Offset-dependent overburden time-shifts from ultrasonic data

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Summary

Depletion or injection into a reservoir implies stress and strain changes in the reservoir and its surroundings. This may lead to measurable time-shifts for seismic waves propagating in the subsurface. We have measured multi-directional ultrasonic P-wave velocity changes for three different field shale cores, each probed with four different stress paths (i.e. different ratios between the horizontal and the vertical stress change), to systematically quantify the time-shifts for overburden shales with respect to ray angle (offset). The laboratory data show that for a given offset, the time-shifts are stress path dependent, where the isotropic stress path is associated with larger time-shifts as compared to the constant mean stress path or the triaxial stress path. Generally, the time-shifts are largest for zero offset (propagation normal to the bedding) and are decreasing for increasing offsets. The constant mean stress path has the most significant decrease of time-shifts with offset. By utilizing pre-stack seismic offset data, such controlled laboratory experiments can be used to constrain the inversion of 4D seismic data to quantify the stress and strain changes due to production. This may have important implications for improved recovery and safety, particularly in mature fields.

Main objectives:
Use multi-directional velocity data from overburden field cores to investigate the offset-dependence of time-shifts for a range of stress paths.

New aspects:
This work shows the importance of calibrated rock physics models for improved 4D seismic inversion. Provided an appropriate rock physics model to constrain the geomechanical model, pre-stack offset time-shifts may quantify stress and strain changes that is essential for safe and efficient field operations.

Introduction

The petroleum sector has over the last years been under pressure to deploy safer and more efficient operations for improved utilization of the resources. During the production, the reservoir shrinks (depletes) implying significant alterations in the overburden manifested as stress, strain and pore pressure changes. Repeated (4D) seismic surveys turn out to be a powerful tool for monitoring these subsurface changes. Since the seminal time-lapse data on reservoir compaction in the Valhall field by Hall et al. (2002) a lot of 4D data analysis have been published (e.g. references in Herwanger and Horne, 2009; MacBeth et al., 2018). Although 4D seismic interpretation has become a conventional tool in the petroleum industry, most of the studies are based on post-stack data providing rather qualitative results. The time-shifts in the overburden rocks are often as significant as the changes in the reservoir (Røste et al., 2015). The overburden is also associated with safety issues as well-instabilities, fracture growth and leakages. Precise and efficient time-lapse seismic inversion may therefore significantly improve the recovery from mature fields (Calvert et al., 2018) and ultimately enable appropriate well abandonment.

The time-lapsed signal is commonly used to quantify the physical impact in the subsurface. For the single-layer isotropic case, the strain (compaction or expansion) may be separated from velocity changes by comparing near- and far-offset pre-stack 4D data (Landrø and Stammeijer, 2004). In reality, subsurface is more complex with multiple layers and intricate structures. To resolve the non-uniqueness in inversion of time-lapsed strain and velocity data it is often assumed that the vertical velocity change is linearly related to the vertical strain, commonly termed as the *R*-factor model (Hatchell and Bourne, 2005; Røste et al., 2005). By using ray-path analysis, the *R*-factor and thereby the (vertical) strains may be determined as function of depth (e.g. De Gennaro et al., 2008). Furthermore, to accommodate for both intrinsic and stress (strain) induced anisotropy, non-linear corrections to the elastic transversely isotropic (TI) dynamic stiffness are used to invert seismic time-shifts (e.g. Herwanger and Horne, 2009).

However, there seems to be a significant potential for improved interpretation of the stress and strain dependences of subsurface velocities. In this abstract we will discuss time-shifts obtained in laboratory experiments from three different field shales, and how these time-shifts are related to offsets and stress paths that are relevant for improved 4D seismic interpretation.

Experimental method

The three field shale cores (cf. Table 1) were stored as preserved seal peals at ambient conditions prior to testing. All measurements and further analysis assume TI symmetry. The ultrasonic data (500-600 kHz) were acquired on a single plug for each shale, where the P-wave velocities were measured along multiple ray (group) angles upon different stress variations (stress paths) around in situ stresses and pore pressures cf. Figure 1 (stress change: $\Delta\sigma$; strain: $\Delta\varepsilon$; horizontal direction: *r* and vertical direction: *z*). With three distinct oblique (off-principal) velocity measurements, the error in the determination of the fifth TI elastic parameter (C_{13}) is significantly reduced compared to use of only one oblique ray angle (commonly the 45°). The stress variations were done in step-and-hold sequences, with appropriate consolidation prior data sampling. The investigated stress paths were: constant mean stress (CMS), triaxial stress (TRIAX); zero radial strain (K_0) and isotropic stress (ISO) changes. All tests were conducted at ambient (room) temperatures. During the stress cycles the pore pressure was undrained, that is assumed to be most representative of bulk overburden rocks.

