Offset-dependence of production-related 4D time-shifts: real data examples and modeling

Summary
We present examples of 4D time-shifts obtained with offset and angle sub-stacks of seismic data acquired in deep (Gulf of Mexico) and shallow water (North Sea) marine environments. We compare the observations with two proposed rock-physics models using different linear relationships between the velocity change and the strain field induced by reservoir compaction. The model involving only vertical strain component predicts a similar time-shift with offset behavior as that observed from the data. We do not observe a strong decrease of time-shifts with offset as reported in previous publications.

Introduction
Time-lapse seismic monitoring is an important tool for interpretation of data acquired over producing fields. Production-related compaction of a reservoir is visible on the time-lapse seismic data because it causes deformation of the subsurface resulting in velocity and path-length changes that lead to time-shifts that are commonly observed above the reservoir (Guilbot and Smith, 2000; Barkved and Kristiansen 2005; Hatchell et al. 2003)

With the recent advancements in long-offset and wide azimuth data, more attention is being paid to pre-stack data to have a better understanding of the geomechanical processes in the field and increase the accuracy of interpretations.

A simple examination of the components of the stress and strain tensors resulting from geomechanical models leads to the expectation that significant offset dependence might occur. For example, in the rocks above a compacting reservoir the vertical normal strains are extensional whereas the horizontal normal strains are compressional. Waves travelling vertically and horizontally might behave quite differently if the velocity-strain coupling is anisotropic. Many previous studies predict such an anisotropic velocity response (Sayers and Kachanov, 1995; Prioul et al., 2004) and others predict significant offset-dependence of 4D time-shifts (Fuck et al., 2009; Herwanger et al., 2007; Smith and Tsvankin, 2012).

If observed in the data, the offset- and azimuth-dependence of time-shifts can serve as an additional constraint in interpretation of 4D signals. Additionally, the model that describes the data can be used to calibrate parameters of geomechanical models.

We present examples of high-quality data acquired in deep and shallow marine environments that do not show significant offset-dependence. These observations are analyzed by simple geomechanical modeling to understand what model best explains the data.

Geomechanical model for offset-dependent time-shifts
We extend the empirical model first proposed by Hatchell and Bourne (2005) for normal-incidence P-waves to non-zero offset. The model suggests linear dependence of the vertical strain component $\varepsilon_{zz}$ and the fractional velocity change $\Delta v/v$

$$\Delta v/v = -R \varepsilon_{zz},$$

where the factor $R$ is a dimensionless parameter that describes the sensitivity of the relative change in vertical velocity to the normal strain resulting from the geomechanical changes in the subsurface. This parameter has different values for rocks under extension ($R^+$) and compression ($R^-$). The model provides qualitatively correct predictions of 4D time-shifts observed at many compacting reservoirs around the world. For normally incident waves, equation (1) predicts a time-shift, $\Delta t/\Delta z = (1+R)\varepsilon_{zz}$.

We will study extensions of this approach to non-zero offset by incorporating offset-dependent strain couplings and by summing the travel time-shifts along the ray path.

The time-shift is defined as the difference in the two-way travel time between the base and monitor surveys along the ray paths $l$ and $l_0$, respectively:

$$\Delta t = \int \frac{dl}{v} - \int \frac{dl}{v_0},$$

Following Landrø and Stammeijer (2004), we consider straight rays and isotropic velocities.

In Figure 1, $\theta$ is the angle of incidence for the baseline data, $x$ is the offset and $\Delta z$ is the depth-shift of the horizon of interest. We assume small changes in layer thickness and velocity ($\Delta z/z << 1, \Delta v/v << 1$), and use a straight ray path assumption for the monitor survey as well as for the base.
Offset-dependent time-shifts

line survey to calculate time-shifts - this is justified to the first order, according to Fermat’s principle of minimum travel time (Landrø and Stammeijer, 2004).

