface is involved. When aluminum is used as the lower layer these is a $\Delta T = 20\ \mu\text{sec}$, while when plexiglass is used as the lower layer $\Delta T = 30\ \mu\text{sec}$. This difference is because of the high aluminum velocity. The reflected energy which peaked from detectors 1 to 6 comes from corner $D_1$ and is reflected from "c" when the fault plane dip is $70^\circ$.

Longitudinal to shear converted event $R_{a(ps)}$ is present mainly when the Plexiglass-free air surface interface is involved. Its $\Delta T$ is about $75\ \mu\text{sec}$.

Diffraction $D_a$ is very well defined by both an increasing in moveout and an amplitude decreasing with distance. Its $\Delta T$ is about $130\ \mu\text{sec}$ except for the fault plane
dip is $70^\circ$. In this case the diffractions are picked up only from detectors 1 to 6.

Diffraction $D_b$ is not clearly identified. However, these are slight evidences of this event as a continuation of reflection $R_b$.

Amplitude-variation graphs: Reflection $R_a$ shows a consistent average amplitude variation throughout all the fault models. In all graphs a maximum value is present between receivers 16 and 17, and then the amplitude decreases toward receiver 24. It is noticeable that in the receivers nearest the source the amplitudes do not reach the maximum values. This phenomenon may be explained by signal overlapping which causes a destructive effect. In the Plexiglass-free air interface models the amplitude maximum value is about 34 db and the minimum about 24 db. In the Plexiglass-aluminum interface models the maximum value is about 27 db and the minimum about 14 db.

The amplitude variation of $R_b$ is consistent only for the first two geometries (Figures 19 to 37). The maximum value is reached between receivers 6 and 7 and decreases to both sides. The amplitude decreasing toward the source may be caused by an overlapping of signals. The amplitude variation of this event is different for the fault plane dip at $70^\circ$, because $R_b$ is an reflected energy coming from corner $D_1$. The amplitude for this last case shows a small increase in its value toward receiver 1. The maximum and minimum values are as follows: Plexiglass-free air from 20 to 14 db, Plexiglass-aluminum from 11 to 8 db, and Plexiglass-wax from 14 to 10 db.
Reflection $R_c$ has measurable amplitude values only when Plexiglass-wax-Plexiglass interfaces are involved. When Plexiglass-aluminum is used only weak traces of this signal appear because these are not well separated from the tails of reflection $R_b$. An extra record was obtained using a wider aluminum sheet which shows this event very well separated from $R_b$. There is not appreciable variation in the amplitude values but the low energy level is evident in comparison with those corresponding to reflections $R_a$ and $R_b$. The maximum values are as follows: Figure 25 about 6 db, Figure 37 about 9.5 db, and Figure 46 about 3.5 and b.

The reflection $R_{a(ps)}$ amplitude curve is similar to that of $R_a$ but with smaller values. These curves are characterized by a decrease toward the source point reaching values of the order of 1 db in detector 14. The maximum value of about 17 db is found between receivers 22 and 24.

The multiple reflection $R_{am}$ has very weak amplitude signals and these are only evident when the Plexiglass-free air interface is involved. The variation is like that corresponding to the reflection $R_a$, but the values are very small.

Diffraction $D_a$ shows, in all curves, a decrease in amplitude with distance from the source. The amplitude values are, in general, smaller than those of reflection $R_a$, and smaller still than those of reflection $R_b$ except
in the detectors nearest the source. The maximum values corresponding to the Plexiglass-free air interface are about 20 and 25 db with the minimum of about 6 db for the first two cases, and about 12 db in the last case. The event $R_b$ obtained in the last geometry is very interesting, this event is a diffracted reflected event coming from $D_1$.

Diffraction $D_b$ shows weak traces on its amplitude, and is present only on a few time-distance profiles.

A $180^\circ$ converted phase was noticeable when the interfaces involved were Plexiglass-free air and Plexiglass-wax. These phase changes are only present for reflected and diffracted events but not for the transmitted energy. They can be seen in Figure 47 where the seismograms are amplified four times.

