Experimental Studies of Multipole Acoustic Logging with Scaled Borehole Models

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Abstract

A scaled multipole acoustic tool was built for laboratory measurements at ultrasonic frequencies in borehole models. The source with four separate transducers can generate monopole, dipole, and quadrupole waves through different combinations of the transducers. Each receiver has two separate transducers and six receivers which records twelve acoustic components of the multipole waves propagating along a borehole.

The experimental results in the borehole models show the center frequency of the multipole waves responding in a soft formation is lower than in a hard formation. The monopole system can measure the $P-$wave and $S-$wave in hard formation, but no $S-$wave or slow shear wave in soft formation. In a dipole system, flexural and hexapole modes in both the soft and hard formation can be observed. These dispersive modes propagate at velocities that are slightly slower than the formation shear velocity. The quadrupole system records the screw waves in soft and hard formations, which also propagate slower than the formation shear velocities. In the soft anisotropic formation, no slow screw wave is recorded.

1 Introduction

Traditional full-wave acoustic well logging uses monopole acoustic source Tsang and Rader (1979); Cheng and Toksöz (1981). A monopole source generates P, S, pseudo-Rayleigh, and Stoneley waves in a hard formation borehole, but only the $P-$wave and Stoneley wave are generated in a soft formation borehole. A dipole logging tool was then developed to generate a flexural wave in both the hard and soft formation boreholes. The velocity of the flexural wave is very close to the formation shear wave velocity at low frequencies. More recently, a quadrupole logging system has been developed for a Logging-While-Drilling (LWD) tool Tang et al. (2002). The velocity of the screw wave generated by a quadrupole source is close to the shear wave velocity in a soft or hard formation borehole Rao et al. (1999); Huang (2003). The development of acoustic well logging systems shows that the source mode is the key to the different logging methods. In order to understand and compare acoustic modes generated by the multipole sources, we conduct laboratory experiments with a multipole source and a two-component receiver in different scaled borehole models.

We fabricated a scaled multipole acoustic tool for laboratory measurements at ultrasonic frequencies in a borehole model. The source with four separate transducers can generate monopole, dipole, and quadrupole waves by means of different combination of the transducers, respectively. Each receiver has two separate transducers. Six receivers can record twelve acoustic components of the multipole waves propagating along a borehole. A connector is used to connect the source and receiver sections to simulate a LWD tool. Four borehole models are made with different materials to simulate a soft, a hard, an isotropic, and an anisotropic borehole. The acoustic fields are first measured in a water tank to observe the tool waves generated by the multipole source and propagating along the tool(with the connector) between the source and receiver sections. Because of high amplitude tool wave, we then conduct experiments in the four borehole models to record the multipole waves and to compare the results when the tool is used without the connector.

2 Scaled Multipole Tool

We built a scaled multipole logging tool with PZT crystal disks working in the ultrasonic frequencies to investigate the propagation of a monopole, dipole, or quadrupole wave in a scaled borehole model. This tool can generate multipole acoustic waves by means of a switch to change the polarization of the electric source signals applied on each side of the source disks. Therefore, the experimental results can be compared without changing or moving a tool placed in a borehole.

In this section we introduce the structure of the scaled tool and its working modes. In the next sections we introduce the acoustic characteristic of the tool, and the measurements in the borehole models.

2.1 Structure of a scaled multipole tool

Figure 1 shows the structure and size of the scaled tool made of steel. The tool includes three parts of the source, receivers, and connector. PZT crystal disks, 0.635 cm in diameter and 0.37 cm in thickness, are used as the source and receiver. This tool is 17th scale version of a 6.75 inch tool. The center frequency at the free piston vibration mode is about 500 kHz.

The source is composed of four separate crystal disks shown in the B-B profile of Figure 1. The arrows on the disks indicate their piezoelectric polarization. All of their electrodes (eight electrodes of the four disks) are electronically separated. The vibration mode can be controlled by changing the electric polarization applied on each crystal disk to generate a monopole, dipole, or quadrupole wave in a borehole.

The receiver section is composed of six pairs of the receivers. Each pair has two transducers whose piezoelectric polarizations are shown in the A-A profile of Figure 1. Twelve independent electric signals can be recorded by the twelve transducers of the six receivers.

The connector (Figure 1) is made of steel with a hole in the center and threads on each end. When the source and receiver sections are tightly connected, it simulates a non-attenuated hard connection in a LWD tool. When the screws on the two ends are loosened or the connector is removed, the coupling between the source and receivers decreases and the energy propagating from the source to receiver along the tool decreases simulating a LWD tool with source isolators and/or damping. Several plastic centralizers are used to keep the tool centered in a borehole.

2.2 Working modes of the tool

Because the transducers of the source and receivers are electronically independent, we may generate four working systems of the monopole, dipole, cross-dipole and quadrupole by changing the polarization of the electric signals on the source and combining the components received by the receivers.

We assume that the phase of an acoustic wave is positive, if the piezoelectric polarization of the source transducer is consistent with the positive pulse of a single sine signal exciting the transducers, and vice versa. And we assume that the polarization of the received acoustic field is the same as the piezoelectric polarization of the receiver transducers. Figure 2 shows the five working modes: monopole, dipole, cross-dipole, quadrupole, and cross-quadrupole. The combination of the received acoustic components provides four logging systems: monopole, dipole, cross-dipole, and quadrupole loggings shown in Figure 2.

When the transducers are mounted on a steel tool with epoxy glue, their center frequency decreases from 500kHz to 300kHz. When the working frequency is lower than the center frequency, the sensitivity decreases and the frequency bandwidth increases. In the following measurements these logging systems can record acoustic signals from 15 kHz to 300 kHz. The main radiation is in the direction perpendicular to the surface of the piezoelectric disk or to the axis of the tool.

The advantage of this scaled tool is that it allows us to conduct multipole logging at a certain position without changing the transducers or moving the tool in a borehole. We may therefore compare the multipole logging results using identical conditions. During the measurements we only change the polarization of the electric signal applied to the source transducers through a rotary switch.

3 Ultrasonic Borehole Models

In order to investigate the multipole acoustic propagation in a borehole, four borehole models are made of natural rocks (sandstone and slate) or man-made materials (Lucite or Phenolite) to simulate a hard or soft, isotropic or anisotropic borehole formation. The diameter of the borehole is $1.7cm$. The P- and S- wave velocities and densities are shown in Table 1. The fast and slow shear velocities in Phenolite are higher and lower than that in water, respectively, so we call it a soft or intermediate (Wang and Tang, 2003) anisotropic formation. The anisotropy in slateis very strong. The strong anisotropy makes the results very clear in the splitting of the fast and slow shear velocities. Figure 3 shows the velocity distribution in three main directions in Phenolite (a) and slate (b).

In this paper, high frequency refers to frequencies higher than 100 kHz while low frequency means those that are lower than 100 kHz.

4 Tool Waves in Water

In order to understand the acoustic characteristics of the scaled multipole tool, we first conduct measurements using the tool without (Figure 4a) or with (Figure 4b) the connector in a water tank.

Figure 5 shows the received waveforms when the source and receiver are separated and the system works as a monopole (Figure 5a), dipole (Figure 5b), and quadrupole (Figure 5c), respectively. The waves received after 0.2 ms are the reflection from the boundary of the tank. The amplitudes are normalized by the same number (40410) as those of the waveforms (Figure 6) received in the case shown in Figure 4b. This number is the maximum of the amplitudes in the dipole mode shown in Figure 6. Because the main radiation of the multipole acoustic source is in the horizontal direction, only a very weak acoustic arrivals with high frequency can be received in the case without the connector(Figure 4a).

In the monopole and quadrupole cases (Figure 5a and 5c), the source generates a water wave in the tank, which has a weak component in the vertical direction. In the monopole case a weak arrival at velocity of 2670 m/s is recorded before the wave propagating at the water velocity. This is an arrival that propagates as a tool mode in the source and receiver sections and as a water wave between the two. This arrival is observed in the monopole case and weakly in the quadrupole case. In the dipole mode (Figure 5b), the arrivals are weaker than those in the monopole and quadrupole cases.