Model 1: Isotropic velocity change depending on \( \varepsilon_{zz} \)

The simplest extension of the model by Hatchell and Bourne (2005) to non-zero offset is to assume the velocity change is isotropic so that the relative change in velocity in any direction only depends on \( \varepsilon_{zz} \), according to equation (1). Substitution of this relation into the integral equation (2) and using the approximations mentioned above results in the time-shift

\[
\Delta t = \frac{1}{V_0 \cos(\vartheta)} \int (\cos^2(\vartheta) + R \varepsilon_{zz}) dz. \tag{3}
\]

After that the NMO correction must be applied as we are modeling post-stack data (Landrø and Stammeijer, 2004):

\[
\Delta t_{\text{NMO}} = \Delta t \sqrt{\frac{x^2}{t_0^2 + \frac{x^2}{t_0^2}}, \tag{4}
\]

where \( t_0 = 2z/v \) is the two-way zero-offset travel time and \( x \) is the offset. Equation (4) suggests that the observed time-shifts will be magnified as a result of NMO-correction with the baseline velocity model (standard processing).

Model 2: Isotropic velocity change depending on \( \varepsilon_{pp} \)

There are many ways to include stress-strain anisotropy. Such models have been considered, for example, by Smith and Tsvankin (2012), Herwanger et al. (2007), Sayers and Schutjens (2007), Scott (2007), Herwanger and Horne (2009) and Fuch et al. (2009). Despite the elegance of many models presented in the literature, it is still challenging to use them to explain the observations from real data. Firstly, it is challenging to build a model that accurately describes a complicated anisotropic velocity change introducing only a few parameters. Simplifications are required to reduce uncertainty in determination of these parameters. Secondly, it is challenging to define even a few parameters, because of the difficulties in reproducing the reservoir stress conditions in the laboratory. The inconsistency of predictions by some models and the data can also be explained by the fact that a different physical mechanism dominates in reality, rather than the one accounted for in the theory.

We present here a simple heuristic model where all strain components contribute to the velocity change. Conceptually, if for vertical waves \( \Delta v/v_z = -R \varepsilon_{zz} \) then we can expect for horizontal waves \( \Delta v/v_x = -R \varepsilon_{xx} \). Rodriguez-Herrera et al. (2015) generalized this simple concept by suggesting that the velocity change depends on the strain along the ray path direction:

\[
\frac{\Delta v}{v} = -R \varepsilon_{pp}, \tag{5}
\]

where \( \varepsilon_{pp} \) is the strain component along the ray path direction, and \( p \) is a unit vector of the direction along the ray path. Then the formula for the time-shifts reads

\[
\Delta t = \frac{1}{V_0 \cos(\vartheta)} \int (\cos^2(\vartheta) \varepsilon_{zz} + R \varepsilon_{pp}) dz. \tag{6}
\]

To compare the offset-dependence predicted by Model 1 and Model 2, we calculate strains in an isotropic half-space with a compacting reservoir using an analytical solution for a block-shaped reservoir based on Geertsma (1973) nucleus of strain solution (Kuvshinov, 2008).

Figure 2 shows the results of applying equations (3) and (6) to a simple model of a compacting block-shaped reservoir 1.5 km square on the sides, with a thickness of \( h = 30 \) m. The velocity of the unperturbed medium is \( v = 2000 \) m/s and the Poisson ratio is \( \nu = 0.2 \). We model a pressure drop that produces 30 cm of compaction in the center of the block. The depth to top reservoir is 4.1 km. The values for the \( R \) factors for compression and extension are \( R^-1 = 1 \) and \( R^+7 = 7 \), respectively, which has proved reasonable in many environments (Hatchell and Bourne, 2005).