Consideration of Error

The experimental model method used in this study may be considered as an approximation to a mathematical model. The source area has finite dimensions, and the models used have finite thicknesses. It is possible that both the epoxy resin and the wax influence the amplitude values due to the presence of small air bubbles.

An attempt was made to keep in the source and receiver systems the electrical and physical conditions as even as possible during a complete seismogram set recording.
Figure 47. Seismogram with 180° phase change.

1a, 11a, and 18a - Plexiglass-free air interface
1b, 11b, and 18b - Plexiglass-aluminum interface
1c, 11c, and 18c - Plexiglass-wax interface
Other causes of amplitude reading errors are:
Changes on the directivity of the receiver transducer, pressure changes on the pick up receiver, error in the peak to peak amplitude readings, errors caused by photography overlappings, and by changes in the photography line thicknesses.

Secondary Amplitude Variations

The secondary maximal and minimal values which appear in all amplitude-variation graphs, may have a relative relation with the consideration of error indicated above.

These variations may be also related to the following two causes: first, overlapping of signals other than the reflection and diffraction, presence of side, converted, ghost, and multiple reflections, and second, the fact of refraction critical angle which causes no transmitted P energy, and an increase of the reflected energy.

In order to support the above reasoning an extra graph was obtained (Figure 48), which has a smooth variation on both direct \( P_1 \) and reflected \( P_{1P} \) events. On this graph there is no overlapping of signals and there is no influence by the refraction critical angle. This graph was obtained by using a rectangular-shaped plexiglass sheet, 190 cm in length, 120 cm in width and 0.15875 cm in thickness. The pickup transducer was moved in a vertical direction, 10 cm each time. The amplitude decrease is caused only by traveling distance.
Figure 48. Smooth amplitude variation graph.
VI. CONCLUSIONS

Travel-time patterns are a good confidence factor for locating seismic model events. For reflected events the time-distance curves vary in their curvature ratios with depths. Both moveout increase and amplitude decay with distance, are present for diffracted events. When a P wave is traveling from a high-velocity medium to a low-velocity medium, a $180^\circ$ phase change in the reflected and diffracted signals is present. A Plexiglass sheet about $2\lambda$ inches wide gives a good resolution of reflected signals. Shadow zones appearing on fault models are illuminated by diffractions: i.e. in, the last fault geometry, the reflection coming from the downthrown side of the fault is a diffracted-reflected event. Amplitudes show high values when a Plexiglass-free air interface is used. Amplitude values show changes when the thin wax layer is varied in its width. Side, multiple, and converted events play an important role in the signal overlappings which have constructive or destructive effects. Seismograms become more complex as the geometry involved becomes more complex.
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APPENDIX I

Figure 49 shows the directionality of the receiver transducer. Figure 49a was obtained by moving the pickup 3° each time in the bottom of a Plexiglass sheet. At an angle of 39° the amplitude is reduced to about 58.3 percent with respect to the 0° position. Figure 49b was obtained setting the pickup at 50 cm distance, and then by rotating its position to different angles. At 80° the amplitude is reduced to about 91%, while at 20° it is reduced to about 54.5 percent with respect to the 90° position.

Figure 50 shows the experimental velocities obtained for a Plexiglass sheet, and Figure 51 shows the experimental velocities obtained for both aluminum and wax sheets.
Figure 49. Directionality of the receiver transducer.
Figure 50. Experimental velocities through Plexiglass.

- x x x Plexiglass Rayleigh velocity
- - - Plexiglass Shear velocity
- - - - - Plexiglass Longitudinal velocity

\[ V_R = 1250 \text{ m/sec} \]
\[ V = 2340 \text{ m/sec} \]
\[ = 1350 \text{ m/sec} \]
Figure 51. Experimental velocities through both aluminum and wax.
APPENDIX II

Figure 52 shows the Rayleigh and shear waves before they were reduced. Figure 53 shows the electrical pulse applied to the source transducer, and Figure 54 shows the acoustical pulse incident at the free-air surface.
Figure 52. Rayleigh waves

Figure 53. Electrical pulse applied at the source transducer

Duration
80 microsec
50 microsec
20 microsec

Figure 54. Acoustical pulse at the free-air surface.