When the source and receiver section are tightly connected (Figure 4b), relatively larger amplitude arrivals are recorded. Figure 6 shows the recorded monopole (a), dipole (b), and quadrupole (c) waves in the water tank and their semblance. The signal applied to the source is a single sine wave cycle with a center frequency of 50 kHz. The acoustic waves recorded after $0.20ms$ (Figure 6) are the reflection from the boundary of the tank.

The center frequency and velocity of the monopole tool wave are 20 kHz and about 3100 m/s (Figure 6a), respectively. The frequency of the tool wave with quadrupole excitation is higher, at about 30 kHz. The frequency of the dipole tool wave is less than 18 kHz and the velocity is about 980 m/s.

In the above experiments, the different sources generate tool modes that have different frequency responses and velocities in water. When the exciting frequency increases to 150 kHz, the tool modes amplitudes become very weak. In the following experiments we do not use the connector in order to avoid the strong tool waves.

5 Measurements in Isotropic Borehole Models

We perform the multipole measurements in the water-saturated Lucite and sandstone borehole models using the tool without the connector to simulate the measurements in a soft or hard formation borehole. The center frequency of the source signal is 50 kHz. The waveforms are recorded by monopole, dipole, and quadrupole systems, respectively.

We already understand some results of the multipole wireline logging in a borehole through theoretical simulation (Tsang and Rader, 1979; Cheng and Toksöz, 1981; Kurkjian and Chang, 1986b; Sinha et al., 1994), laboratory experiments (Chen, 1988, 1989), and field measurements. P-wave, S-wave, Stoneley wave, flexural wave, and screw wave can be generated by monopole, dipole, and quadrupole sources, respectively.

Figures 7 and 9 show the multipole waveforms and their semblance in time domain in Lucite and sandstone borehole models using the tool without the connector, respectively. The horizontal lines in the semblance plots indicate the velocities of formation P and S-wave speeds and water velocity.

5.1 In a Lucite borehole

The time series and time semblance is shown in Figure 7 and dispersion analysis is presented in Figure 8. In the Lucite borehole with monopole source, a P arrival, a tool arrival and a weak stoneley arrival are present (figure 7a). Shear is not recorded in this soft formation model. The stoneley arrival is clearer in the dispersion analaysis in Figure 8. Here the P arrival is above 160 kHz and the tool mode is seen around 50-100 kHz.

The dipole system (Figure 7b) records a P and arrivals whose phase speed is lower than the shear velocity. The dispersion analysis in Figure 8 exemplifies that the dominant arrival, from 0.1 to 0.3 ms, is composed of flexural and hexapole (n=3) components. The frequency response of the dipole system is narrower than the monopole and quadrupole systems. Therefore, the received dipole waveforms are more ringy than the others.

The quadrupole system (Figure 7c and Figure 8) records a clear screw wave whose velocity is below the lucite shear, around 50 kHz. Additionally a weak P above 200 kHz and the monopole tool mode, between 50-100 kHz are also observed.

5.2 In a sandstone borehole

The time series and time semblance is shown in Figure 9 and dispersion analysis is presented in Figure 10.

The sandstone formation model data(Figure 9), has more high frequency content compared to the Lucite data. With a monopole system, P and S arrivals can be discerned in the time semblance (Figure 9a). Based on Figure 10, the arrival with phase speed close to the shear velocity is composed of two components, a screw mode at around 75 kHz and a pseudo-rayleigh mode at around 200 kHz. The compression arrival is recorded at high frequencies (greater than 200 kHz) with the feature near the P velocity and at 150 kHz corresponding to arrivals that are very weak, (about 30 dB below peak amplitude) but coherent. This feature is due weak compressional arrivals reverberating between the the finite boundaries of the the tool in the borehole. Stoneley waves are not observed due to the high working frequency.

The quadrupole system has arrivals near the shear velocity which include the screw mode at 75 kHz and the pseudo-rayleigh at 150 kHz. Further, around 50 kHz there is some energy propagating slightly faster than the shear (2900 m/s at 50 kHz), corresponding to the monopole tool mode. Compressional arrival is not observed.

The dipole system records waves slower than the shear velocity which correspond to dipole and hexapole modes (Figure 10). A very weak P is recorded at frequencies above 200 kHz.

Many features of these results are comparable to previous theoretical and experimental results Chen (1988, 1989); Kurkjian and Chang (1986a); Rao et al. (1999).

6 Measurements in Anisotropic Borehole Models

In order to investigate the multipole acoustic fields in an anisotropic borehole, we fabricated two borehole models, one a synthetic material of Phenolite XX-324 and the other a natural block of slate.

6.1 In a Phenolite borehole

Figure 11 shows the monopole (a), dipole (b), and quadrupole (c) waveforms and their semblance in time domain, measured in the Phenolite XX-324 borehole model at 50 kHz using the tool without the connector.

The monopole system records a P-wave (3940 m/s) and a fast shear wave (1940 m/s), but no slow shear wave due to its velocity (1390 m/s) which is slower than the water velocity (1480 m/s). The dipole system records the fast flexural wave and the strong slow flexural wave. When the polarization of the dipole source is at the same vibration direction of the fast or slow shear waves, the amplitude of the fast or slow flexural wave increases. The observed velocity of the fast flexural wave is the almost the same as the fast shear wave (1940 m/s), but the slow one (1370 m/s) is slightly lower than the slow shear wave (1390 m/s). The quadrupole system records the P-wave and the fast screw wave, but no slow screw wave. The velocity (1940 m/s) of the fast screw wave is the same as the fast shear wave. The P-wave is recorded at a high frequency range and its amplitude is weak.

The experimental results show that only the dipole system can generate a slow flexural wave whose velocity is very close to the slow shear wave in a soft anisotropic borehole. Both the monopole and quadrupole systems cannot generate a slow shear wave or slow screw wave in soft formation.

6.2 In slate borehole

The time series and time semblance is presented in Figure 12 and the dispersion ananlysis of the data is in Figure 13.

The monopole system detects arrivals propagating close to the fast and slow shear waves. Their velocities of these arrivals are below 4150 m/s and 2650 m/s, respectively. A very weak P is recorded at high frequencies, evident only in the dispersion analysis results in Figure 13.

The dipole oriented in the fast and slow directions records the corresponding fast shear and and slow flexural waves. Further, when oriented in the slow shear direction, a weak fast flexural wave is also detected. The velocity of the fast flexural wave is nearly equal, but slower, than the fast shear wave (4150 m/s), while the slow flexural one (2150 m/s) is slower than the slow shear wave (2650 m/s).

The quadrupole system records the fast and slow screw waves whose velocities are close to the fast and slow shear wave. In figure 13, the components arriving faster than the shear at 50 kHz are weak tool monopole mode arrivals, similar to that observed in the monopole case.

The above measurements with the separate source and receiver sections in anisotropic borehole models show the similar results to those from wireline measurements (Kurkjian and Chang, 1986b; Zhu et al., 1993; Esmersoy et al., 1994; Sinha et al., 1994; Tang et al., 2002). In a hard anisotropic borehole, the three different measurement systems generate the corresponding fast and slow arrivals which propagate close to the fast and slow shear waves.

7 Conclusions

In order to simulate a LWD tool, a scaled multipole logging tool was built to conduct ultrasonic experiments in the isotropic or anisotropic borehole models. The tool can generate a monopole, dipole, or quadrupole wave in a borehole without changing the tool or its position. Therefore the experiment's results can be compared very well between the different working modes.

Multipole measurements are performed in the four borehole models: hard or soft, isotropic or anisotropic models. The monopole source generates $P-$wave and $S-$waves in a hard formation borehole, but no shear waves can be generated in a soft borehole. The dipole system measures the dipole and hexapole modes in both the soft and hard formation. Their velocities are slightly slower than the formation shear waves due to their frequency dispersion. The quadrupole system records the screw waves and monpole waves in soft and hard formations. The screw wave velocities are slower than the formation shear velocities, but in the soft anisotropic formation, no slow screw wave is recorded. These results help us to compare the characteristics of the multipole logging in the different formation boreholes.