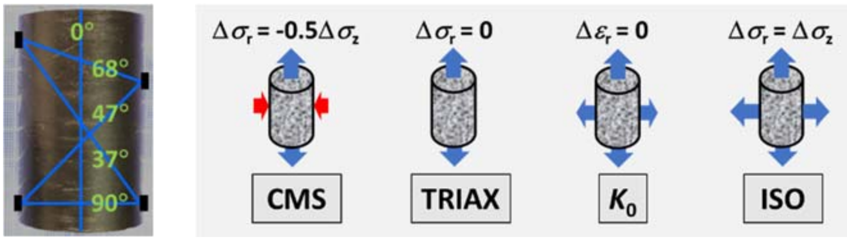

Figure 1 *Ray angles (offset) of the measured P-waves, where 0° (vertical) is normal to the bedding plane (left). In situ stress path variations (right).*

Table 1 *Overview of the tested offshore field cores. TVD: true vertical depth; wt%: weight percent.*

Shale	TVD [km]	Porosity [%]	Clay content [wt%]	Age
1	1.4	36	68	Middle Miocene
2	2.5	29	73	Eocene
3	3.4	24	76	Early Miocene

Discussion

In simplified time-shift interpretations, e.g. by using the *R*-factor model, the triaxial stress-path dependence is often not properly addressed as the stacking tend to mask the offset variations. Herwanger and Horne (2009) discuss the complexity and variability of 4D stresses and strains from their inversion of time-lapse data from the South-Arne Field. Laboratory experiments show that for shales (and implicitly other rocks) the *R*-factors are inevitably increasing non-linearly when the stress path is changed from constant mean stress towards isotropic stress (Holt et al., 2018). This trend is still valid also in the case of negligible stress-path dependence of the stress sensitivity of the vertical P-wave velocity, since the vertical strain itself is stress-path sensitive. The laboratory experiments discussed here may be viewed as an analogue (physical simulation) to an idealized single-layer seismic time-lapse survey. In both cases, compressional waves travel through rocks in multiple directions, for which altered stresses, strains and pore pressures result in altered velocities - all factors contributing to the measured travel-time shifts. A major benefit with laboratory experiments is the opportunity to directly measure all these quantities, and to study them for a range of stress paths under controlled conditions.

The left Figure 2 shows the relative time-shifts for the different ray angles and stress paths as defined in Figure 1. The three different shales exhibit similar (almost linear) offset dependence of travel-time shifts. Each data point for a given ray angle and stress path, represents the average value for the three shales. The travel-time shifts are largest, and almost equal for the four very different stress paths, at the zero offset (0°), i.e. for the vertical P-waves propagating normal to the bedding. Furthermore, the time-shifts decrease for increasing offset (negative gradient), and the gradient is steepest for the constant mean stress path. This addresses directly the deviating results reported from 4D seismic inversion in this respect (e.g. MacBeth et al., 2018). Some of these results are based on NMO corrected data (e.g. Landrø and Stammeijer, 2004; Herwanger and Horne, 2009). Thus, in the right Figure 2 we also provide the NMO-corrected time-shifts using the baseline (reference) dynamic TI stiffness, i.e. the stiffness prior the stress path cycling. This is the anisotropic analogue of the isotropic time-shift correction of Landrø and Stammeijer (2004). The NMO is amplifying the stress-path separation of large-offset time-shifts. This may look appealing, but one should note that the NMO corrections are accompanied with a non-linearly increasing error with the offset.

