PROPAGATION OF FLEXURAL WAVES IN AN AZIMUTHALLY ANISOTROPIC BOREHOLE MODEL

by

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ABSTRACT

Flexural waves generated by a dipole source have been studied theoretically and used to estimate the shear parameters of a formation. The basic principles and main properties of flexural waves propagating in a borehole are reviewed in this paper. A mono/dipole transducer made of a PZT piezoelectric tube is used for laboratory experiments in borehole models. The radiation pattern of the dipole source is measured in a water tank. In order to simulate the hard and soft formations, measurements are performed in borehole models made of aluminum and lucite, respectively. Experimental results are in good agreement with the theoretical dispersion characteristics. Measurements are also performed with the transducers in an azimuthally anisotropic borehole model made of Phenolite XX-324. Both fast and slow flexural waves with different velocities are generated by a dipole source in the model. The flexural waves are related to the fast or slow shear waves in the anisotropic material. Experimental results show that the flexural wave splits into a fast and a slow component in an azimuthally anisotropic borehole; therefore, dipole acoustic well logging could be an effective means for estimating a formation's anisotropy.

INTRODUCTION

For the past twenty years, full waveform acoustic well logging with an axi-symmetric source has been developed in both theory and numerical analysis. It has been found that important parameters of compressional and shear waves can be obtained with single-well logging. Theoretical studies (Cheng and Toksöz, 1981; Tubman et al., 1984) show that refracted compressional waves, refracted shear waves, pseudo-Rayleigh waves and Stoneley waves can be excited by an axi-symmetric source (monopole source) in a fluid-filled borehole surrounded by a hard formation, and that only compressional waves and Stoneley waves can be excited in a soft formation. It is easy to determine the acoustic parameters of a compressional wave because it is the first arrival in a recorded waveform. For the shear wave, extensive data processing must be performed to extract its parameters from the full monopole waveforms. The inversion of Stoneley wave velocity is typically used to obtain the shear velocity in a soft formation (Cheng and Toksöz, 1983; Stevens and Day, 1986).

Determining the shear wave parameters is one of the most important applications of full waveform acoustic well logging. However, conventional monopole sources cannot generate a direct shear head wave in a soft formation where the shear wave velocity is lower than the acoustic velocity of the borehole fluid. Direct shear wave logging using dipole or multipole sources has been developed and applied in oil fields for recent years (Kitsunezaki, 1980; Zemanek et al., 1984, 1991; Zhu et al., 1990). Theoretical studies (Kurkjian and Chang, 1986; Schmitt, 1988; Schmitt et al., 1988; Winbow, 1985, 1988) showed that a dipole source can generate a flexural wave in a borehole surrounded by either hard or soft formations. This wave is a guided wave propagating along the borehole wall. At the cut-off frequency, its velocity along the borehole axis is equal to that of the shear wave in the formation. This flexural wave is a bending vibration mode and does not generate the conventional compressional mode. Therefore, the flexural wave at the shear velocity is the first arrival in the received waveforms and the data processing for determining the arrival and amplitude becomes simple. Laboratory experiments were carried out with dipole and quadrupole transducers in a borehole model (Chen, 1988, 1989), and verified the existence of such a flexural wave.

The vibration mode of the flexural wave is totally different from that generated with a monopole source. Chen and Eriksen (1991) showed that in a cased borehole the flexural wave can be excited and the velocity of its low-frequency component is equal to the shear velocity of the formation. This means that not only in an open hole with hard or soft formation, but also in a cased hole, the shear parameters of the formation can be directly measured with the flexural wave generated by a dipole source.

One situation of particular interest to shear wave logging applications is the situation where the formation is azimuthally anisotropic. In this case, which can result from in situ stress difference between two principal stress axes or from subvertical fractures or aligned cracks, there exist two shear waves propagating with different velocities. Because of the complexity of the geometry, only simplified numerical models of this situation have been studied, using perturbation methods or a finite difference approach. In this paper we use laboratory scale models of a borehole in an azimuthally anisotropic formation to study the behavior of flexural waves under such conditions.

In this paper, the basic principles of the dipole source and acoustic field in a fluid-filled borehole are briefly reviewed. A mono/dipole transducer is made for the laboratory borehole models. Its radiation pattern is measured in a water tank. Ultrasonic borehole models are made of aluminum, lucite and phenolite. The acoustic field in the boreholes is measured with the mono/dipole transducers. The experimental results show that the flexural wave can be generated in both hard and soft boreholes. The splitting of a flexural wave into fast and slow waves is observed in an anisotropic model borehole.

FLEXURAL WAVE IN A BOREHOLE

A small expanding and contracting ball with a radius smaller than a wavelength can be considered as a point or monopole source. A dipole source is constructed by placing two monopole sources across the axis symmetrically. In our laboratory work, a PZT piezoelectric tube vibrating in the radial direction is applied as a monopole transducer, while two halves of the tube vibrating 180 degrees out of phase constitute a dipole transducer.

Kurkjian (1986) calculated the displacement potential in a fluid-filled borehole surrounded with an elastic formation. The displacement potential $\Phi(r,\theta,z,t;k_z,\omega)$ contains both the direct field term Φ_D and the reflected field term Φ_r affected by the formation:

$$\Phi(r,\theta,z,t;k_z,\omega) = \Phi_D + \Phi_r$$
$$= \frac{-i}{4} V_o(\omega) J_n(k_r^{(f)} r_o)[\epsilon_n H_n^{(1)}(k_r^{(f)} r) + A_n(k_z,\omega) J_n(k_r^{(f)} r)] \cdot e^{ik_z z} \cdot e^{-i\omega t} \cdot cos[n(\theta - \theta_o)] \quad (1)$$

where J_n and $H_n^{(1)}$ denote the nth order Bessel function and Hankel function of the first kind, respectively; ϵ_n is Neumann's factor; n is the multipole order of the source; $V_o(\omega)$ is the source spectrum; $A_n(k_z,\omega)$ is a weighting function determined by the boundary conditions. Axial wavenumber k_z and radial wavenumber k_r^f in the fluid satisfy the following condition:

$$k_r^{(f)} = (\frac{\omega^2}{V_f^2} - k_z^2)^{1/2}$$

where ω is the circle frequency and V_f is the compressional velocity in the fluid.

The characteristic equations can be obtained by assuming the denominator of the weighting function $A_n(k_z,\omega)$ to be zero (Kurkjian, 1986). The phase and group velocity dispersions, the excitation curves and the waveforms have been numerically calculated in various boreholes (Kurkjian and Chang, 1986; Schmitt, 1988; Zhu et al., 1990). There is a frequency at which the flexural wave velocity is equal to the formation shear velocity. The softer the formation and the bigger the borehole diameter, the lower the cut-off frequency becomes. There is a maximum in the excitation curve near the minimum in the group velocity. Because of these characteristics of the flexural wave, it becomes a very useful means to measure shear parameters of a formation.

When a dipole source generates a flexural wave in a borehole, the bending vibration of the borehole wall is in a particular azimuthal direction. If the formation shear wave propagating along the borehole axis is anisotropic, i.e., the velocities of shear waves with different polarization are different from each other, then the velocities of the flexural waves should also vary with polarization and should be related to the shear wave velocities. Shales are known to be anisotropic and fractures and/or thin beds can be considered as equivalent anisotropic materials. It is possible to determine the formation anisotropy with flexural waves.

In this paper, several ultrasonic model borehole experiments are performed using different materials, both isotropic and anisotropic. The propagation of flexural waves in water-filled boreholes is studied experimentally. Comparison of the monopole and dipole waveforms received in a borehole is helpful to understand the main characteristics of flexural waves.

MONO/DIPOLE TRANSDUCER

In order to generate and receive the flexural waves in the borehole models and to compare them with monopole waveforms at the same conditions, we designed a mono/dipole transducer and measured the dipole radiation pattern in a water tank.

Figure 1 shows the construction of the mono/dipole transducer which is made of a PZT piezoelectric tube 0.625 cm in outer diameter, 0.317 cm in inner diameter and 0.635 cm in height. The tube is cut into two parts. Four electrodes are connected to the outer and inner side of the two half tubes, respectively, and are gathered and insulated from each other by sealing them with rubber resin. The diameter of the transducer is about 0.9 cm. This transducer can be connected as either a monopole or a dipole by simply flipping a switch (see Figure 1).

When the transducer is connected as a dipole, electric currents of opposite polarity are applied to the two half PZT tubes, one part expands, the other contracts (Figure 2) and a horizontal force is produced in the surrounding water. If this dipole source is placed in a fluid-filled borehole, the flexural wave will be generated.

The radiation pattern of our dipole transducer is measured in a water tank. Figure 3 shows a schematic diagram of the measurement system. One dipole source is installed at the end of a rod which can rotate within 360° azimuth. A 50 kHz sine-burst excites the dipole source. The acoustic waves are received by a hydrophone placed in the far field. When the dipole source is rotated, the waveforms are recorded every 20° and are shown in Figure 4. The amplitude of the radiated acoustic waves at various azimuths can be measured from the received waveforms. The radiation pattern of the dipole source is shown in Figure 5. From Figure 4, it is seen that the phases of the two main lobes in the pattern are of opposite signs.

From Figure 5, we see that this transducer has the main characteristics of a dipole source: sharp radiation and opposite phases. Because of the limitations in the technology for making the transducer, the sizes and the axis of the main lobes are not exactly symmetrical. Therefore, the generated or received waves in a borehole are not pure flexural waves. The effect of this asymmetry on the waveforms will be seen in the following experiments.

The advantage of this transducer is that it can be connected as a monopole or a dipole just by changing the connection of the electrodes and not by changing the transducer. Therefore, the difference between the waves generated by a monopole or a dipole can be easily compared in the same geometric situation.

FLEXURAL WAVE IN THE ISOTROPIC MODELS

To simulate an isotropic hard or soft formation borehole, ultrasonic borehole models are made of aluminum and lucite, respectively. Table 1 shows the physical and geometrical parameters of the models. The measurements with monopole and dipole transducers are performed in aluminum and lucite models and the received waveforms are shown in Figures 6 – 9, respectively.

Figure 6 shows the received waveforms with monopole transducers in the aluminum model. It is obvious that refracted compressional waves, shear waves and Stoneley waves are generated. Their velocities are the same as those shown in Table 1.

Figure 7 shows the received waveforms with dipole transducers in the aluminum model. The head wave in the waveforms is a flexural wave. Its center frequency is about 200 kHz and the phase velocity is 3100 m/s. Because the cut-off frequency of the flexural wave in this model is about 70 kHz, the flexural velocity at 200 kHz is a little less than the shear velocity(3150 m/s). It is known from the dispersion equation that the phase velocity of the flexural wave at 200 kHz is 3100 m/s which agrees with the experimental one. In Figure 7, we see that the acoustic wave propagating with P-wave velocity is effectively eliminated, but because of the asymmetry of the dipole transducer, the Stoneley wave with low frequency and high amplitude is still partially recorded.

Figure 8 shows the received waveforms with monopole transducers in the lucite model. Because the lucite shear velocity is less than the water velocity, only P waves and Stoneley waves are generated. Measured velocities are the same as those in Table 1. The refracted shear wave is not excited in this lucite model.

Figure 9 shows the received waveforms with dipole transducers in the lucite model. The velocity of the flexural wave at low frequency (about 70 kHz) is 1050 m/s, which is less than the shear velocity in lucite. From the dispersion equation of the flexural wave, it can be calculated that the cut-off frequency is 30kHz in the model and the phase velocity at 70 kHz is 1050 m/s which is in good agreement with the measured one.

