Measuring reservoir compaction using time-lapse timeshifts

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Summary

Time-lapse timeshifts refer to the differences in two-way seismic travel times that are frequently observed in the analysis of time-lapse seismic surveys. One source of timeshifts originates inside the reservoir interval as a result of changes in the pore-fluid properties that alter the seismic velocity. Another is from changes in seismic velocity and layer thickness that occur both inside and outside of the reservoir as a result of reservoir compaction and stress and strain redistribution in the surrounding formations.

Timeshifts induced by changes in fluid properties are always zero above the top reservoir reflection event and constant below the base of the reservoir. These fluid-induced timeshifts can be significant (for example, when gas is released as an oil passes through bubble point) and are routinely calculated using Gassmann or similar theories and are not the focus of this paper.

The compaction-induced timeshifts have opposite gradients on the inside and outside of the reservoir. Within the reservoir, the reduction in layer thickness and the expected increase in seismic velocity will reduce the seismic travel time across these layers. Outside the reservoir, the decrease in reservoir thickness is exactly balanced by surface subsidence and rock expansion. The expanding overburden produces increased layer thickness and slower seismic velocities that increase the seismic travel times.

Observations on real time-lapse seismic data over compacting reservoirs show that the positive timeshifts that accrue in the overburden are larger than the negative timeshifts that accrue inside the reservoir (the sign convention chosen is that positive timeshifts result when the seismic travel time increases). The amount of overburden elongation cannot exceed the amount of reservoir compaction. So if the change in velocity were simply proportional to the change in vertical strain, the reduction in travel time through the reservoir would exceed the increase in travel time though the overburden. The net effect would be a negative timeshift below the reservoir. Instead positive timeshifts are observed below compacting reservoir indicting velocity reduction per unit elongation strain significantly exceeds the velocity increase per unit contraction strain.

Using simple models of the velocity-strain response it is shown that time-lapse timeshifts are proportional to the stretching of the overburden layers and that this is highly correlated with the reservoir compaction. The net result is that time-lapse timeshifts are a good measurement of the reservoir compaction.

Introduction

Pressure depletion as a result of oil and gas production will cause a reservoir to compact and transmit long wavelength changes in the stress and strain fields to the rocks bounding the reservoir. Geomechanical modeling combined with a suitable rock physics model that relates the changes in seismic velocity to the changes in the stress and strain fields are used to predict the time-lapse timeshifts. Comparisons of real timeshifts to those generated from geomechanical models show good agreement in two fields (Hatchell et al, 2003; Stammeijer et al 2004; Hatchell et al 2005).

The timeshift at a given depth is a sum of contributions from shallower layers. In what follows it is shown that a simple rock physics model based on a velocity-strain relationship allows us to readily sum up the shallow layer contributions and relate the timeshift to the reservoir compaction.

To begin with it is important to demonstrate that the expansion of the overburden is strongly correlated to the reservoir compaction. Figure 1 shows a geomechanical calculation of the vertical displacement field that occurs when a block shaped reservoir is depleted. In the example shown, the reservoir is buried at a depth of 3000m and has horizontal dimensions of 1000 x 1000 m and a vertical thickness of 30m. The rock mechanical properties chosen for the block and the overburden material are identical (ν=0.25). The fluid pressure has been reduced such that the product of the pressure depletion, uniaxial compressibility, and reservoir thickness equal 1 m.

There are three surfaces in Figure 1 that are important to characterize: the free surface (at 0 m) and the top and base of the depleting reservoir. The changes in vertical displacement at the free surface layer are also known as the surface subsidence and are downward (although by only a small amount in the example shown). The displacement at the top of the reservoir is also downward and by an amount equal to approximately half of the reservoir compaction. At base of the block the displacement is upward by an amount that is also nearly half of the compaction.

As demonstrated by Geertsma (1973) for disk-shaped reservoirs, the ratio of the block size and its burial depth determine the relative amounts of vertical displacements at each of these three surfaces. Figure 2 shows the vertical displacements calculated at the center of various square-shaped reservoirs as a function of the ratio between the burial depth and the block size (i.e. the length of one side).