8 Acknowledgments

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References

Chen, S. T. (1988). Shear wave logging with dipole source. *Geophysics*, 53:659–667.

Chen, S. T. (1989). Shear wave logging with quadrupole source. *Geophysics*, 54:590–597.

Cheng, C. H. and Toksöz, M. N. (1981). Elastic wave propagation in a fluid-filled borehole and synthetic acoustic logs. *Geophysics*, 46:1042–1053.

Esmersoy, C., Koster, K., M.Williams, Boyd, A., and Kane, M. (1994). Dipole shear anisotropy logging. *SEG 64th Ann. Internat. Mtg., Expanded Abstracts*, pages 1139–1142.

Huang, X. (2003). Effects of tool position on borehole acoustic measurements: a stretched grid finite difference approach. *Ph. D Thesis, Massachusetts Institute of Technology.*

Kurkjian, A. L. and Chang, S. (1986a). Acoustic multipole sources in fluid-filled borehole. *Geophysics*, 51:148–163.

Kurkjian, A. L. and Chang, S. K. (1986b). Acoustic multipole sources in fluid-filled boreholes. *Geophysics*, 51:148–163.

Rao, V. N. R., Burns, D., and Toksöz, M. N. (1999). Models in lwd applications. *ERL Industry Consortia Annual Report, MIT, Cambridge, MA.*

Sinha, B. K., Norris, A. N., and Chang, S. K. (1994). Borehole flexural modes in anisotropic formation. *Geophysics*, 59:1037–1052.

Tang, X. M., Wang, T., and Patterson, D. (2002). Multipole acoustic logging-while-drilling. *SEG 72th Ann. Internat. Mtg., Expanded Abstracts.*

Tsang, L. and Rader, D. (1979). Numerical evaluation of the transient acoustic waveform due to a point source in a fluid-filled borehole. *Geophysics*, 44:1706–1720.

Wang, T. and Tang, X. M. (2003). Lwd quadrupole shear measurement in anisotropic formation. *SEG 73th Ann. Internat. Mtg., Expanded Abstracts.*

Zhu, Z., Cheng, C. H., and Toksöz, M. N. (1993). Propagation of flexural waves in an azimuthally anisotropic borehole model. *SEG 63rd International Meeting Expanded Abstracts*, pages 68–71.

	water	Lucite	sandstone	Phenolite(XX-324)	slate	steel
V_p (m/s)	1480	2700	4660	3940	6950	5800
V_{s1} (m/s)	/	1290	2640	1940	4150	3100
V_{s2} (m/s)	/	/	/	1390	2650	/
ρ (g/cm^3)	1.00	1.18	2.20	1.34	3.20	7.9

Table 1: Parameters of the materials used in the experiments.

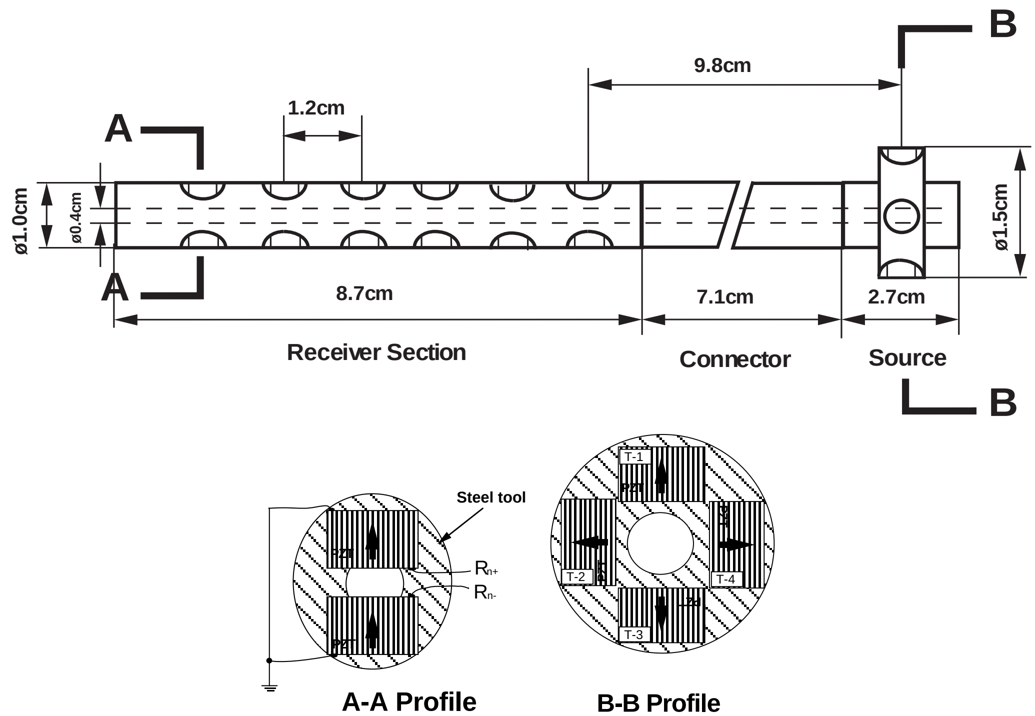

Figure 1: Schematic diagram of a scaled multipole logging tool with a source and six receiver pairs. The single transducer is a PZT cylinder crystal with 0.64 cm in diameter and 0.37 cm in thickness. The arrows indicate the polarization of the piezoelectric crystal.

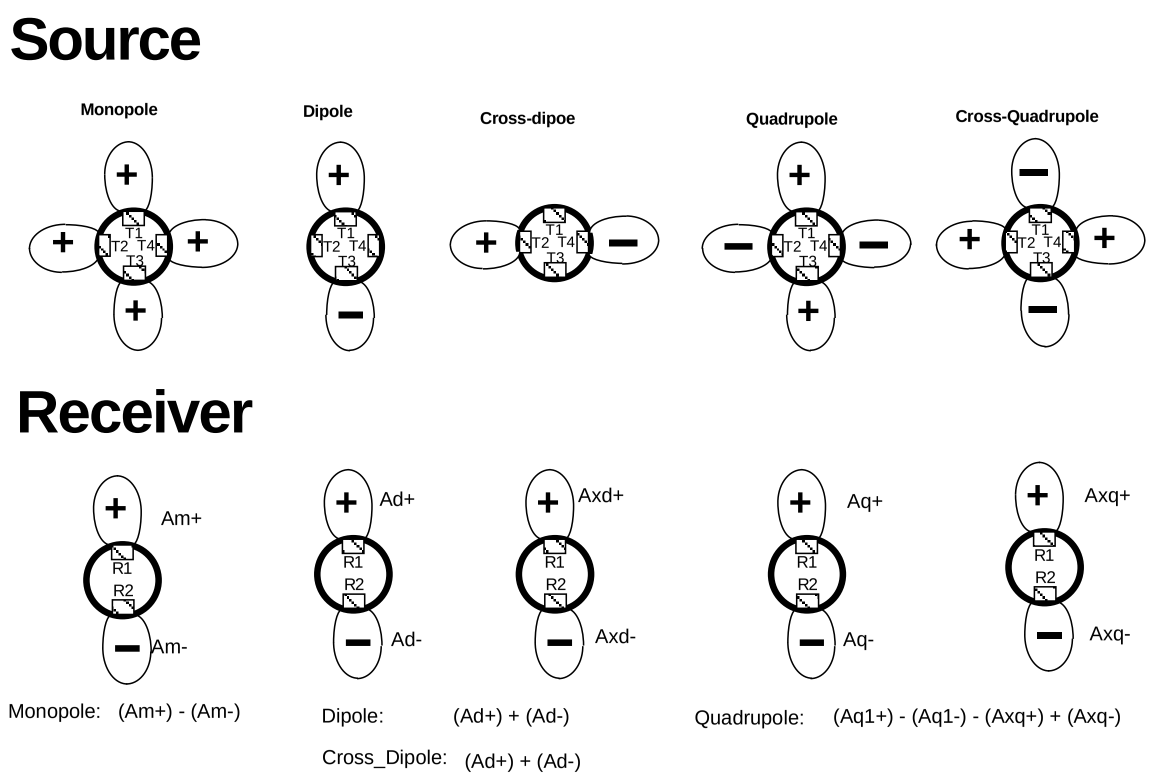

Figure 2: Schematic of the working modes and data processing for the multipole logging. The "+" and "-" indicate the polarization of the electric source signals in source case and the polarization of the piezoelectric crystals in receiver case.