Incidence angle, degrees

Figure 2: Vertical cross-section through the center of the reservoir area. Time-shifts predicted by Model 1 (upper panel) and Model 2 (lower panel) for different angles of incidence \( \theta \).
Time-shifts calculated along a vertical cross section through the center of the block are depicted in Figure 2 for angles of incidence from $\theta = 0$ to $\theta = 50$ degrees. The results for Model 1 are shown in the upper panel and for Model 2 in the lower panel. In these pictures we modeled wide-azimuth data and averaged the results of many calculations at different azimuths. We observe that the predictions of the offset dependence for the time-shifts by the two models discussed above are quite different. Looking first at the region above top reservoir, for Model 1 the time-shifts are flat to slightly increasing with offset (as a result of the NMO-correction), whereas for Model 2 they decrease at far offsets (as a result of the flip in polarity of the horizontal to vertical strain components).

In the region below the reservoir interesting effects happen including the possibility of raypaths that “undershoot” the reservoir so that in the deep part of the image the time-shifts start to vanish at far offsets – an effect that does not occur at zero offset.

To investigate the influence of azimuth, Figure 3 shows a map view of a horizontal slice calculated 50 m above top reservoir for the angle of incidence $\theta = 40$ degrees and varying azimuths, for Model 1 (upper panel) and Model 2 (lower panel). Azimuth is defined here as an angle between the projected ray and the vector pointing east (x axis direction) at the reference plane (x-y plane). Again, a drastic difference is observed in the predictions of two models. Model 2 exhibits a strong azimuth dependence because of the coupling with horizontal strains that is not present in Model 1.

Data examples

Data examples showing the offset dependence of time-shifts at two different fields are given in Figure 4 and Figure 5. Figure 4 shows the time-shifts obtained from data acquired with narrow-azimuth streamer surveys in the Shearwater field of the North Sea. The full stack is depicted in the leftmost panels, followed by angle stacks to the right. The vertical cross-sections depicted in the lower panel are indicated by a dotted line on the maps depicted in the upper panel. We do not observe any significant offset dependence of the time-shifts.

Figure 5 shows a similar display of depth shifts obtained from the data acquired with OBN surveys in the Mars field in the Gulf of Mexico. Again, no significant offset-dependence is observed. In this example, we observed the “undershooting” phenomenon at far offsets below the reservoir.

The comparison of the data examples with the predictions by the models given in Figure 2 suggests that the predictions by Model 1 are consistent with the data, while Model 2 predicts a significant offset-dependence of time shifts with increasing offset that is not observed in the data. There is also no strong azimuthal dependence in the data, as predicted by Model 2, although these data examples are not presented here.

These results suggest, firstly, that the R-factor model can be easily extended to non-zero offset rays. Furthermore, it is suggested that taking into account lateral components of the strain tensor leads to significant offset dependence at far offsets, which was also reported in previous publications. However, this offset-dependence is not observed in our data. Model 2 presented in this paper can be seen as a simplified version of a more general model where additional parameters can be introduced governing the sensitivity of the components of the stiffness tensor to small strains.

We find it very informative to observe the drastic difference between the two models. Given the fact that it is hard to estimate the parameters governing stiffness sensitivities, one must be careful in using the models taking into account lateral strain components, which are required, for example, for calibrating geomechanical models.
Conclusions

We have presented two examples of offset-dependent time-shifts observed in real data acquired in shallow and deep water marine environments. We do not observe any significant offset dependence of the time-shifts. This result is different from expectations based on several models published in literature.

We compared our results with two different model predictions. The model that used a linear relationship between the fractional velocity change and the vertical strain component worked best for describing the offset-dependence of the data. This suggests that vertical strains are dominant in the compaction regime and that the elastic parameter governing P-wave propagation is sensitive to small perturbations in the normal strain component induced by compaction.

The predictions of a second heuristic model where velocity change is related to the directional strain (the strain component along the ray path) show a large and clearly visible offset-dependence of time-shifts which is not consistent with the observations presented in this paper.

Our results suggest that there is no additional value in offset-dependence of 4D time-shifts measured in compacting reservoir environments.

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REFERENCES