The difference between the base- and top-reservoir displacements is the compaction of the reservoir and is very close to 1.0 m regardless of the depth/size ratio. The difference between the free surface and top reservoir subsidence is the amount of overburden elongation due to reservoir compaction. Note that for reservoirs with depth/size ratios > 2, the elongation of the overburden is approximately half of the reservoir compaction. The same holds true for the underburden that also gets elongated by approximately half of the reservoir compaction. These results hold for an isotropic homogeneous medium. However, the presence of layers with contrasting stiffness will simply change the partitioning of elongation between the overburden and underburden. For example, a rigid basement means that reservoir compaction and overburden elongation become almost equal for deeply buried reservoirs.

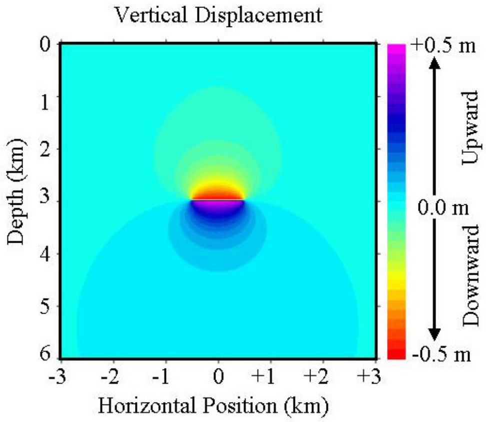

Figure 1: Vertical displacement field through the center of a depleting 1000m square reservoir buried at a depth of 3000m.

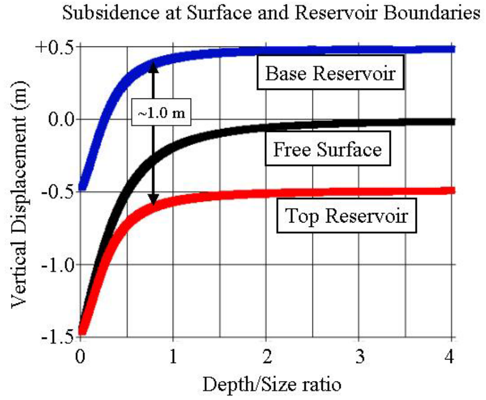

Figure 2. Vertical displacement of the free surface and top and base reservoir boundaries calculated at the center of a thin compacting square-shaped reservoir.

The surface subsidence may or may not introduce a timeshift for the shallowest layer. In a repeat marine streamer survey, the free-surface subsidence occurs at the sea floor resulting in a larger water column at the time of the repeat survey and therefore a non-zero timeshift approximately equal to 1.3 ms per meter of seafloor subsidence. It could very well be that the subsidence timeshift will be removed in the seismic processing. In OBC or OBS data the situation is modified as the receivers are attached to the subsiding surface. In onshore data, both the sources and receivers are attached to the subsidence bowl. In what follows, we will not explicitly keep track of the shallow timeshifts that result from subsidence.

Relating the timeshifts to compaction

The timeshifts that accumulate in the overburden are the sum of contributions due to changes in seismic velocity and path length. For simplicity, we concern ourselves with vertical raypaths. For a single layer of thickness, z, the change in relative seismic travel time is (Landro and Stammeijer, 2004)

$$\Delta t/t = \Delta z/z - \Delta v/v, \qquad (1)$$

where t represents the two-way travel time across the thin layer and v is the velocity of the layer.

The biggest uncertainty in the above relationship is relating the change in the seismic velocity to the change in the stress and strain fields of the rocks through which it propagates. In the general case, this change in seismic velocity will be anisotropic (see for example Wang, 2002; Sarkar et al, 2004; Sayers, 2005;), and it is of great interest to measure this anisotropy from the in-situ seismic data.

If we test out simple hypothetical velocity relationships such as relating the change in velocity to the change in total vertical stress, Szz, or the vertical strain $Ezz=\Delta z/z$, we find that each of these produce qualitatively similar responses in the overburden. As pointed out by Hatchell et al (2005), if we parameterize the change in velocity to vertical strain then Eq. (1) becomes very simple. For example, setting $\Delta v/v = -R^* Ezz$ (adopting the sign convention that positive strains are extensional and tend to decrease velocity), we can then write the relative change in the seismic travel time as being proportional to the vertical strain,

$$\Delta t/t = (1+R)^*Ezz. \qquad (2)$$

The dimensionless parameter R in the above equation represents the ratio of timeshifts that result from changes in velocity to timeshifts resulting from changes in path length.