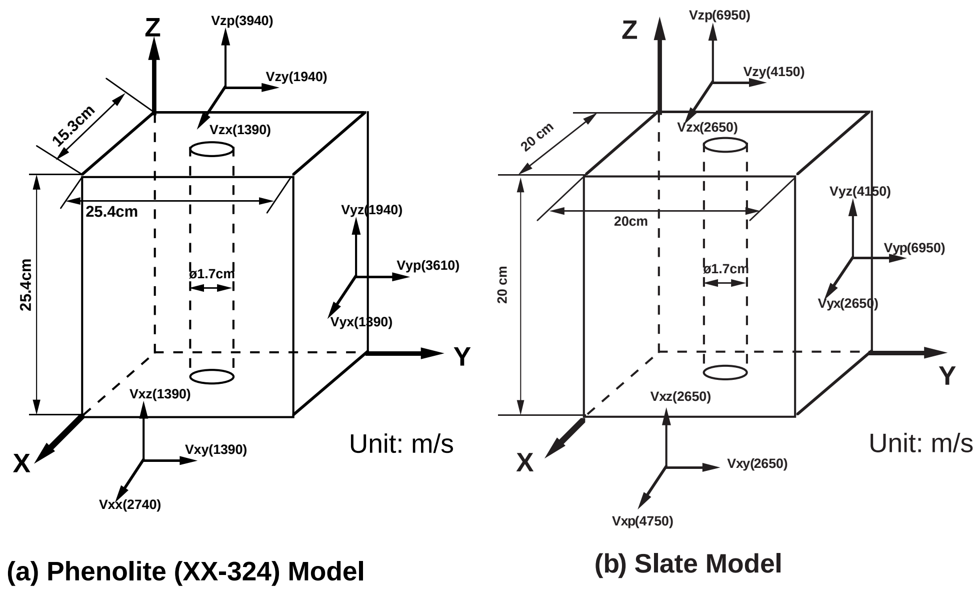

Figure 3: Distribution of the velocities in Phenolite XX-324 (a) and slate (b). Both are transverse isotropic in X direction and anisotropic in Z direction. The slow shear velocity in Phenolite is slower than water (1480m/s).

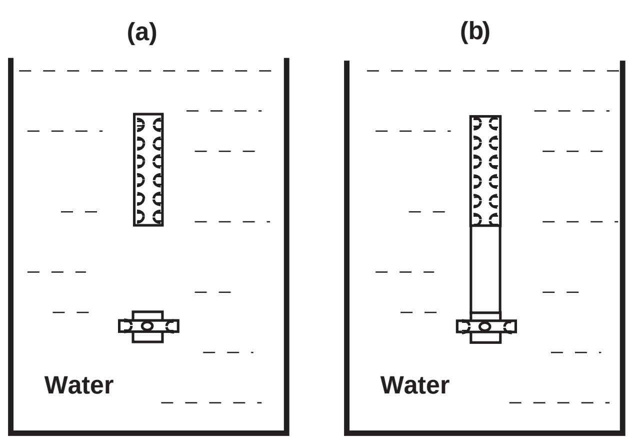

Figure 4: Schematic diagram of the measurements in a water tank without (a) or with (b) the connector.

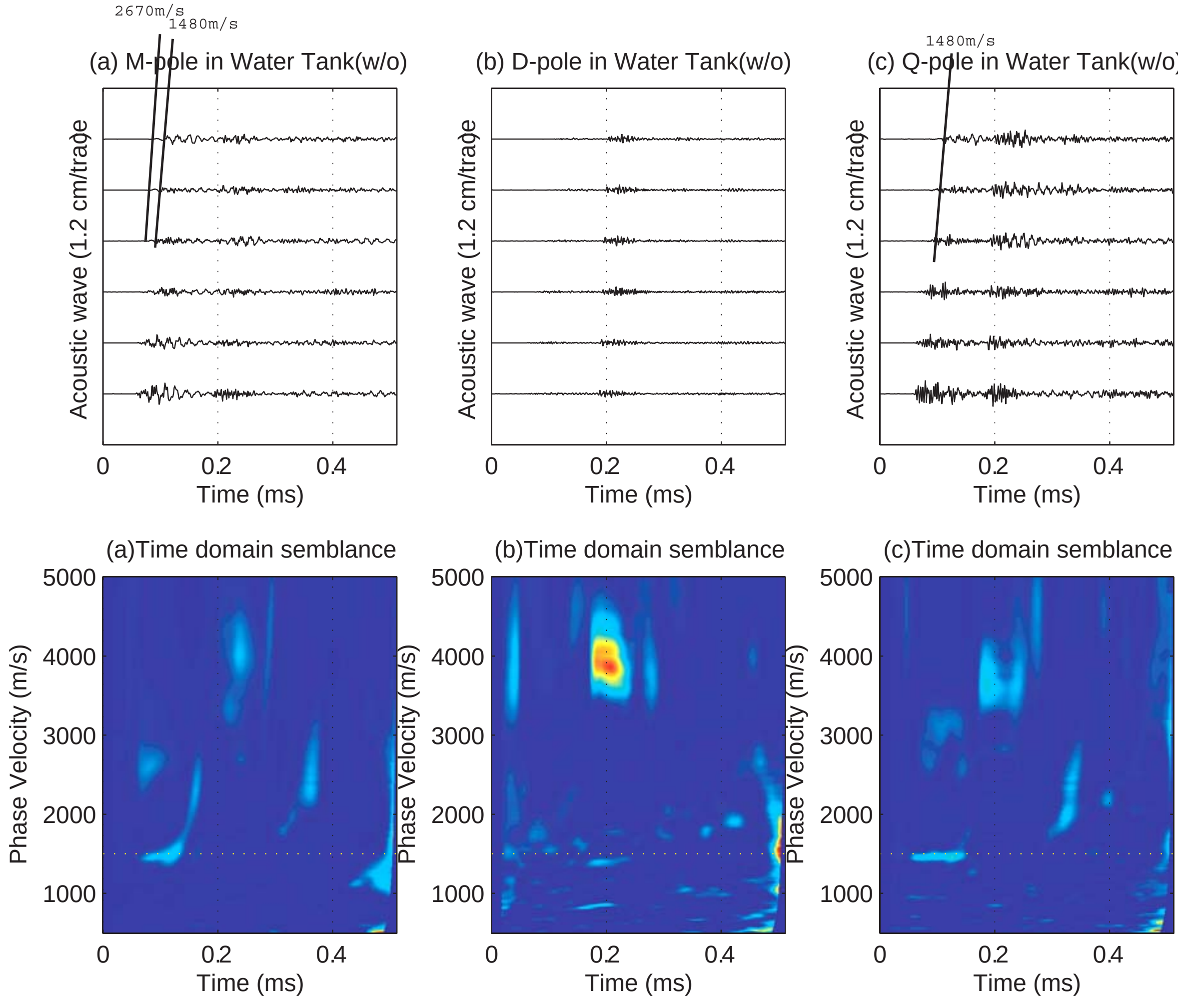

Figure 5: Water tank, source and receiver sections separate: Acoustic waveforms when the separate multipole source and receivers work in a water tank at monopole (a), dipole (b), and quadrupole (c) modes The received high-frequency signals after 0.20 ms are the reflection from the boundary of the water tank. The source is excited by a single sine burst with 50 kHz in center frequency. The amplitudes of the waveforms are normalized by 40410, the maxium amplitude of the waveforms recorded in the case of Figure 4b and shown in Figure 6.