The above experiments show that the flexural waves are successfully generated and received with the transducer in both hard and soft formation borehole models. Its theoretically expected characteristics are observed in the experiments. We next study the propagation of flexural waves in an anisotropic borehole model using this pair of mono/dipole transducers.

FLEXURAL WAVE IN AN ANISOTROPIC MODEL

We chose a man-made material with strong acoustic anisotropy to make an ultrasonic borehole model. We first introduce the acoustic properties of the material and then the experimental results.

Acoustic Properties of Phenolite

Table 2 shows the main physical and mechanical parameters of Phenolite XX-324.

A cubic sample of Phenolite XX-324 is fabricated. The measurements of P- and S-wave velocities with different polarizations along three axis directions are performed, respectively. Figure 10 shows the method to measure the velocities along the X-axis.

We use the Parametric V152 Standard Shear Transducers to measure the acoustic waves propagating along the X-axis on the two surfaces. Figure 11 shows the received waveforms. Because the shear transducer generates some P waves simultaneously, not only S waves but also P waves and reflected P waves are observed in the measurements. In Figure 11, three sets of the waveforms are generated by locating the source at $0^o, 45^o$ and 90^o and the receiver at $0^o, 45^o, 90^o, 135^o$ and 180^o, respectively.

When the source is located at 0^o, the vibration direction is along the Z-axis and the wave propagating along the X-axis is a slow shear wave with a velocity of 1390 m/s. When the source is at 90^o (Y axis), a fast shear wave with a velocity of 1940 m/s is generated. The anisotropy of the shear waves is about 28%. From Figure 12 we can see that no shear wave is recorded when the polarization of the source and receiver are vertical to each other and that the P wave is not affected by the polarization direction. The velocity of the P wave along the X-axis is 3940 m/s.

When the source is at 45^o, two components of shear waves are generated in both the Y and Z directions. If the receiver is at 0^o or 180^o (Z-axis direction), only slow shear waves are received. If the receiver is at 90^o (Y-axis direction), only fast waves are received. If the receiver is at 45° or 135°, both slow and fast shear waves are received at the same time. Similar results can be found in the other two main axes.

Measurements in an Anisotropic Borehole Model

An anisotropic borehole model is made of the anisotropic material Phenolite XX-324 and has the dimensions 25.4 X 25.4 X 15.2 cm^3. A hole 1.27 cm in diameter is drilled along the X-axis (Figure 13). The measurements are carried out by changing the spacing between the source and receiver or by changing the vibration direction of one transducer (or both).

Array-Offset Measurements

The measurements are performed with the mono/dipole transducers in the anisotropic model. Figures 14 and 15 show the waveforms received by changing the spacing between the source and receiver step by step. The monopole acoustic field in the borehole (Figure 14) is similar to that in the hard formation borehole because the fast shear velocity is faster than the water velocity. It is very clear that there are P waves, fast S waves and Stoneley waves in Figure 14. The slow shear wave is not generated with the monopole source because its velocity is lower than the water velocity. The measured velocities of the P wave and fast S wave are the same as those measured with the sample. Measured Stoneley wave velocity (1250 m/s) agrees with that calculated theoretically using the slow shear wave velocity.

Two kinds of flexural waves are generated by the dipole source (Figure 15). Their velocities are 1920 m/s and 1340 m/s respectively. The center frequencies of the fast and slow flexural waves are about 150 kHz and 110 kHz, respectively. Comparing these velocities with those measured on the sample, we know that the fast flexural velocity is almost equal to that of the fast shear wave and the slow flexural velocity is lower than that of the slow shear wave because of the different characteristics of the phase velocity dispersions near the cut-off frequency range (Kurkjian and Chang, 1986).

From Figure 15 we see that the amplitude of the slow flexural wave is larger than that of the fast wave. The acoustic impedance of the slow shear wave is lower and is better matched with the water impedance than that of the fast wave. Therefore the slow flexural wave is more easily generated and the amplitude is also higher than that of the fast flexural wave. The slow flexural wave, like the Stoneley wave, is of high amplitude and low frequency. Indeed it may be doubted that this wave is in fact the slow flexural wave; perhaps it is a Stoneley wave, but the higher phase velocity as compared with the Stoneley wave generated by the monopole source (Figure 14) eliminates that possibility.

Figure 16 shows the waveforms received by fixing the positions of both source and receiver in the borehole and changing their status between monopole and dipole. A very strong Stoneley wave is generated by the monopole source (Figure 16a), but it cannot be received by the dipole receiver (Figure 16b). On the other hand, a strong slow flexural wave is generated by the dipole source (Figure 16d), but it is not received by the monopole receiver (Figure 16c). In comparing the waveforms in Figure 16a with those in Figure 16d, the shapes, amplitudes and frequencies of the waveforms received by the different acoustic systems are different from each other. From the following experiments, we will see that the variations in the phase and amplitude of flexural and Stoneley waves are totally different. Therefore we conclude that the wave received with the dipole system is the flexural wave and is not a Stoneley wave.

Azimuthal Measurements

The measurements of the acoustic field in various azimuths are performed by rotating the transducers in the borehole.

(1) Fixing Source and Rotating Receiver

From Eq. (1) we know that the dipole acoustic field is different from the monopole one and that it varies with the azimuth. The acoustic field at various azimuthal angles is measured by fixing the source and the spacing and rotating the receiver around the borehole axis.

Figure 17 shows the waveforms received by fixing the monopole source and rotating the monopole receiver. In this case, the amplitude does not change azimuthally. Figure 18 and Figure 19 show the waveforms received by fixing the dipole source along the Y- and Z-axes and by rotating the dipole receiver, respectively. Not only the amplitude but also the phase of the fast and slow flexural waves vary with the azimuth. When the vibration direction is fixed along the Y-axis, the stronger fast flexural wave is generated (Figure 17). When the particle vibration is along the Z-axis, the stronger slow flexural wave is generated and the fast wave is very weak (Figure 18). This experimental result shows that both the amplitude and phase of flexural waves generated by a dipole source in a borehole vary with the azimuth. In the azimuthally anisotropic borehole, flexural waves with different velocities are generated by the dipole source at different azimuths.

(2) Rotating Both Source and Receiver

We mount the dipole source and receiver in either the same direction or orthogonal to each other and then rotate them synchronously, measuring the flexural wave field at various azimuths. Figure 20 shows the waveforms received by fixing the dipole source and receiver in the same polarization direction and then rotating them synchronously. Because of the same vibration direction of the dipole source and receiver, the stronger flexural waves are received at each azimuth, but the amplitudes of the fast and slow flexural waves vary periodically with the azimuth. The strongest fast and slow flexural waves are generated and received around the Y-axis (90^o and 270^o) and Z-axis (0^o or 180^o) respectively. The flexural wave at a certain direction depends on the related shear wave. Therefore the shear parameters at a certain direction can be measured by the flexural wave at the same direction.

Figure 21 shows the waveforms received by fixing the dipole source and receiver orthogonal to each other. If the wall material is isotropic, no flexural wave can be received because of orthogonality. But in the anisotropic borehole, the flexural wave is not received only at a few positions ($0^o, 90^o, 180^0$ and 270^o). The fast and slow flexural waves are received everywhere else. This shows the cross-coupling between the fast and slow flexural waves when not aligned with the principal axes.

It can be seen from the shear body wave measurements (Figure 11b) that when the source is at 45^o, two shear waves, vibrating in the Y- and Z-directions and propagating with different velocities along the X-axis, are generated simultaneously. It is similar to the case when the polarization of the dipole source is not along the main axes (Y- or Z-axis), so that two components of the flexural wave are generated which vibrate along the Y- and Z-axes and which propagate with the fast and slow flexural velocities, respectively. Because of the different velocities, the two components do not counteract each other at the receiver and both are received even though the directions of the source and receiver are at right angles. The result is that two flexural waves can be received along the non-axis direction in an anisotropic borehole, despite the fact that the polarizations of the source and receiver are perpendicular to each other.

CONCLUSIONS

The theory shows that the flexural wave can be excited with a dipole source in both a hard and soft formation borehole and that the velocity at the cut-off frequency is equal to the shear wave velocity. The ultrasonic model borehole experiments presented in this paper show:

1. A transducer made of a PZT-5A piezoelectric tube can be operated as a monopole or dipole transducer with a switch.

2. The experiments with hard and soft models show that the flexural wave can be generated by a dipole source. The velocity of the flexural wave is almost equal to the shear velocity in a hard formation and is a little lower than the shear velocity in a soft

formation in our experiments because of theoretically expected dispersion. The shear wave velocity of the formation can therefore be obtained from the dispersion equation.

3. An ultrasonic anisotropic borehole model is constructed of Phenolite XX-324 in which the shear velocities are related to the direction of particle vibration. The relative difference of the shear velocities is about 28%.

4. Fast and slow flexural waves can be generated by a dipole source in an anisotropic borehole. Their velocities depend on the particle polarization direction. The frequencies of the received waves are above the cut-off frequencies. In general the slow flexural wave is more easily generated than the fast one in our model. This means that the slow flexural wave has a larger amplitude and a lower frequency than the fast one.

5. When the polarization of a dipole source is not along the main axes of the anisotropic material, two components of the flexural wave propagating with fast and slow velocities can be received. This means that the splitting of a flexural wave is observed in the anisotropic borehole and can be used for determining the direction of the principal axes of anisotropy.

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Table 1: Parameters of the aluminum and lucite models

Model	P Wave V_p (m/s)	S Wave V_s (m/s)	Stoneley Wave V_{st} (m/s)	Density (g/cm^3)	O.D. (cm)	I.D. (cm)
Aluminum	6400	3100	1450	2.7	20.3	1.4
lucite	2650	1270	1020	1.18	20.3	1.4

Table 2: Mechanical Parameters of Phenolite XX-324

Density, GM/CC	1.34
specific Volume, CUIN/LB	20.6
Tensile Strength, PSI, Lengthwise	16,000
Tensile Strength, PSI, Crosswise	13,000
Compressive Strength, PSI, Flatwise	34,000
Flexural Strength, PSI, Lengthwise	18,000
Flexural Strength, PSI, Crosswise	14,000
Modulus of Elasticity in Flexure x 10^5	
Lengthwise	14
Crosswise	11
Impact Strength, IZOD Edgewise	
ft lbs./in notch	
Lengthwise	0.55
Crosswise	0.50
Rockwell Hardness, M Scale	105
Bond Strength, lbs.	1,100