The stress-path dependent travel-time gradients (left Figure 2) may in principle be used to gain quantitative information about field data, but this requires integration of an appropriate calibrated rock physics model into the inversion procedure. Hawkins (2008) addressed this by including an anisotropic *R*-factor, in addition to the common vertical *R*, to better match data and implicitly honour the stress path. This heuristic approach is appealing and may be further refined (and calibrated) by laboratory data. Herwanger et al. (2007) make use of the third order (dynamic) elastic model by Prioul et al. (2004) for inversion of time-shift data from the South-Arne Field. This constitutive model assumes that the third order correction is symmetric in strain, implying that the strain sensitivity of velocities is isotropic. However, our laboratory data do not support this latter assumption. This may be rationalized as following: the model by Prioul et al. implies that a single isotropic stress path determines the full set of third order parameters for anisotropic rocks. This contrasts with laboratory data reported by Bakk et al. (2018) and Holt et al. (2008) that demonstrates anisotropic strain sensitivities of the (anisotropic) velocities of shales. As an alternative to constitutive models, crack models may also be an adequate choice providing more intuitive physical understanding (e.g. MacBeth et al., 2018). The negative offset-gradient Herwanger et al. (2007) report is typical for a subsurface with small static stiffness-contrast between the depleting reservoir and the overburden, implying an overburden experiencing close to constant mean stress path. This is also qualitatively in line with our NMO corrected data in the right Figure 2, exhibiting negative offset gradient for the constant mean stress path, in contrast to the isotropic stress path and the K_0 stress paths. Contrary, a relatively stiffer overburden compared to the reservoir implies a completely different stress path pushed towards isotropic stress changes in the overburden (De Gennaro et al., 2008; Morita and Fuh, 2009).

The enhanced time-shift separation between the different stress paths at large offsets (cf. Figure 2) underlines the potential of far-offset pre-stack analysis. In this respect complementary methods may also be of interest as refraction seismic, perhaps combined with diving waves, that may give access to this essential information. Cross-well seismic is also an option, although the potentially extra costs may be a barrier for such deployment. Generally, methods involving better utilization of 4D data is often preferable, contributing to the ongoing digitalization of this industry.

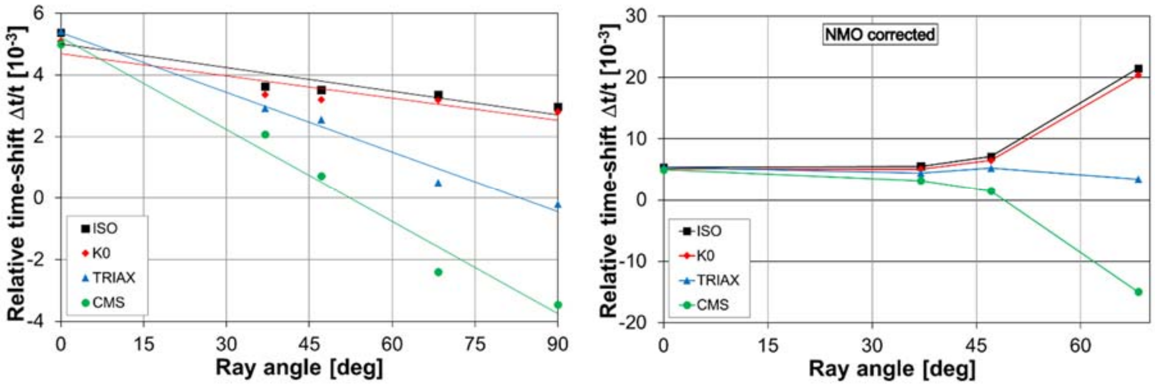

Figure 2 *Relative time-shifts vs. ray angle for four different stress paths (cf. Figure 1) with linear trendlines (left). NMO corrected data with connection lines to separate the stress paths (right).*

One major benefit with our ultrasonic setup is that all velocities and their stress sensitivities are obtained during a single experiment on a single plug. Furthermore, the small size allows for sufficient horizontal isotropy (close to TI), ideal for the systematic quantification and fundamental understanding of "clean" systems. Contrary, in the field one faces challenges influencing the offset interpretation as gas clouds in the overburden attenuating the signal, lateral heterogeneities including a confined overburden strain cloud. Also, the reservoir may be undershot for larger offsets. In the end, all this must be dealt with. Note, since laboratory P-waves propagate at ~10^6 Hz and seismic waves propagate at ~1 Hz, dispersion may have impact on the interpretation. Szewczyk et al. (2016) indicate a higher stress sensitivity for the stiffness at seismic frequencies. It is not clear whether this will imply changes in the offset dependence.

Conclusion

The geophysical community has for a long time tried to understand the offset dependence of time-shifts of 4D reflection seismic data. For three different overburden field shales multi-directional ultrasonic velocities were acquired and probed for four different stress paths. The time-shifts are decreasing for increasing ray angles, and the constant mean stress path exhibit even negative time-shifts for larger angles. This contrasts to the isotropic stress path exhibiting a much smaller offset dependence and positive time-shifts for all angles. These data show the importance of calibrated rock physics models for improved 4D seismic inversion. Provided an appropriate rock physics model to constrain the geomechanical model, pre-stack offset time-shifts may quantify stress and strain changes that is essential for safe and efficient field operations.

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