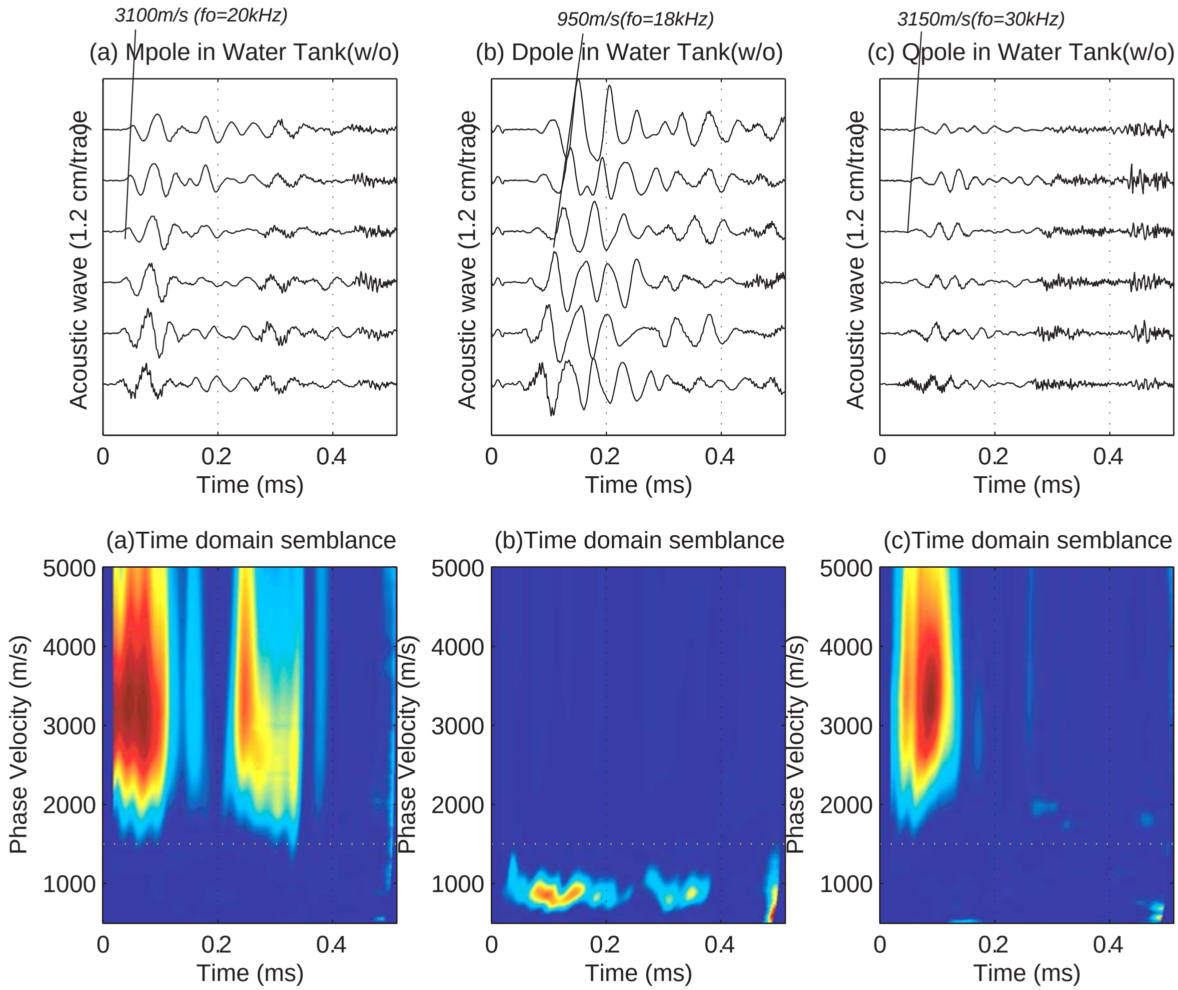

Figure 6: Water tank, source and receiver connected: Acoustic waveforms and their semblance plots when the multipole tool works in a water tank at monopole (a), dipole (b), and quadrupole (c) modes with a tungsten-filled connector tightly connecting the source and receiver sections. The high-frequency signals after 0.28 ms are the reflection from the boundary of the water tank. The source is excited by a single sine burst with 50 kHz in center frequency. The amplitudes of the waveforms are normalized by the same number (40410) in Figure 5, the maximum amplitude recored in the dipole mode.

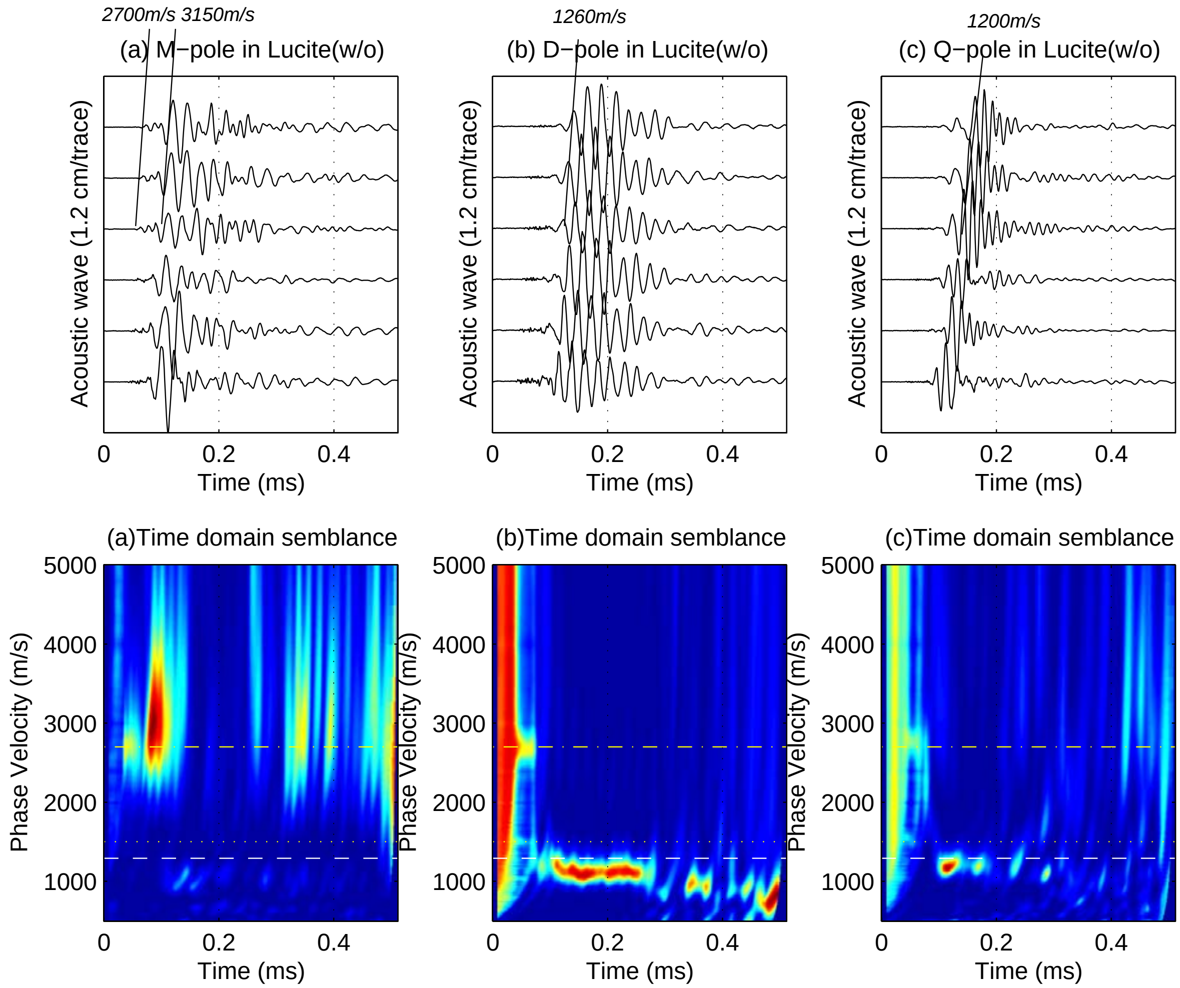

Figure 7: Lucite borehole, source and receiver sections separated: Acoustic waveforms and their semblance plots in time domain when the multipole tool works in the Lucite borehole at monopole (a), dipole (b), and quadrupole (c) modes. The center frequency of the electric signal exciting the source is 50kHz. The dash line indicates the P-wave and S-wave velocities in Lucite, and P wave velocity in water. A plastic centralizer is used to maintain the tool in the center of the borehole.