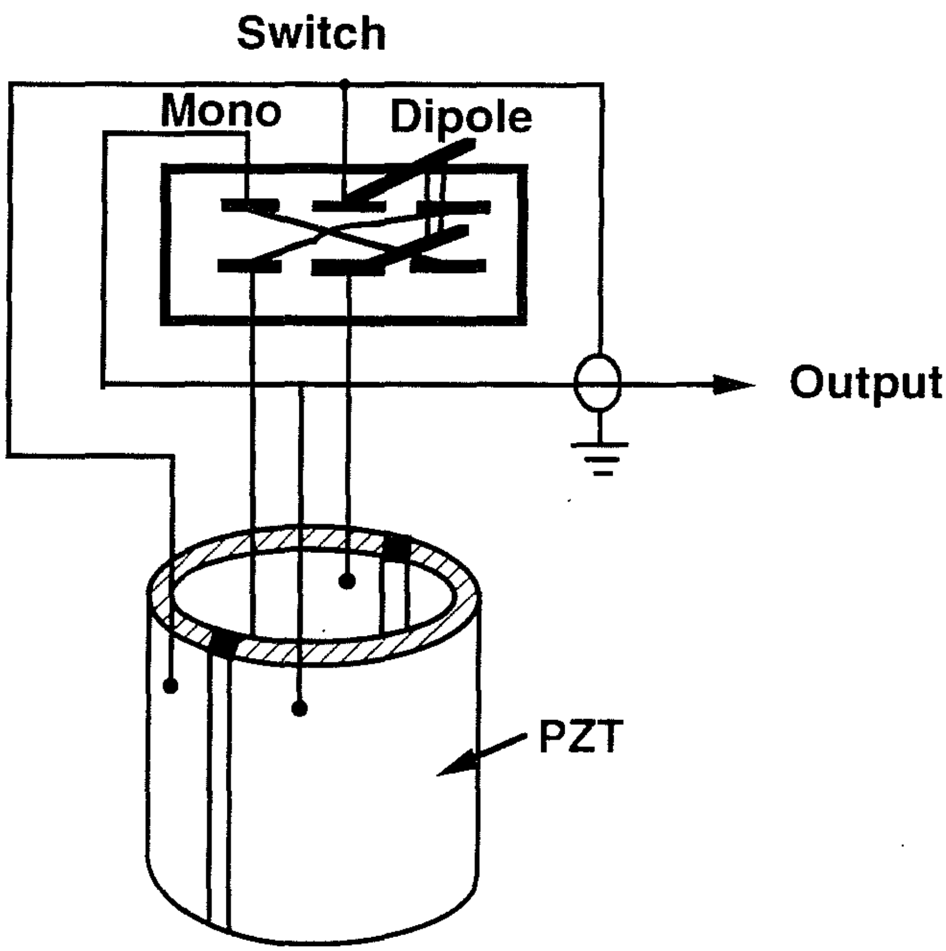


Figure 1: A diagram of the mono/dipole transducer.

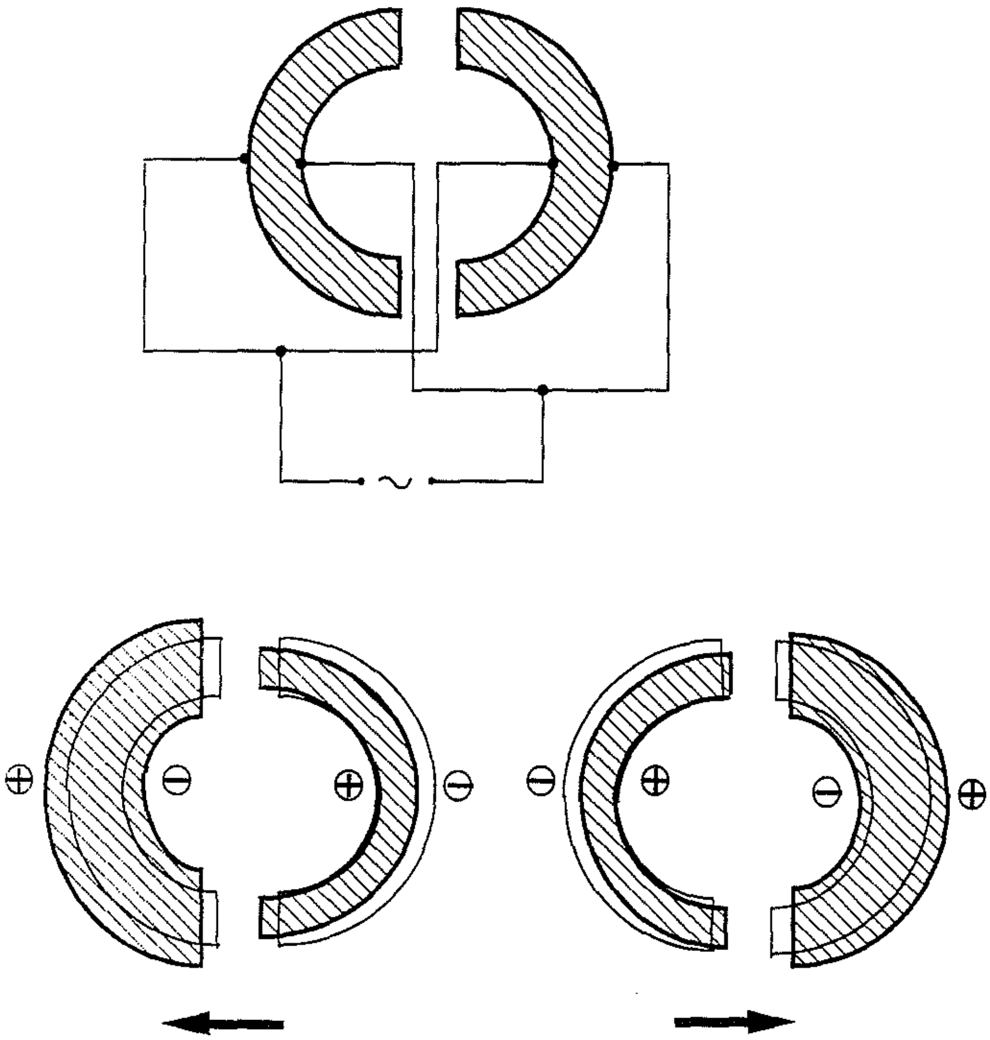


Figure 2: Working diagram of a dipole source.

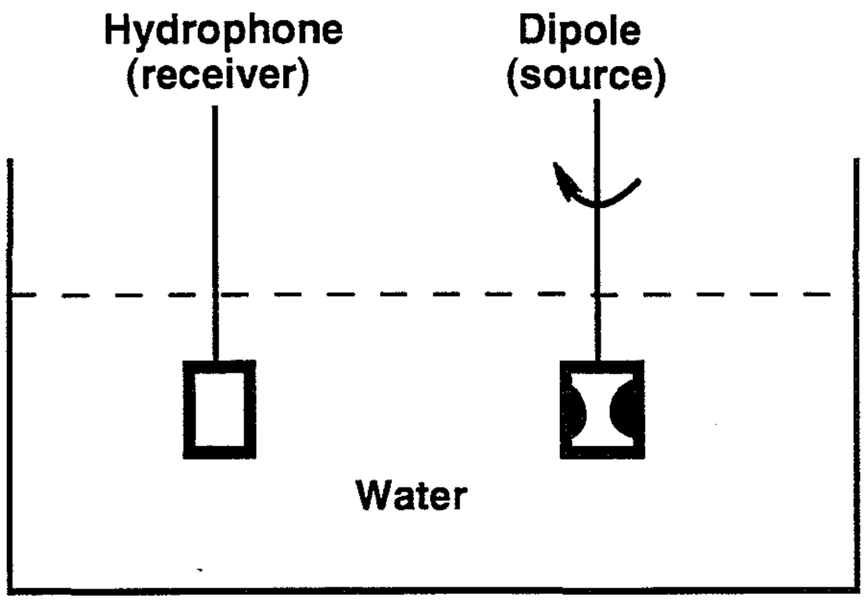


Figure 3: Diagram of measurement for the radiation pattern of a dipole transducer in a water tank.

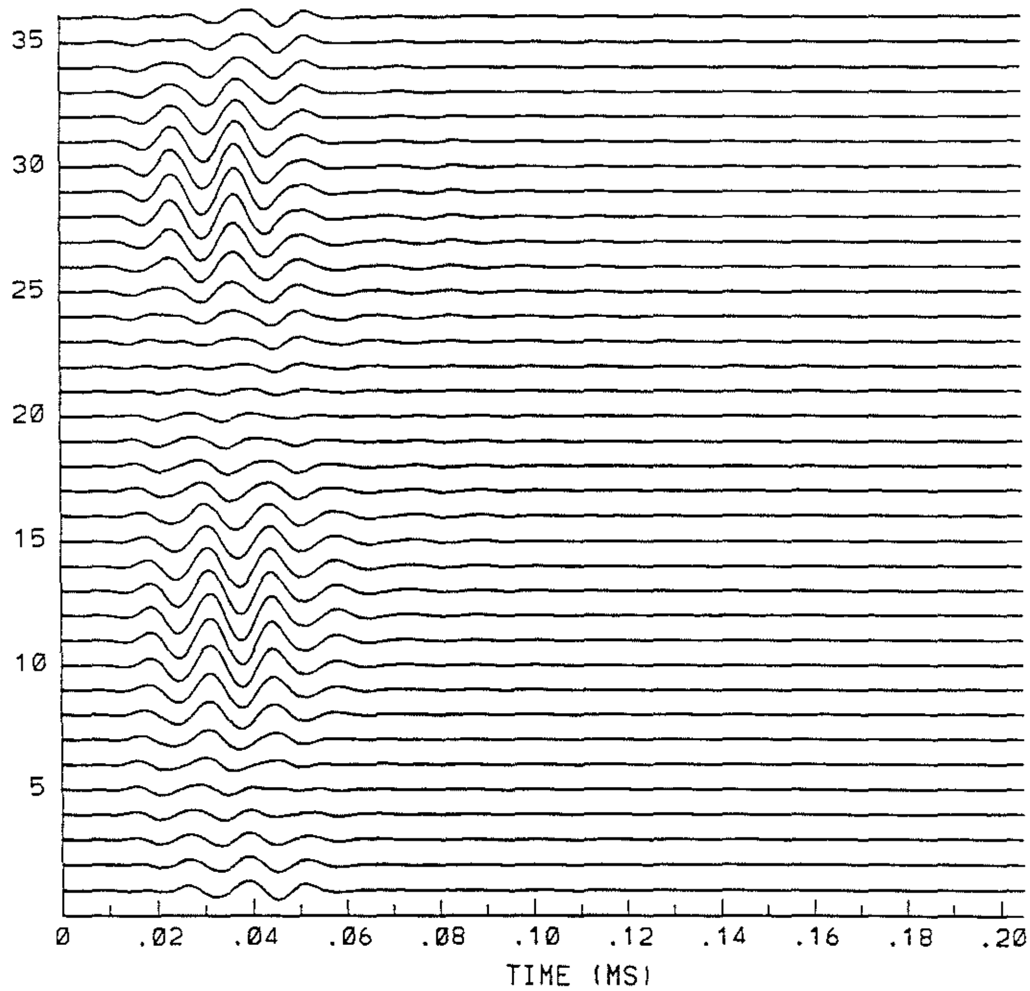


Figure 4: Waveforms received in the radiation measurement. The angular increment is 20^o/trace.

