# Stress-induced velocity anisotropy of unconsolidated sand under realistic reservoir stress conditions

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**Summary**

Ultrasonic velocity measurements were made on dry and oil saturated samples/cores of unconsolidated sands to investigate the stress-induced velocity anisotropy under realistic reservoir stress conditions. Instrumentation was arranged to simultaneously measure five velocities (axial P, axial S, radial P, radial S polarized radially, and radial S polarized axially) and the axial and radial deformation of the samples in a single run.

Within the experimental uncertainties, the measurements show:

(1) Stress-induced velocity anisotropy in unconsolidated sands could be a major contributor to the azimuthal shear wave anisotropy observed in sonic logs from some of the West Africa wells;
(2) Stress-induced velocity anisotropy is stress-path dependent;
(3) P-wave stress-induced anisotropy is stronger than S-wave stress-induced anisotropy;
(4) Vp/Vs ratio could increase or decrease with increasing stress;
(5) For dry samples, P-wave velocity is related to the stress component in the direction of wave propagation, whereas S-wave velocity is related to the average of the stress components in the directions of wave propagation and particle motion.

However, large uncertainties still exist in the exact amount of stress-induced velocity anisotropy. More measurement data are needed for better reservoir characterization where stress regimes are non-hydrostatic.

**Introduction**

Xu (2002) developed an anisotropic rock physics model calibrated to the low stress experimental data of dry sand (Yin, 1992) to explain high Vp/Vs ratios of unconsolidated sands in some wells. The anisotropy was attributed to the shaly minerals and low aspect ratio microcracks in the reservoir rock formations. With this anisotropic rock physics model, Gratwick and Finn (2004) showed that significant improvement on the far-offset seismic-well ties was achieved for several wells.

However, recent research on shear log quality (Huang, 2005) indicates that Vs data are systematically low in some wells due to poor processing of shear log data. Consequently, Vp/Vs ratios were artificially inflated in these under-processed shear log wells. The issues raised were that

(1) The anisotropic rock physics model calibrated to the low stress (a few MPa) data of Yin (1992) may need to be re-calibrated to more realistic reservoir stress conditions;
(2) Since seismic data cannot determine the absolute amount of anisotropy attributed to sand and shale, it is not clear whether the anisotropic rock physics model correctly accounts for the amount of anisotropy in the sand.

Experimental measurements were needed to quantify the exact amount of stress-induced velocity anisotropy of unconsolidated sands under realistic reservoir stress conditions.

**Method: Measurement Details**

Figure 1 shows the schematic of the measurement setup for the ultrasonic experiment. The instrumentation allows 5 velocities to be measured at each pressure step – axial P, axial S, radial P, radial S polarized radially, and radial S polarized axially. Simultaneous to these measurements, the axial and radial deformation of the samples were actively recorded. The samples were loaded along two different types of loading paths: (1) hydrostatic loading (vertical stress $\sigma_v$ = horizontal stress $\sigma_h$; maximum stress = 50MPa) and (2) K0 or uniaxial-strain loading (vertical stress $\sigma_v$ > horizontal stress $\sigma_h$ with zero radial strain). The stress conditions were estimated from a deepwater reservoir.

The two types of samples used were a sand pack and unconsolidated sand from a deepwater reservoir. The sand pack consists of quartz grains (>90%), dark minerals (mica, amphibole, magnetite, etc.), and lithic fragments collected from a beach. The mean grain size is ~500 microns. The initial porosity of the sand pack is about 40%. The sample from the deepwater reservoir came from a massive Ta bed with average sand grain size of ~600 microns with very little silt (0.2%) and no clay. Core analysis shows porosity for core plugs from similar depths to be about 24-25%. The average dimensions of the samples are approximately 3.75cm in diameter and 7.5cm in length.

## Stress-induced velocity anisotropy

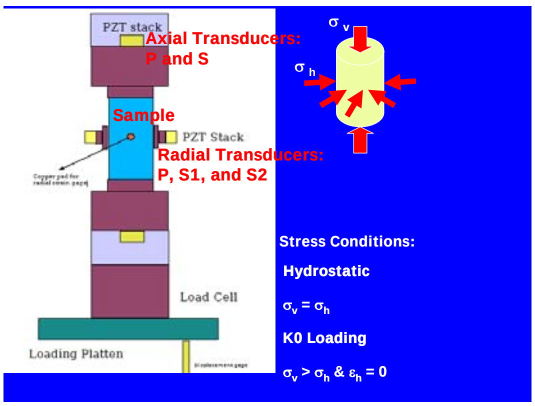


Figure 1. Schematic of the measurement setup for the ultrasonic experiment.

Figure 2 shows some of the better quality waveforms from the sand pack sample loaded hydrostatically to 40MPa (magenta) and 50MPa (black). In general, axial P and S waveforms are of higher quality and allow for better determination of the first arrival times. The radial waveforms have lower frequencies. Determination of the first arrival times are problematic, especially for the radial shear that were contaminated by precursors of the P-waves. However, cross-correlation of the waveforms of the two radial S-modes yields a relatively robust determination of the S-wave stress-induced velocity anisotropy (within ~0.5%). Stress-induced velocity anisotropy from the comparison between the axial velocity and radial velocity (both P and S) has larger uncertainties (2-3%).