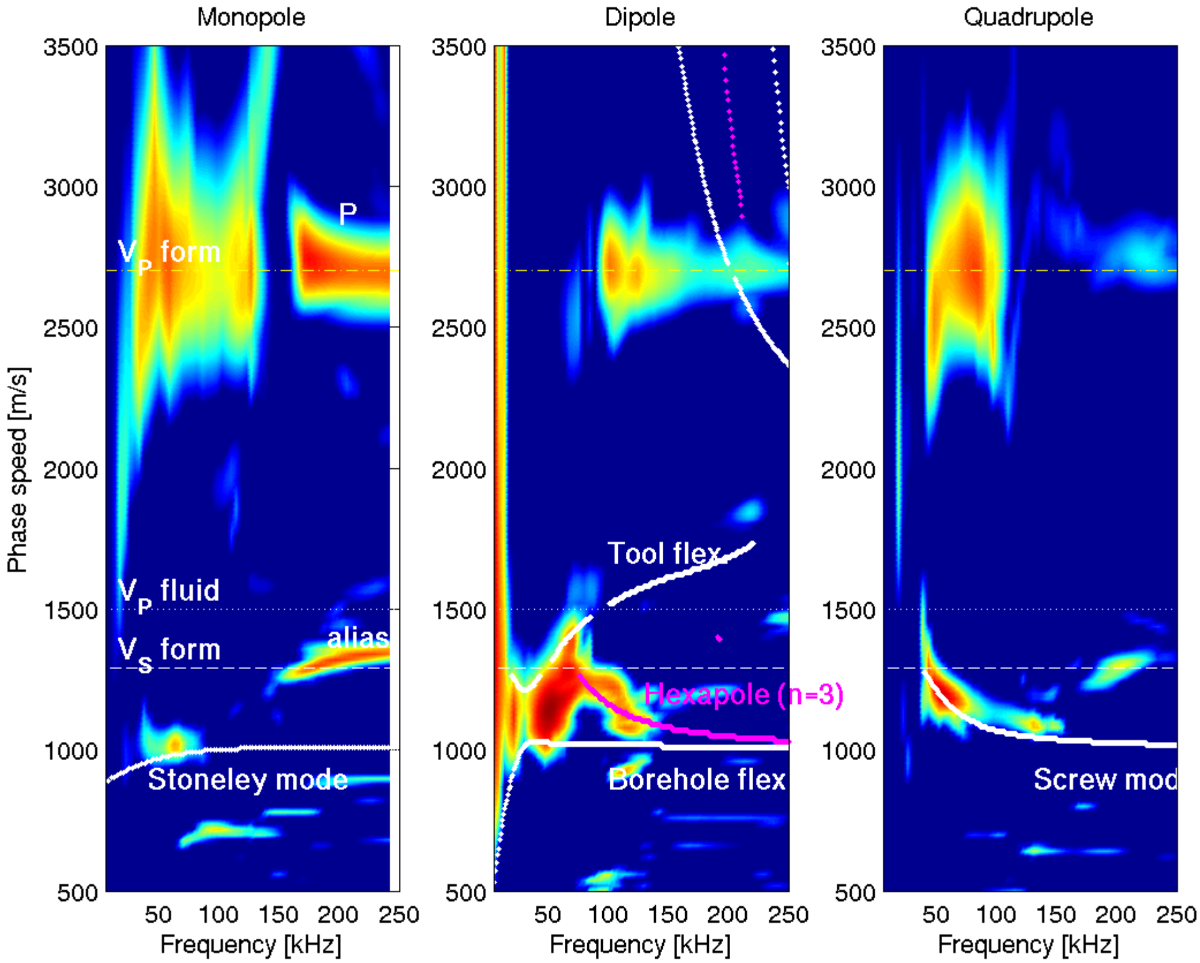

Figure 8: Lucite borehole, source and receiver sections separated: Dispersion analysis results

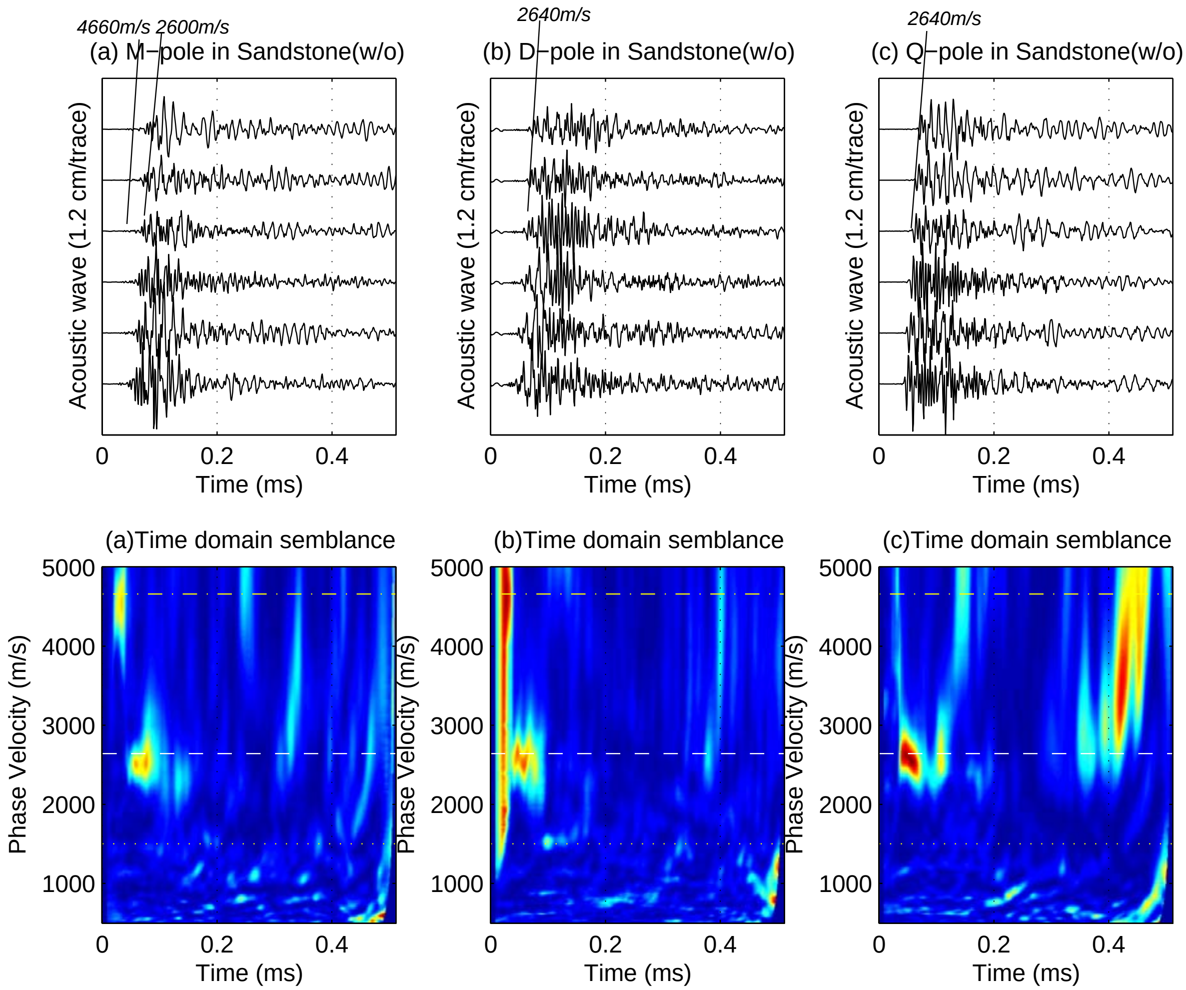

Figure 9: Sandstone borehole, source and receiver sections separated: Acoustic waveforms and their semblance plots in time domain when the multipole tool works in the sandstone borehole model at monopole (a), dipole (b), and quadrupole (c) modes without the connector. The center frequency of the source electric signal is 50kHz.