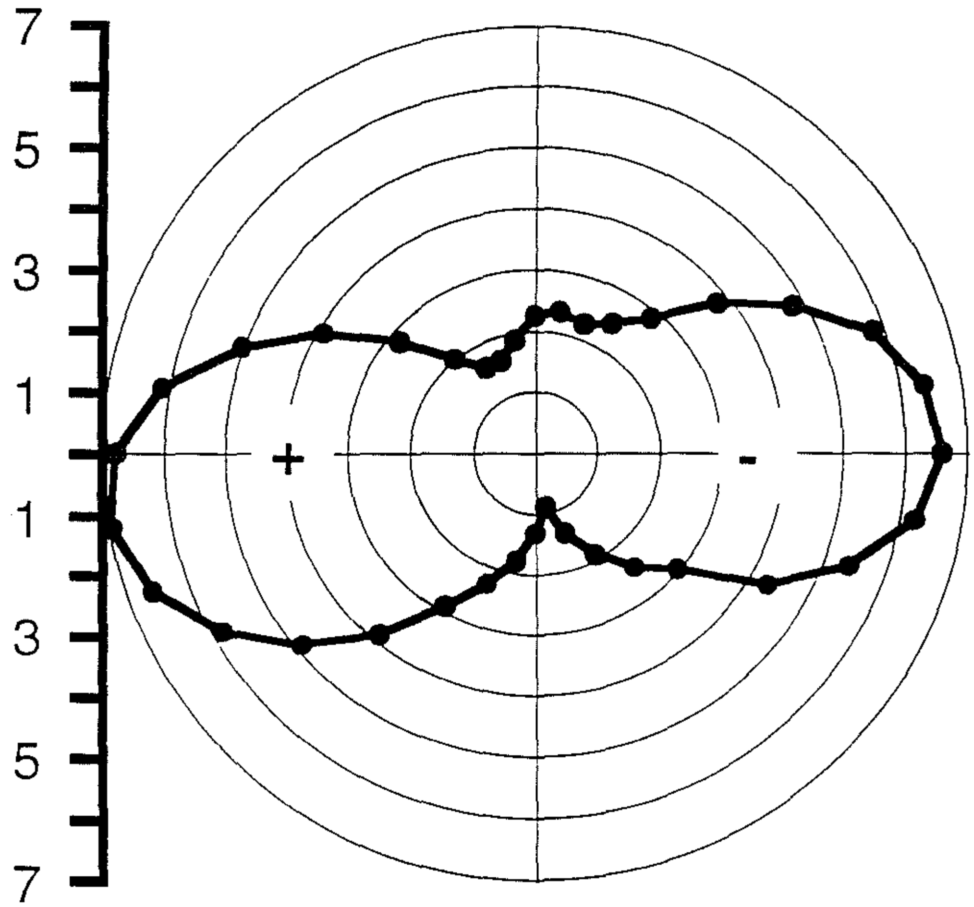


Figure 5: Radiation pattern of a dipole source.

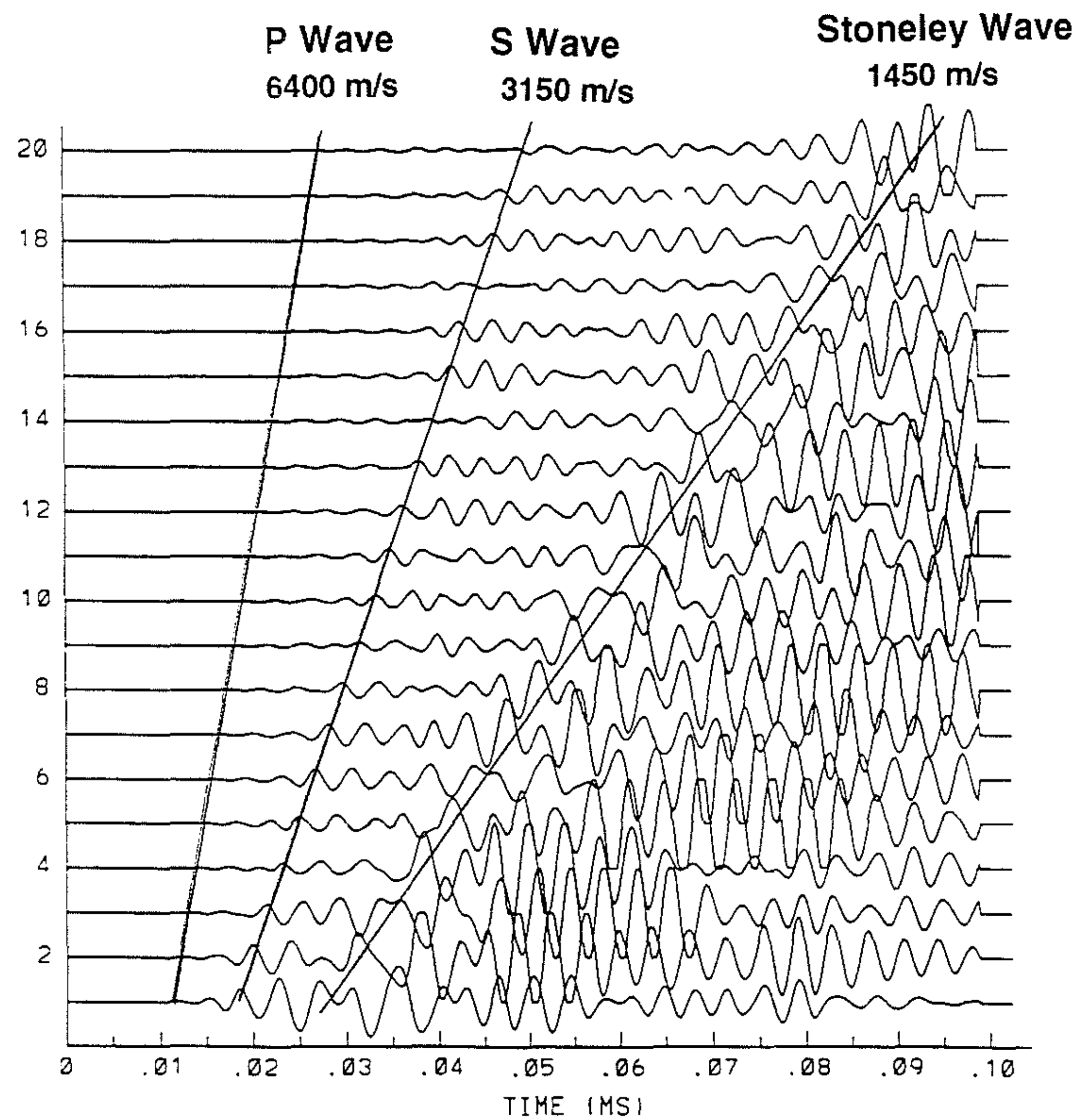


Figure 6: Waveforms measured with monopole transducers in the aluminum model.

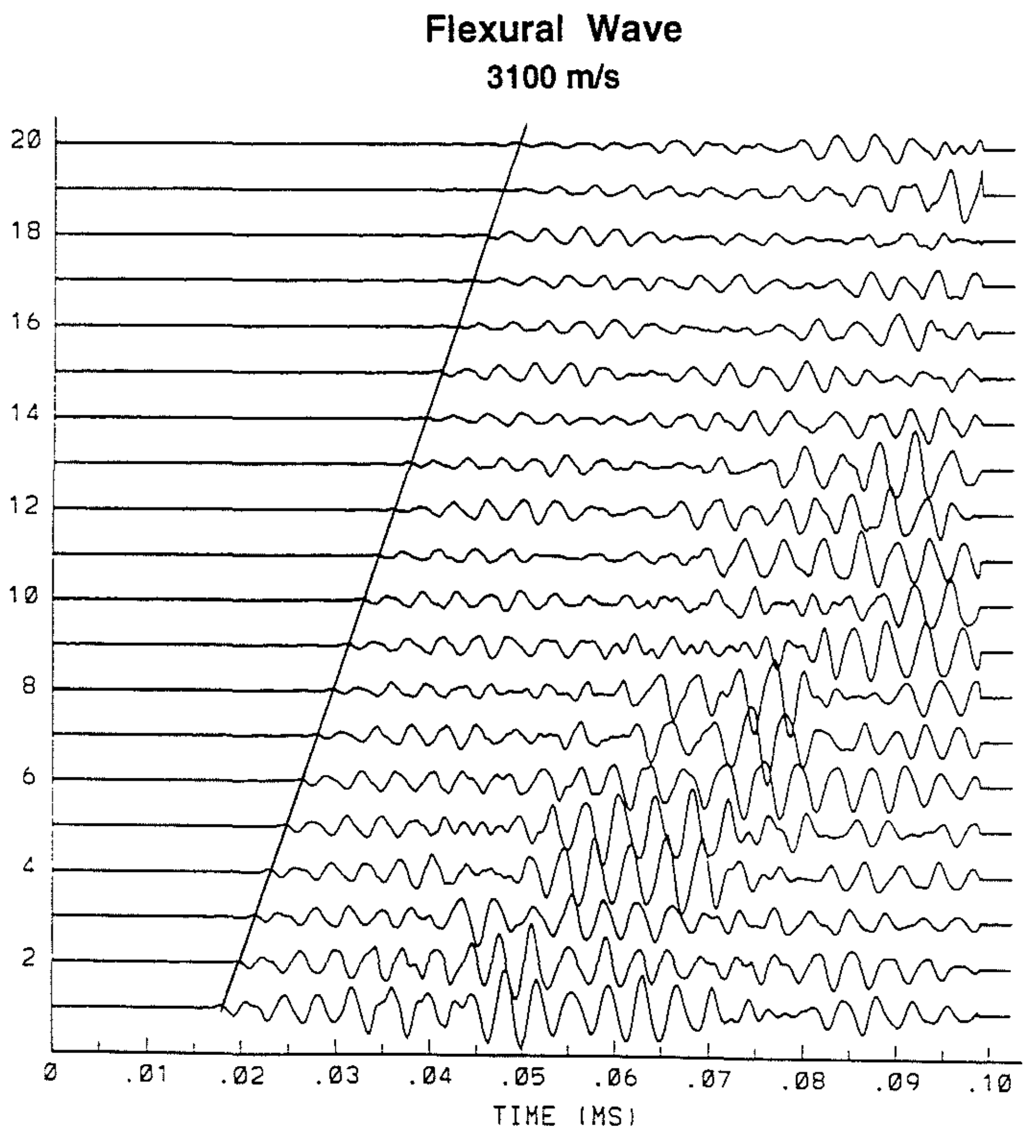


Figure 7: Waveforms measured with dipole transducers in the aluminum model.