### Experimental Results

(1) Intrinsic anisotropy under hydrostatic loading condition.

Both the dry sand pack and the deepwater reservoir sand hydrostatically cycled to 50MPa exhibit “apparent intrinsic anisotropy”. For the dry sand pack, the two radial shear velocities differ by about 2%. The axial P and radial P velocities differ by about 8% at high confining pressures. Results from the deepwater reservoir sand sample show an even larger intrinsic anisotropy (14% for P-wave and 8% for S-wave at 10MPa) that decreases with increasing pressure. One explanation is that the radial transducers contacted the sample via circular surfaces and the plane wave assumption is not valid. Finite difference modeling of the experimental geometry shows that this source of error could account for up to 3.5% higher radial P-wave velocity and smaller for S-wave velocity. It cannot explain the strong pressure dependence observed in the deepwater reservoir sand sample. For the stress-induced velocity anisotropy discussion, we will reference the K0 loading (uniaxial-strain) data to the hydrostatic loading data – deviation of the velocity along the K0 path from the velocity along hydrostatic loading path is referred as “stress-induced”.

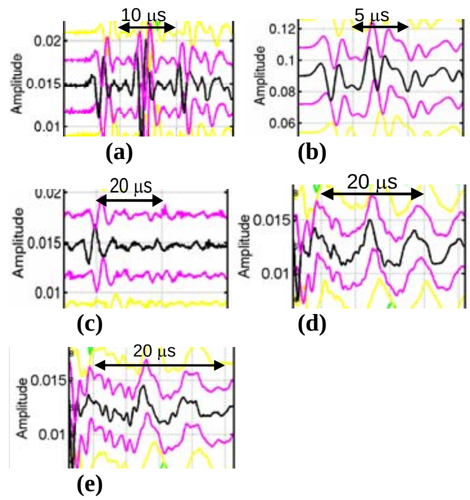


Figure 2. Some of the better quality waveforms from the sand pack: (a) axial P; (b) radial P; (c) axial S; (d) radial S polarized horizontally; (e) radial S polarized vertically.

(2) Stress-induced velocity anisotropy: ultrasonic measurement results.

The stress-induced velocity anisotropy was plotted for a dry sand pack sample and for the same sample saturated with mineral oil. Two K0 loading paths were used on the dry sample: one started from a lower hydrostatic pressure (~7.5MPa or 1000 psi) and one started from a higher hydrostatic pressure (~20MPa or 3000 psi). Both P- sand S-velocities show higher stress-induced anisotropy for the K0 loading path started from the lower hydrostatic stress. Examination of the strain measurement data indicated that the sample experienced different relative axial strains: maximum relative axial strain is about 1% for the K0 loading started from 7.5MPa hydrostatic stress and is about 0.5% for the K0 loading started from 20MPa hydrostatic stress. Furthermore, two observations can be made: (i) S-wave stress-induced anisotropy is weaker than the P-wave; (ii) Stress-induced velocity anisotropy for the oil-saturated sand is weaker that that of the dry sand. Similar conclusions were drawn from measurements on the unconsolidated reservoir sand sample.

The axial Vp/Vs ratios were plotted for the sand pack sample. For the dry sample, Vp/Vs ratios were plotted increase with increasing stress. K0 loading increased the Vp/Vs ratios by a maximum amount of ~10%. For the oil-saturated sample, Vp/Vs ratios decrease with increasing stress. K0 loading elevated Vp/Vs ratios by a maximum amount of ~10%.

(3) Anisotropic fluid substitution on the dry samples.

Analysis of the measurements shows that the oil-saturated results were obtained outside the low frequency limit (Biot, 1956) and, therefore, are not appropriate for well log data interpretation and seismic applications. Attempts to use less viscous fluids led to significant signal deterioration due to attenuation and were not successful. To make the data applicable for well log data interpretation, anisotropic fluid-substitution (Brown and Korringa, 1975) was performed on the dry velocity data. We assumed (i) the stress-induced velocity anisotropy leads to VTI symmetry; (ii) the P-wave velocity at $45^o$ is equal to the average of the axial velocity and the radial velocity; and (iii) the samples are isotropic under hydrostatic loading. We obtained results for the oil-substituted samples:

(i) P-wave stress-induced anisotropy of oil-saturated sample is weaker than that of the dry sample;
(ii) P-wave stress-induced anisotropy is stronger than S-wave stress-induced anisotropy for both dry and oil saturated samples.

(4) Relating K0-loading velocity data to hydrostatic loading data for the dry samples.

We plotted the axial P-velocity of a dry sand pack sample versus the axial stress and the axial S-velocity versus the average of the axial and radial stresses. The results show that stress-induced velocity anisotropy could be estimated from the hydrostatic loading data in the absence of direct measurements along K0 loading paths.

## Conclusions

We carried out an experimental study to quantify the amount of stress-induced velocity anisotropy in unconsolidated sands under realistic reservoir stress conditions. Large uncertainties remain, partially due to the difficulties in radial velocity measurements on these unconsolidated sands. More measurements are needed to quantify the exact amount of the stress-induced velocity anisotropy under realistic reservoir stress conditions to better characterize hydrocarbon reservoirs where the stress regimes are non-hydrostatic.

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