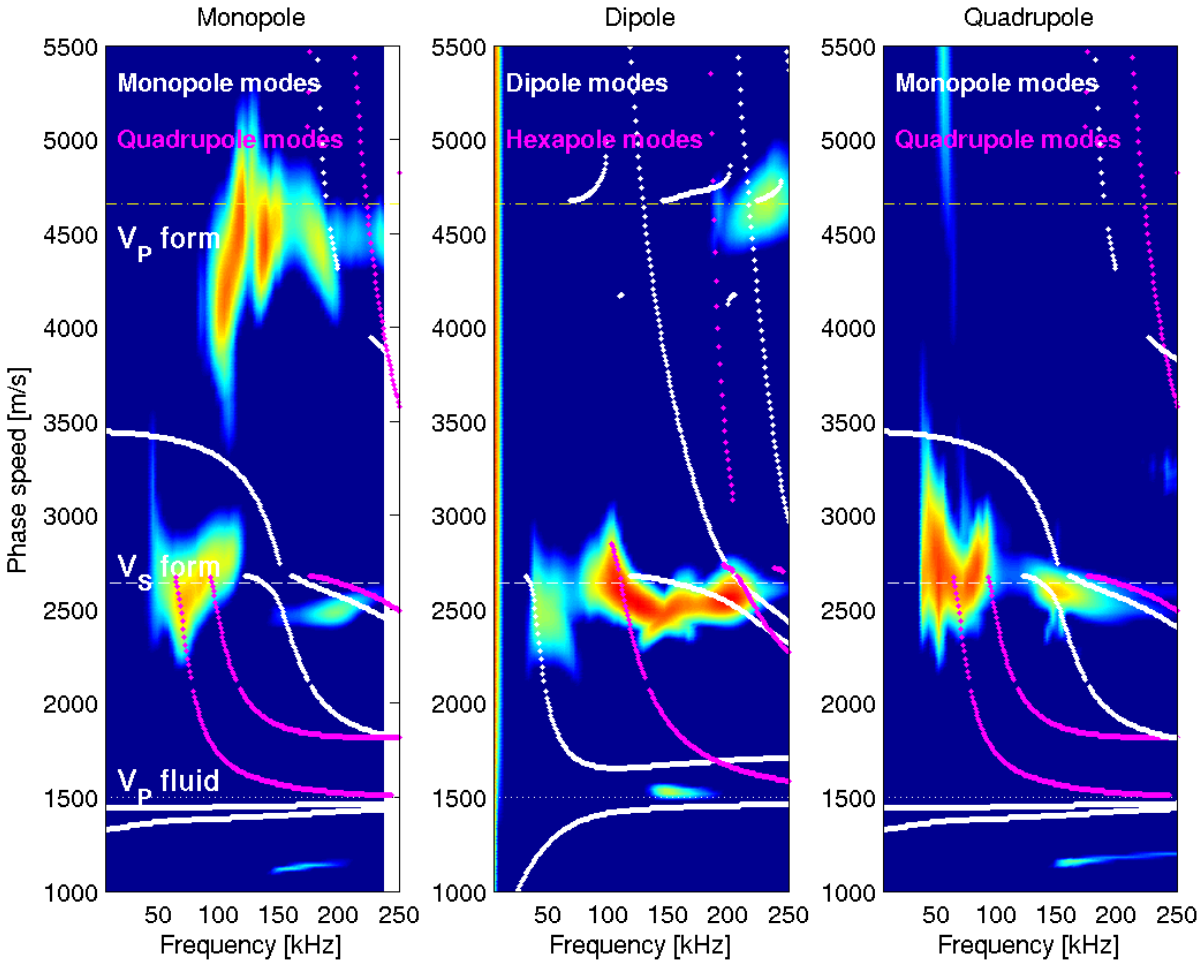

Figure 10: Sandstone borehole, source and receiver sections separated: Dispersion analysis results

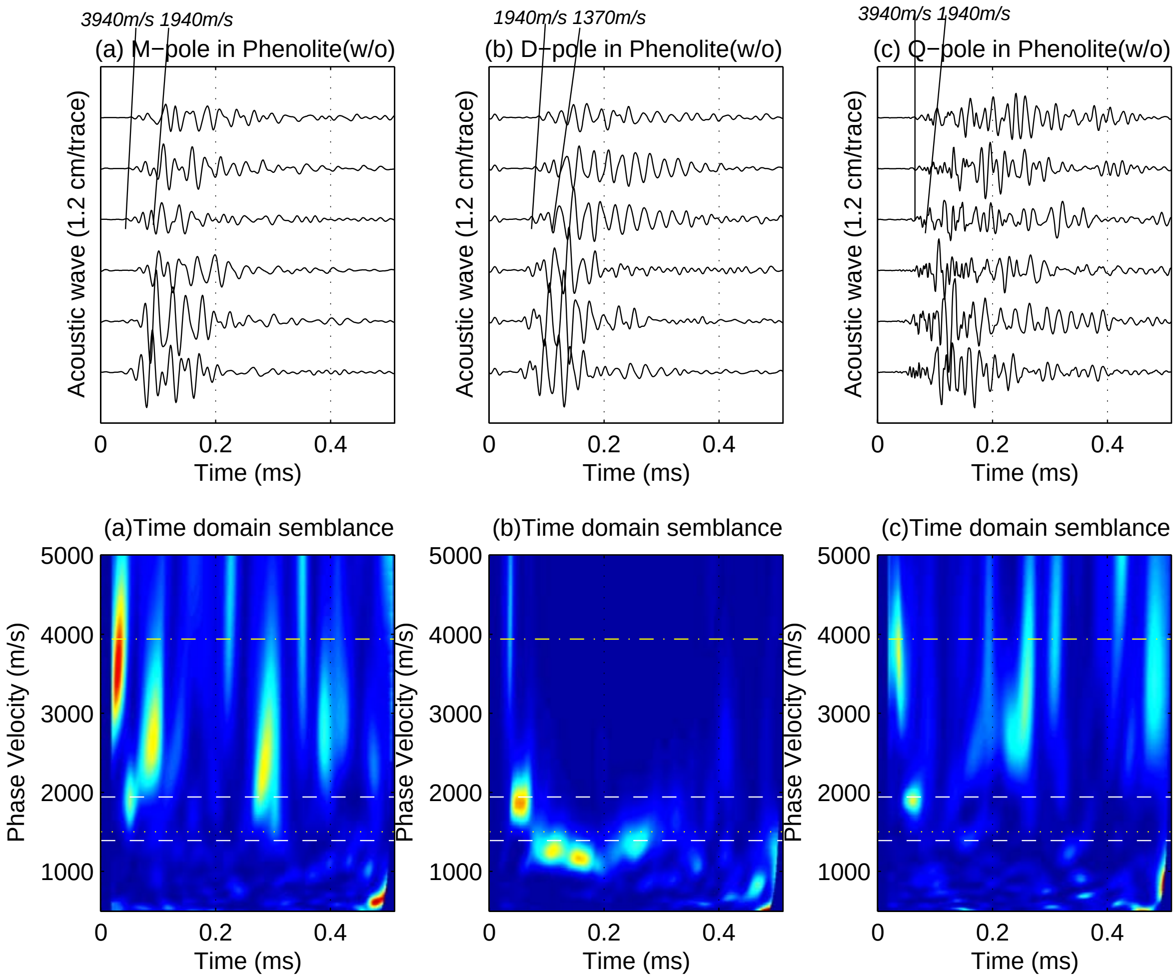

Figure 11: Phenolite borehole, source and receiver sections separated: Acoustic waveforms and their semblance plots in time domain when the multipole tool works in the Phenolite borehole at monopole (a), dipole (b), and quadrupole (c) modes. The center frequency of the source electric signal is 50kHz.