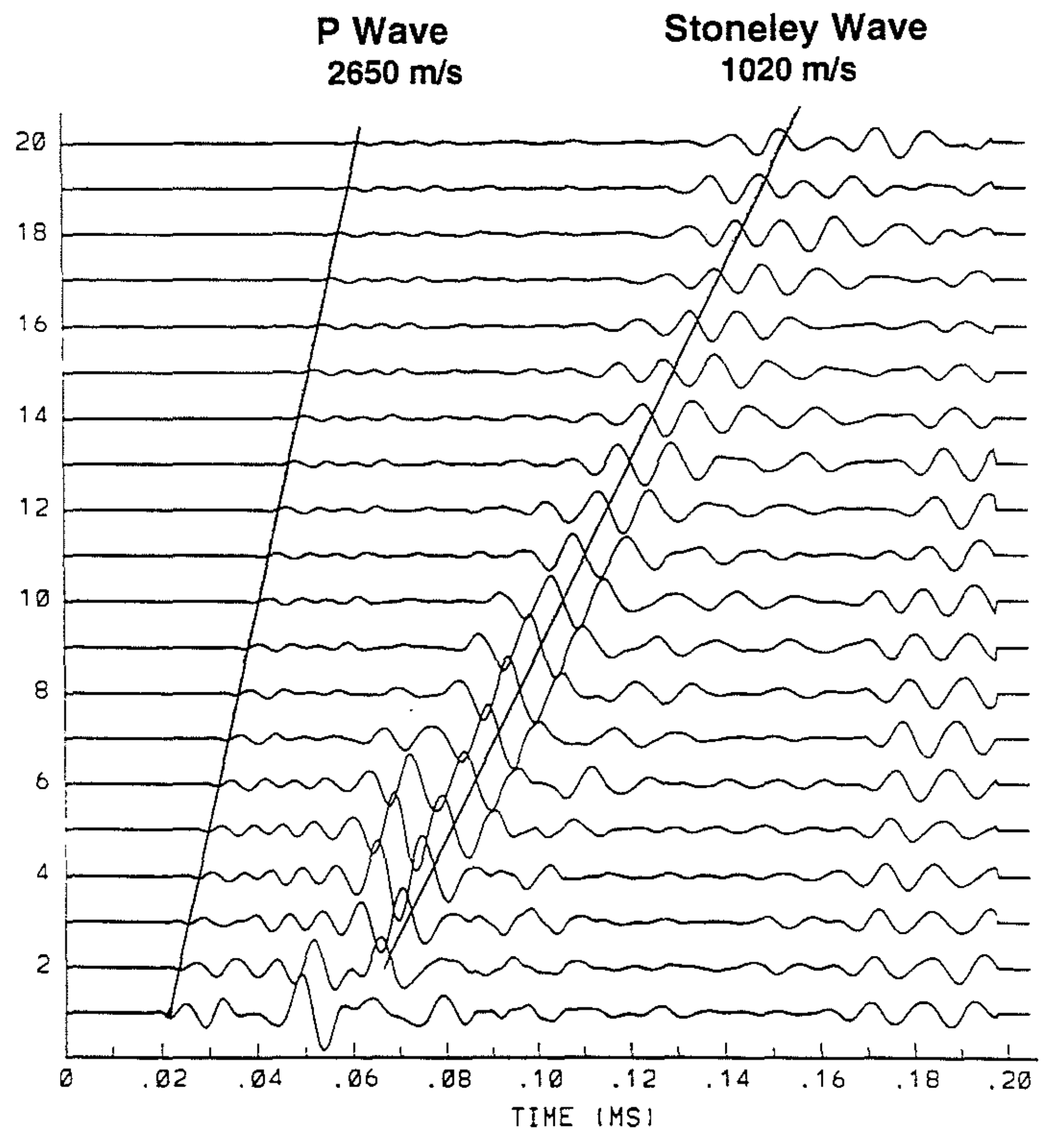


Figure 8: Waveforms measured with monopole transducers in the lucite model.

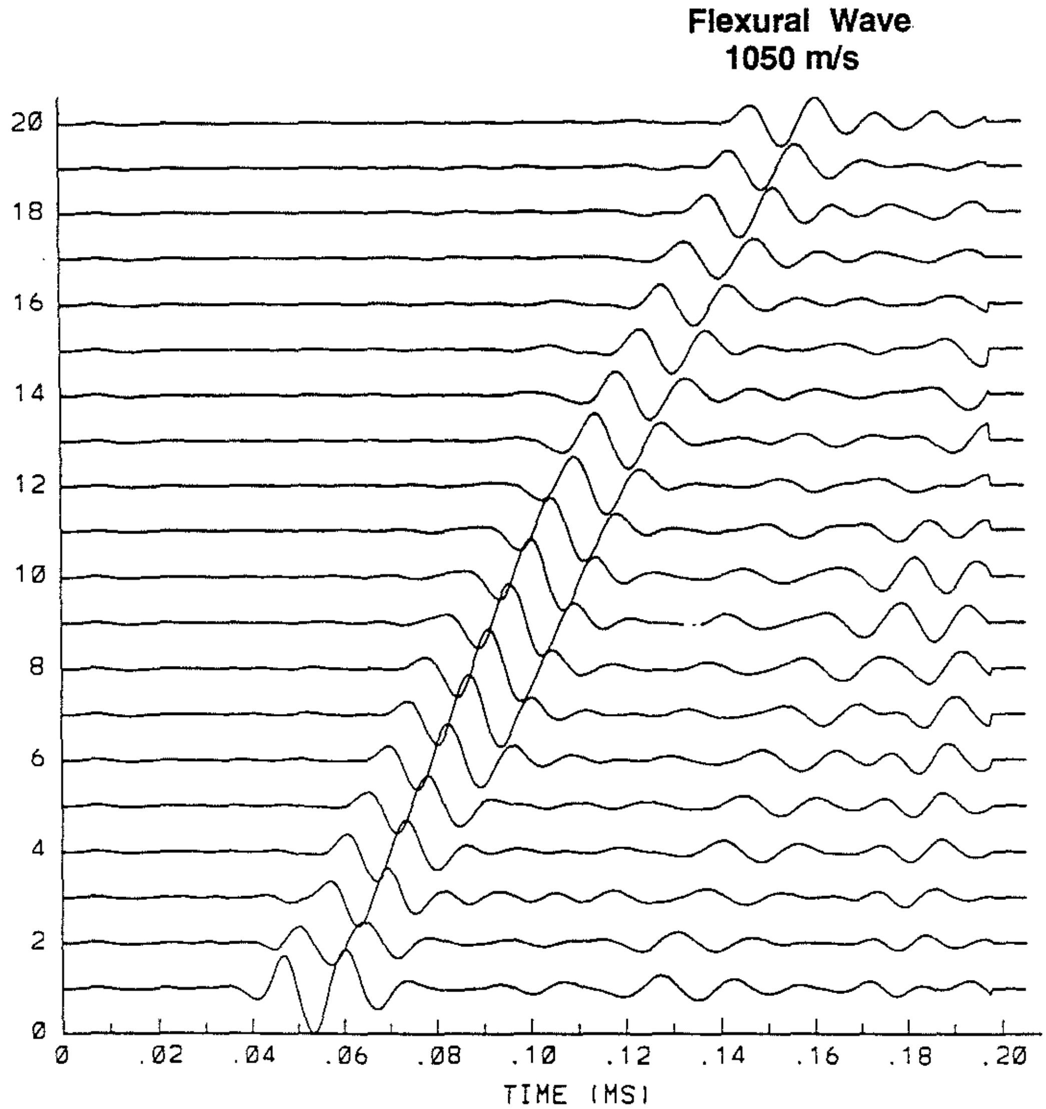


Figure 9: Waveforms measured with dipole transducers in the lucite model.

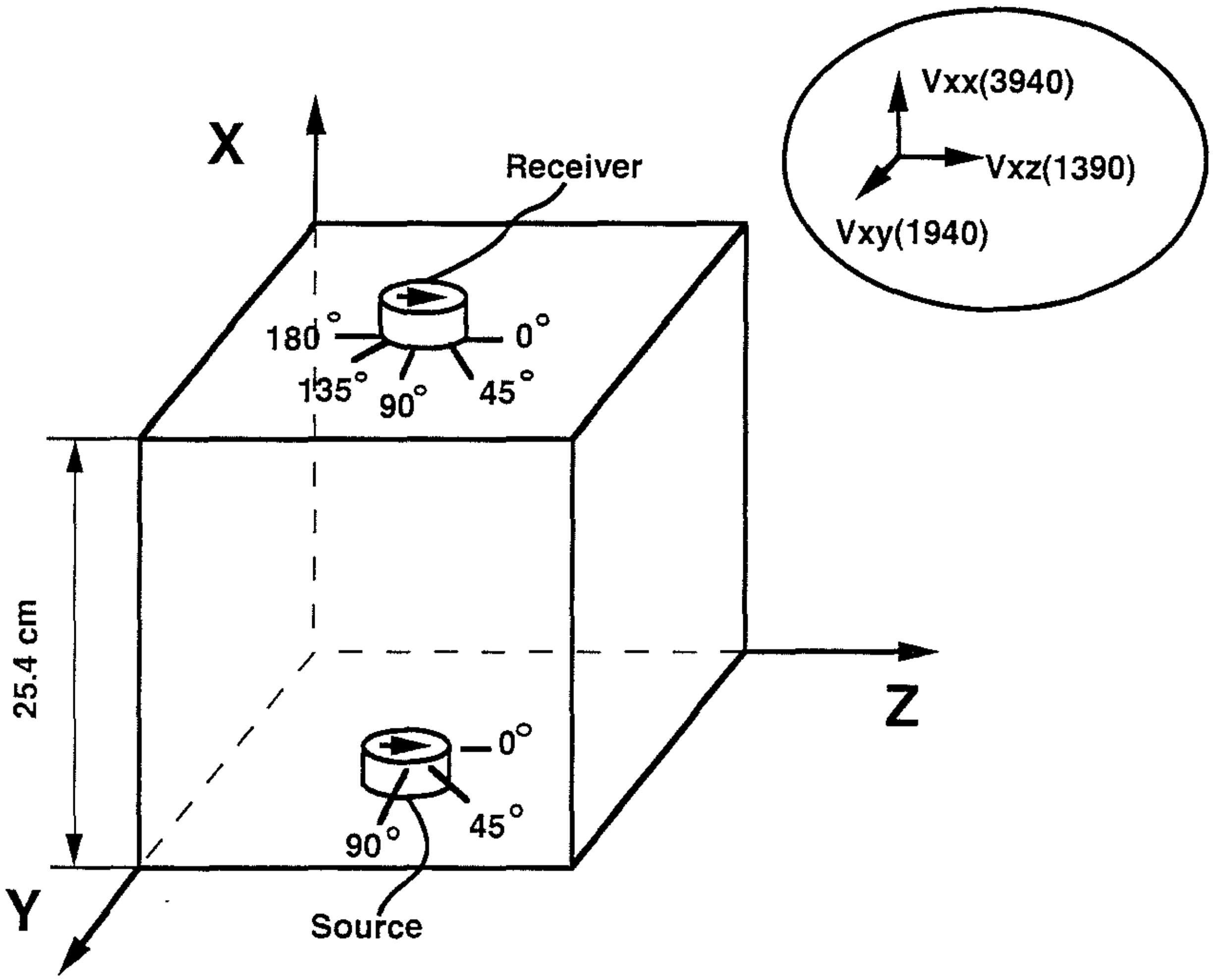
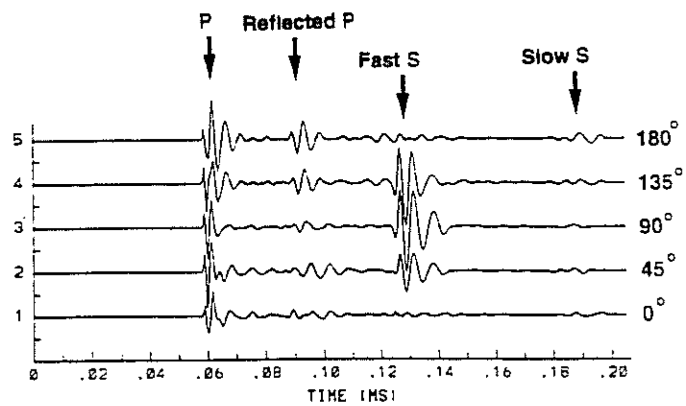
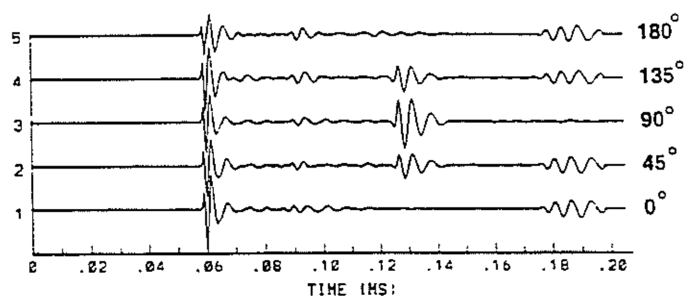


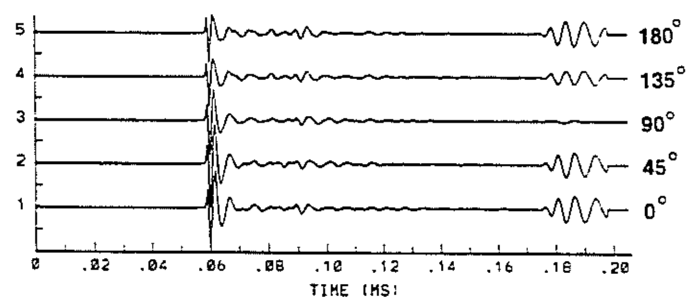
Figure 10: A sample of anisotropic material and the measurement method of shear waves.



