Impact of frequency on velocity stress sensitivity in shales

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Introduction

Time-lapse (4D) seismic is often used for monitoring hydrocarbon fields during hydrocarbon production, enhanced oil recovery, or CO_2 storage operations. When the reservoir pore pressure changes during production or injection, the formation stresses in reservoir and overburden change accordingly. Since velocities in rocks are stress dependent, the stress-induced velocity changes result in detectable time-shifts on 4D seismic data. Knowing the stress sensitivity of rocks, it is possible to invert time-lapse seismic data for stress, strain, and pore pressure changes. This invaluable information can be used for finding undepleted pockets of hydrocarbon, as well as assessment of reservoir and caprock integrity.

To quantify the stress sensitivity of shales in the field, systematic laboratory experiments are very useful. Here, field rocks are brought to the in-situ stress state and probed with different stress changes, whereupon the associated (typically ultrasonic) velocity changes are measured (Holt et al., 2018). The stress sensitivities are most often assumed to be independent of frequency and applicable for time-lapse seismic data interpretation. In our work, based on multi-frequency measurements (1-100 Hz and 500 kHz) with different shale cores, we show that this assumption may not always be valid.

Methodology

Three field shales were tested using SINTEF's low-frequency cell. The measurements included stress dependence of ultrasonic velocities, and dynamic stiffness (Young's modulus, Poisson's ratio) at seismic frequencies. Stress sensitivity was measured for different combinations of vertical and horizontal stress changes (stress paths), as it is known that different parts of overburden can undergo different anisotropic stress changes (Herwanger and Horne, 2009).

Since shales are anisotropic some assumptions must be made to convert changes in low-frequency measured Young's modulus and Poisson's ratios to velocity changes. Here, we assumed, as confirmed by the ultrasonic data, that the stress (and strain) dependence of P-wave velocities perpendicular to bedding can sufficiently well be described by three third-order stiffness parameters (Prioul et al., 2004). From the measured Young's modulus and Poisson's ratio changes for different stress paths, we determined the third-order stiffness parameters and calculated the corresponding seismic-velocity changes.

Results

In Figure 1, the resulting stress sensitivities of seismic P-wave velocities are compared to those at ultrasonic frequencies. Both seismic and ultrasonic stress sensitivities exhibit linear dependences on the stress path (for T and M shales; for Opalinus Clay, data is only available for two stress paths). However, the magnitude of stress sensitivities is in average 4 times higher at seismic frequency than at ultrasonic frequency.

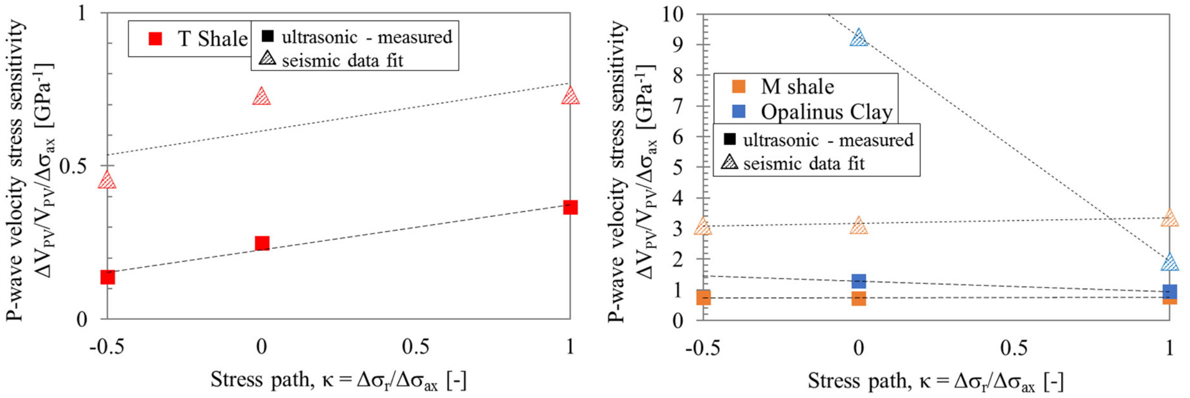

Figure 1: Stress sensitivity of vertical P- wave velocity as a function of stress path. Directly measured stress sensitivities at ultrasonic frequency (filled squares) are compared to stress sensitivities at seismic frequency (hatched triangles). The latter are calculated using Prioul's model, with the three third-order stiffness parameters in the model obtained from best fits to measured changes in dynamic Young's modulus and Poisson's ratios for different stress path.

Discussion and Conclusions

Our results indicate, for all three shales studied, that the stress sensitivity of P-wave velocities is by a factor of ~4 higher at seismic frequency than at ultrasonic frequencies, which would have to be considered when using lab results obtained at ultrasonic frequencies for the analysis of time-lapse seismic data. Since there are relatively large uncertainties in the experimental data and data analysis, further studies are needed to confirm our results. Moreover, these results are based upon the assumption that the strain sensitivity is isotropic which may not be correct. However, as shales generally exhibit relatively large velocity dispersion it is possible that the dispersion is stress dependent, resulting in a frequency-dependent stress sensitivity of velocities. One possible explanation for dispersion and frequency dependent stress-sensitivity of velocities of shales are relaxation processes of adsorbed (bound) water at grain contacts.

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