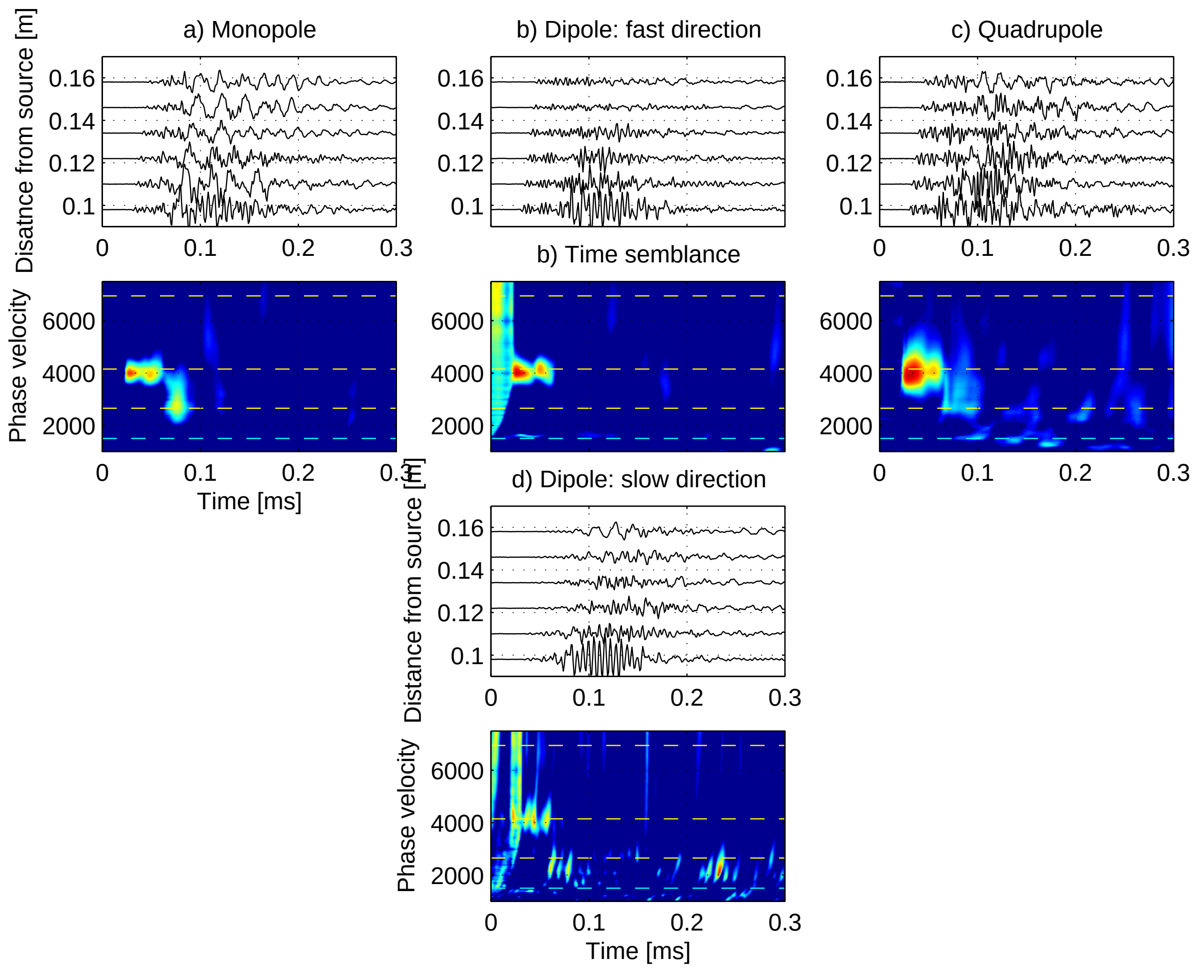

Figure 12: Slate borehole, source and receiver sections separated: Acoustic waveforms and their semblance plots in time domain when the multipole tool works in the slate borehole at monopole (a), dipole (b), and quadrupole (c) modes. The center frequency of the source electric signal is 50kHz.

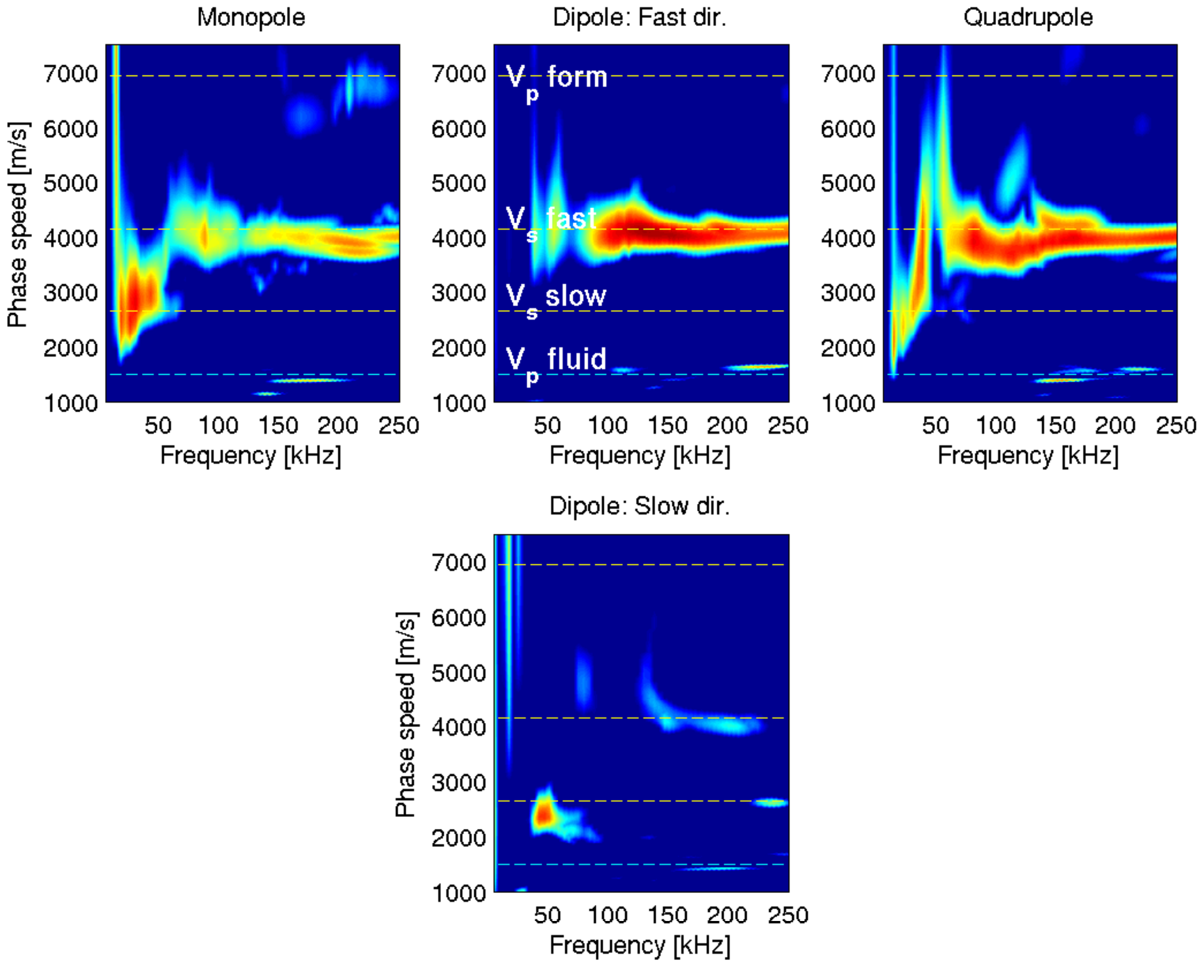

Figure 13: Slate borehole, source and receiver sections separated: Dispersion analysis results