(C). Source is at 90°



(B). Source is at 45°



(A). Source is at 0°

Figure 11: Waveforms measured with the standard contact S transducers in the sample.

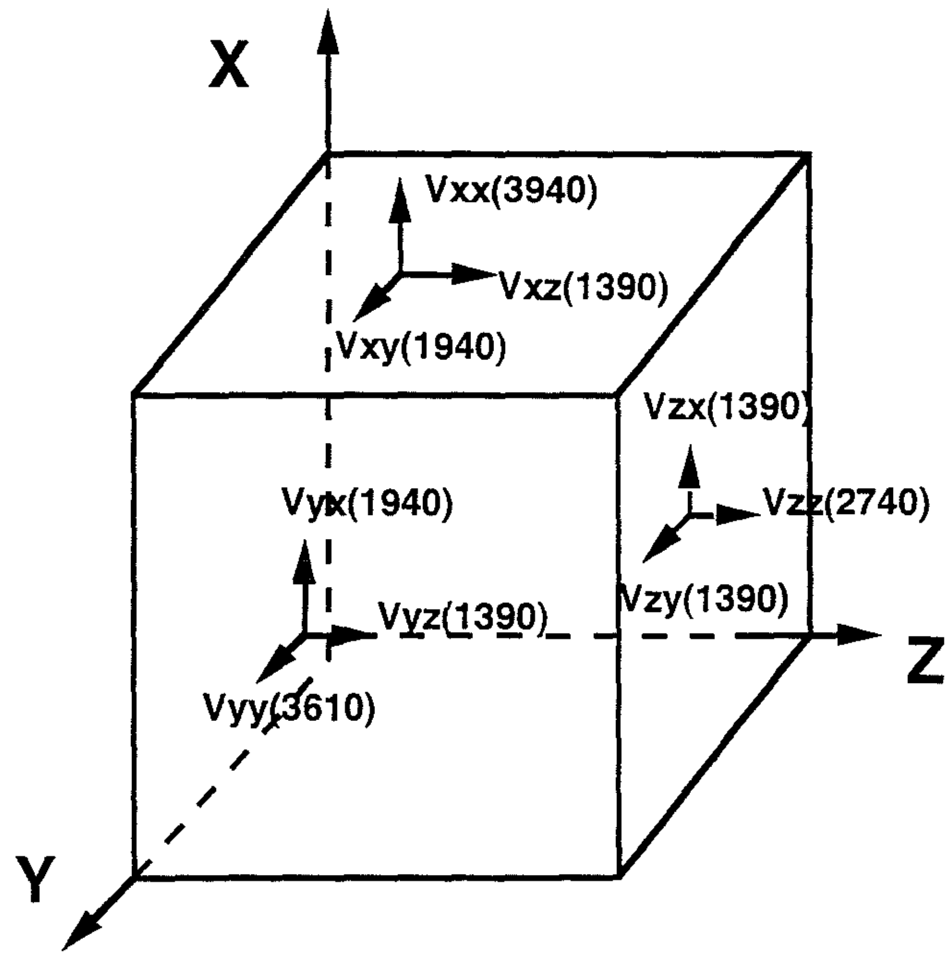


Figure 12: Velocities (in m/s) of Phenolite XX-324 along the three main axes.

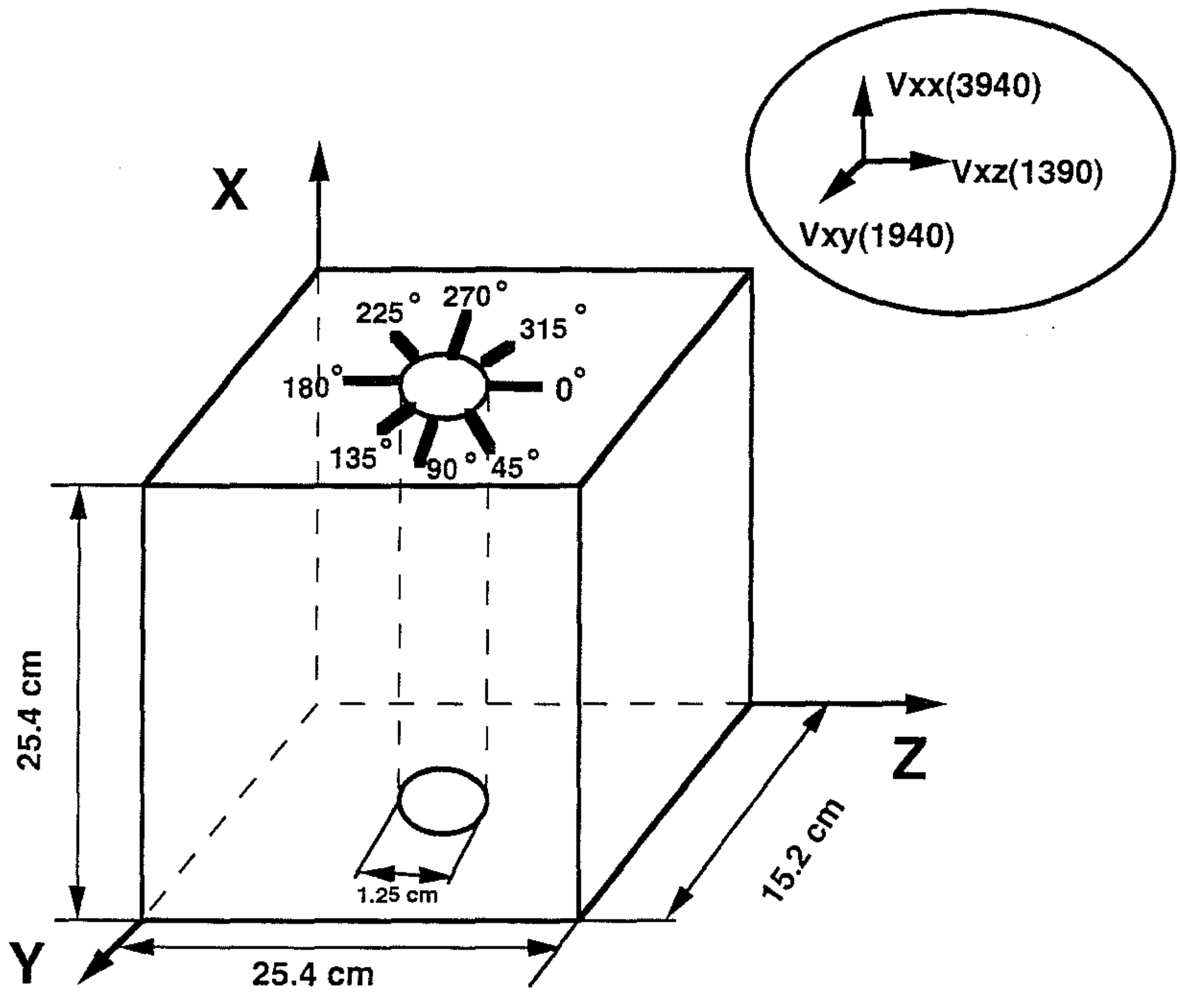


Figure 13: Borehole model of Phenolite XX-324 along the X axis.

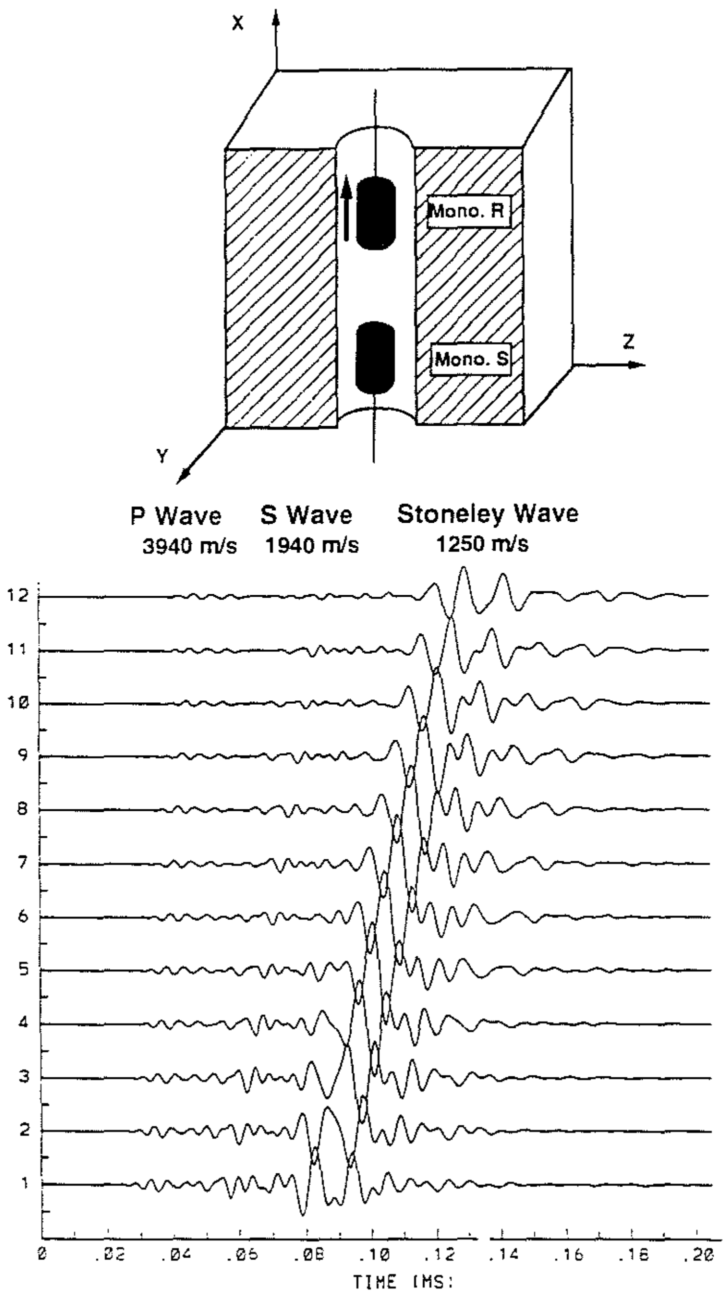


Figure 14: Waveforms measured with monopole transducers in the anisotropic model. The spacing increase is 0.5 cm/trace.

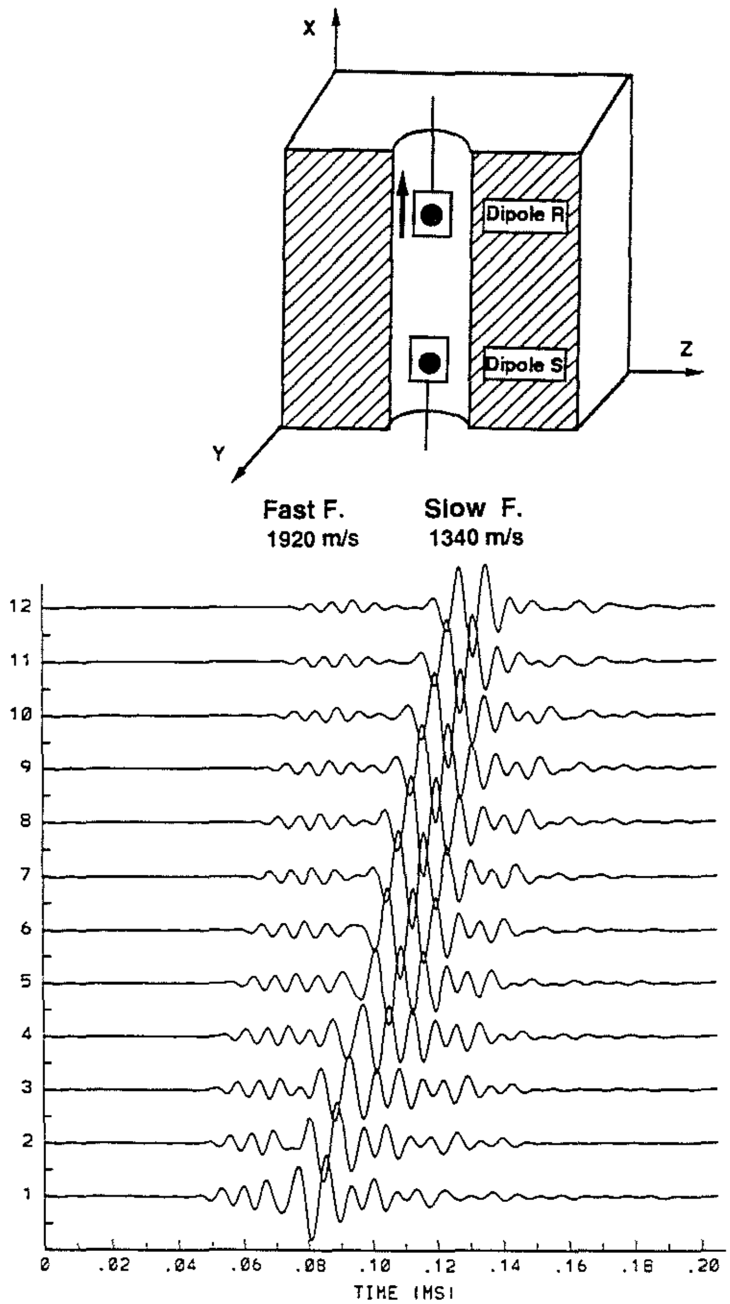


Figure 15: Waveforms measured with dipole transducers in the anisotropic model. The spacing increase is 0.5 cm/trace.

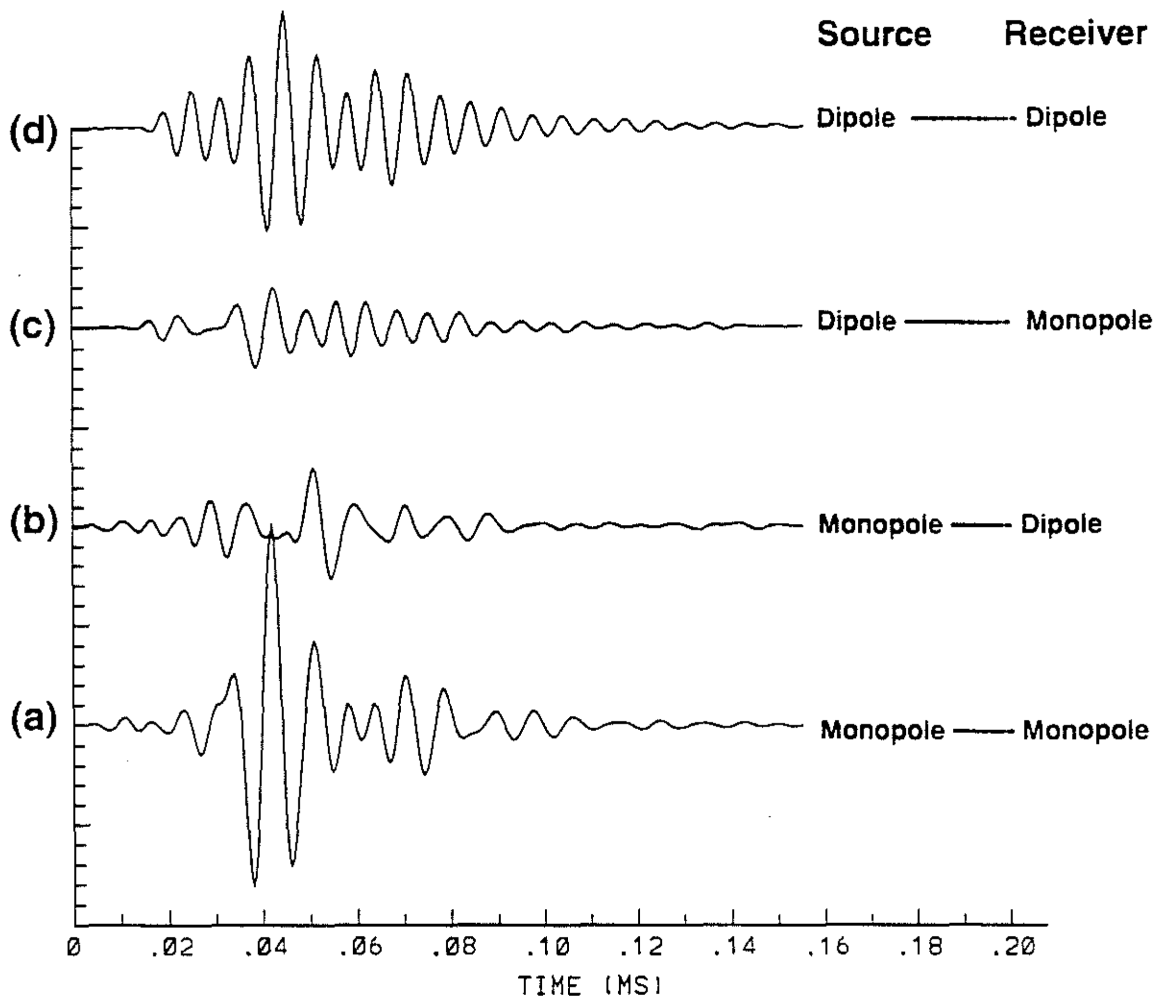


Figure 16: Comparison of waveforms measured with four acoustic systems: (a) monopole source and monopole receiver; (b) monopole source and dipole receiver; (c) dipole source and monopole receiver; and (d) dipole source and dipole receiver.

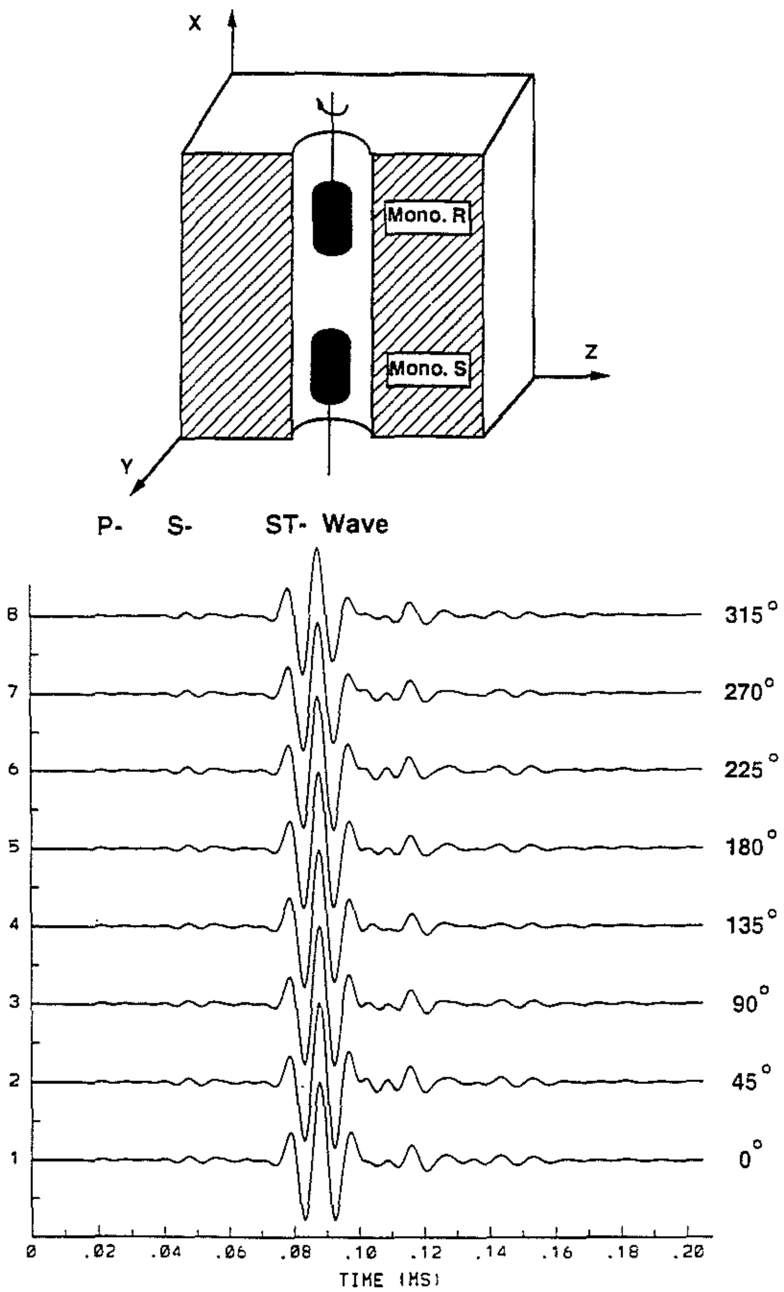


Figure 17: Waveforms measured by fixing the monopole source and rotating the monopole receiver in the anisotropic model.

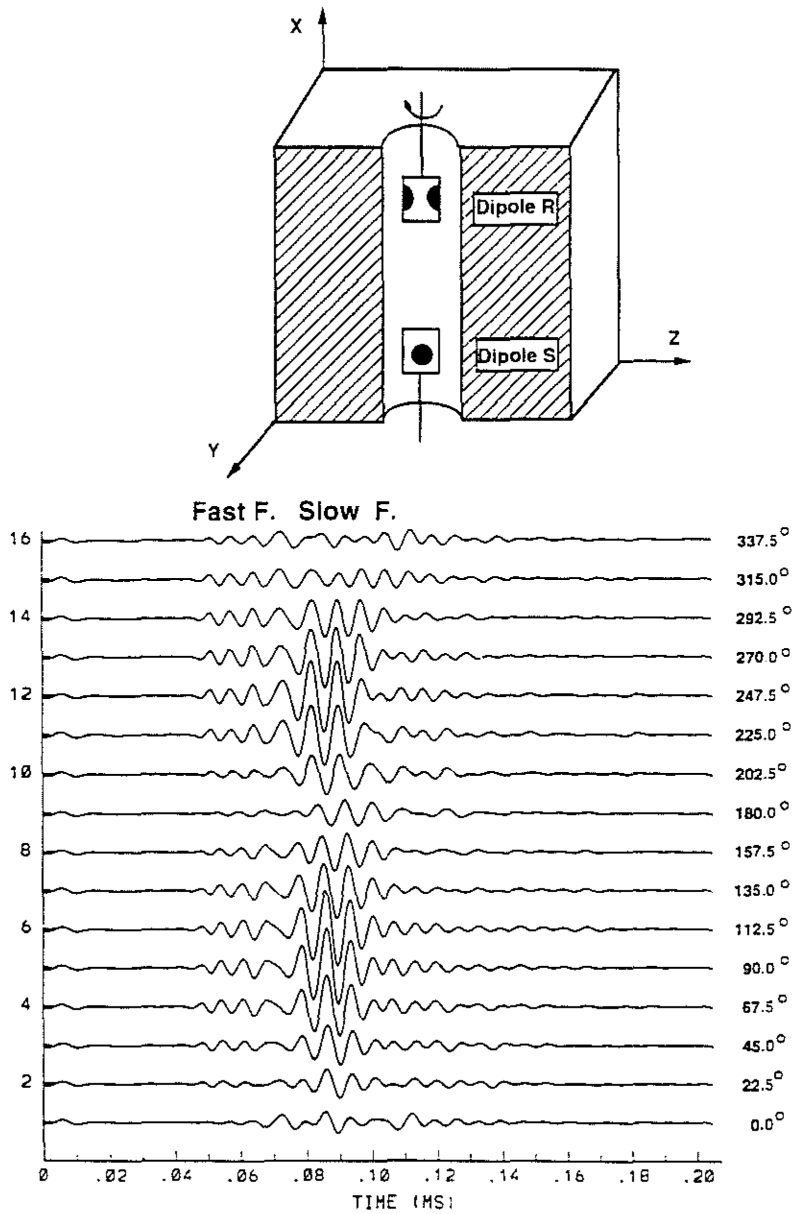


Figure 18: Waveforms measured by fixing the dipole source along the Y-axis and rotating the dipole receiver with 22.5°/trace in the anisotropic model.

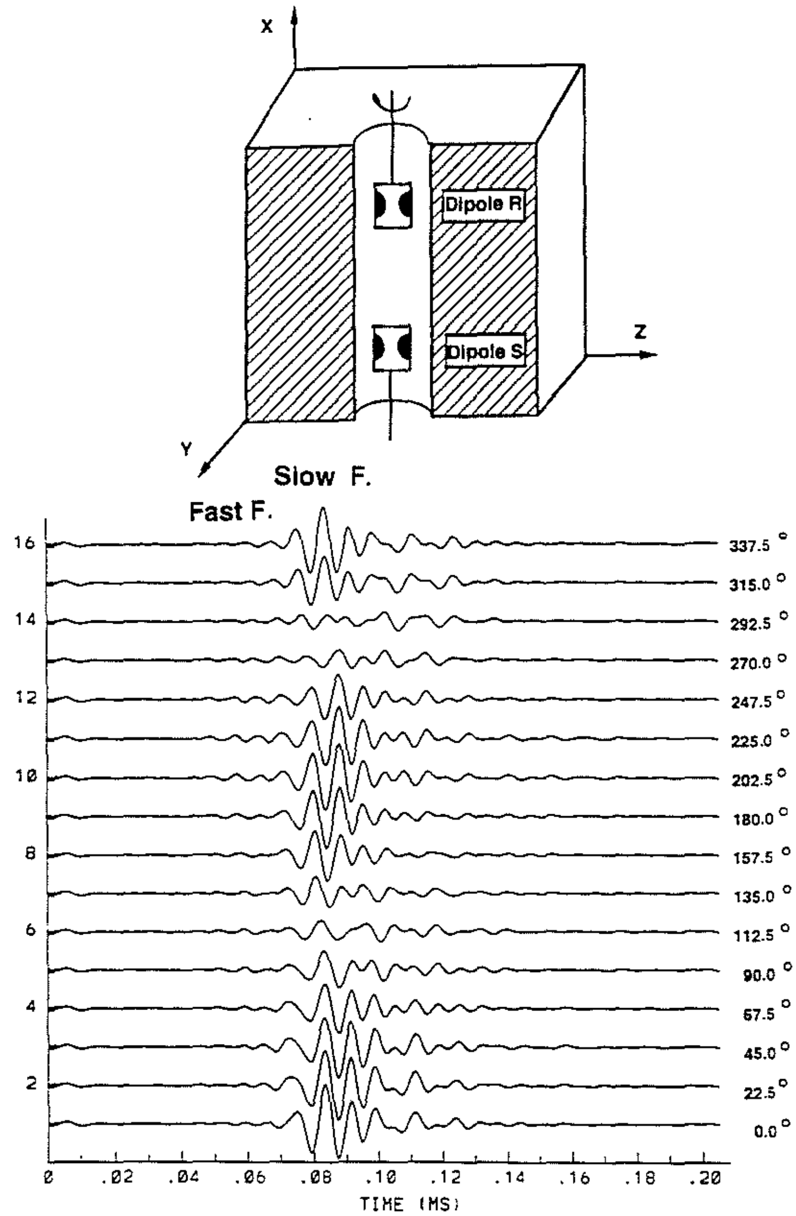


Figure 19: Waveforms measured by fixing the dipole source along the Z-axis and rotating the dipole receiver with 22.5°/trace in the anisotropic model.

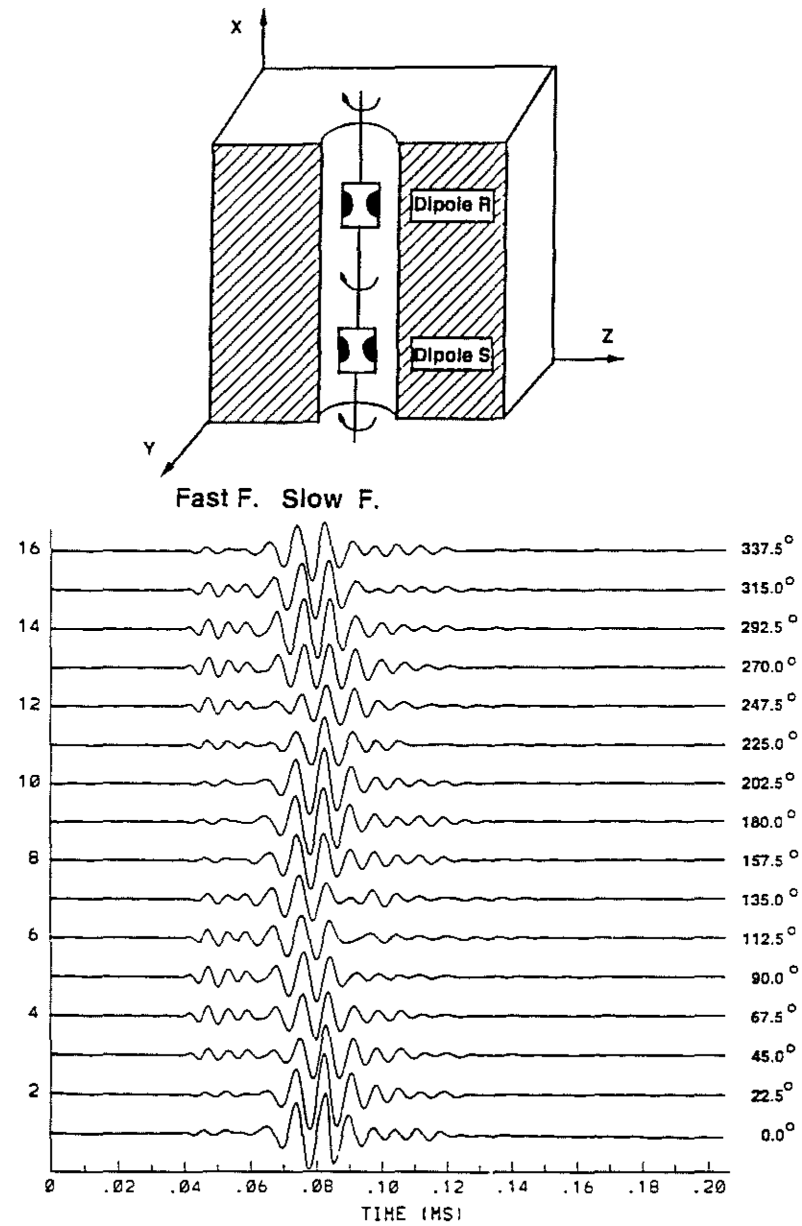


Figure 20: Waveforms measured by fixing the dipole source and receiver in the same polarization direction and rotating both of them with 22.5°/trace in the anisotropic model.

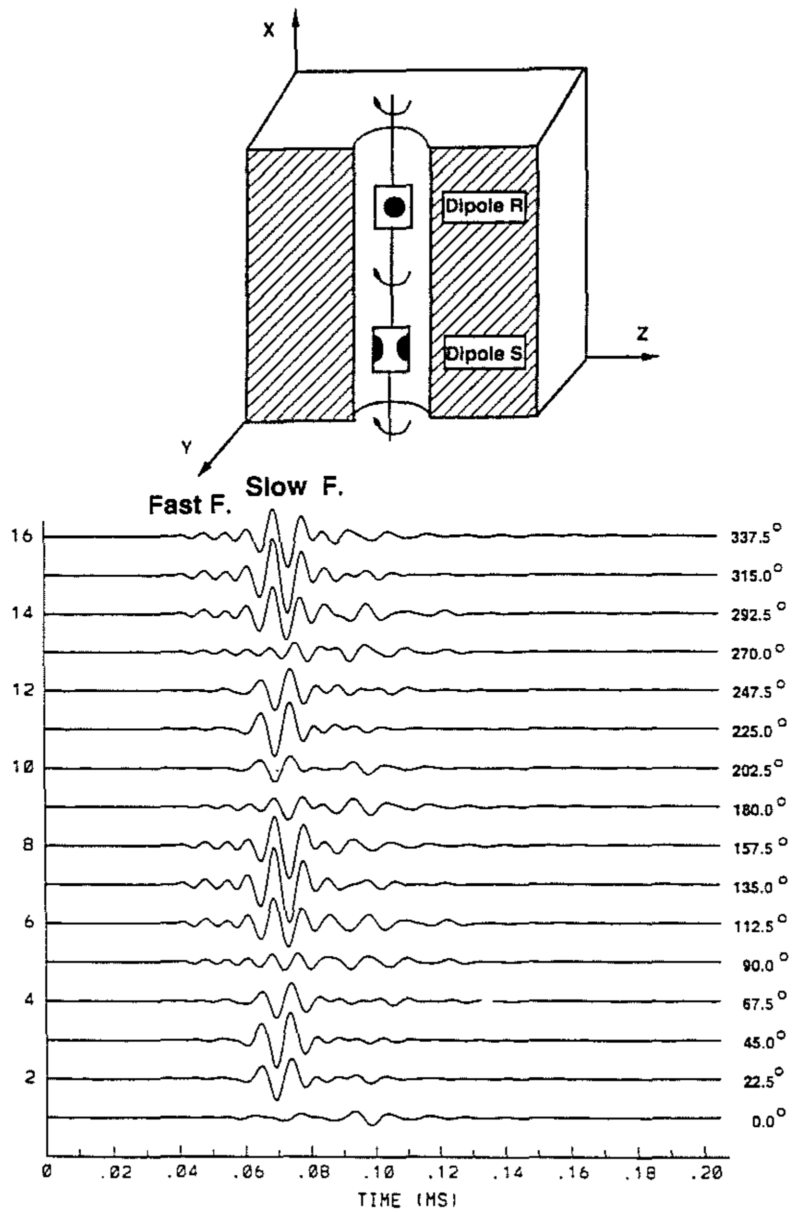


Figure 21: Waveforms measured by fixing polarization directions of the dipole source and receiver at right angles and rotating both of them with 22.5°/trace in the anisotropic model.