Eq. (2) is a simple result. In an overburden of initially constant velocity, the timeshift that accumulates from the free surface is proportional to the integral of the vertical strain so that

$$\text{timeshift}(D) = 2(1+R)\,[\,u(0) - u(D)]/v, \qquad (3)$$

where $u(D)$ is the vertical displacement at depth D. The expression $[u(0)-u(D)]$ is the expansion of the overburden.

If a deeply buried reservoir within a homogeneous medium compacts by an amount, H, we saw in the previous section that the expansion of the overburden is half the reservoir compaction so that,

$$\text{timeshift (Top Reservoir)} = (1+R)\ H/v. \qquad (4)$$

The above result shows that the timeshift at the top reservoir event is proportional to the reservoir compaction.

The presence of layers with contrasting stiffness will simply change how the positive timeshift is partitioned above and below the reservoir. In the absence of any significant lateral stiffness changes, timeshifts measured at the top of the reservoir are still proportional to the reservoir compaction.

Asymmetry between extension and contraction

If the above analysis is continued through the reservoir interval and it is assumed that the velocity-strain relationship is the same for the compacting reservoir rocks as it is for the expanding overburden rocks, then the timeshift will decrease by an amount $2*(1+R)*H/v$ across the reservoir interval so that at the base of the reservoir we should expect to see negative timeshifts that are equal and opposite to those at the top of the reservoir.

In the presence of layers with contrasting stiffness the overburden elongation never exceeds the reservoir compaction. Under these conditions positive time shifts cannot exist below the reservoir. This predicted behavior of the timeshift across the reservoir interval is not observed in practice. Figure 3 shows examples of timeshifts from two North sea fields that have been discussed extensively (Hatchell et al 2003; Hall et al 2003; Barkved et al 2004; Stammeijer et al 2004; Hatchell et al 2005). In both cases the timeshift at the base of the reservoir interval is positive implying that a very different velocity-strain response occurs in the reservoir interval.

The positive timeshift at the base reservoir event implies that the velocity response to strain change in the reservoir interval must be significantly smaller than that occurring in the overburden.

In order to reconcile the weak reservoir response we propose an explanation in terms of a velocity-strain asymmetry. Reservoir rocks are highly sensitive to pressure increases because large time-lapse responses are observed around injection wells that raise reservoir pressures above the initial pressure state. This large pressure-up signal when compared to the weak pressure-down signal implies that there is an asymmetry to the velocity-strain response. It is likely that this strain asymmetry results from irreversible processes such as fractures and separation of grain contacts.

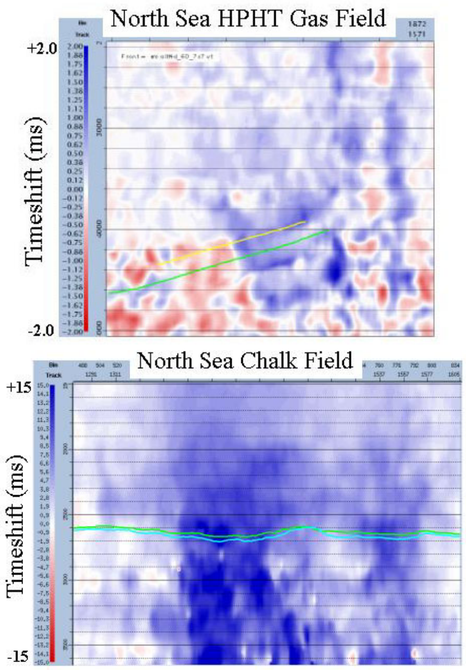

Figure 3. Vertical sections showing time-lapse timeshifts at two different fields in the North Sea. The upper example is from a compacting high-pressure high-temperature sandstone reservoir. The lower is from the compacting Valhall oil-filled chalk reservoir. The seismic horizons in each section indicate the top and base of the reservoir.

In order to account for this proposed strain asymmetry we re-write equation (2) so that

$$\Delta t/t = (1+R^{+})*Ezz\ ,\ \text{ if } Ezz>0 \qquad (5a)$$

$$\Delta t/t = (1+R^{-})*Ezz,\ \text{ if } Ezz<0, \qquad (5b)$$

Based on the observed timeshifts it is expected that $R^{+} > R^{-}$. Trial and error on data from several fields gives values in the range: $4 < R^{+} < 8$, and $0 < R^{-} < 2$.

Figure 4 shows vertical profiles of the predicted timeshifts for various choices of R^{+} and R^{-} through the center of the block-shaped reservoir shown in Figure 1. On the left-most plot, $R^{+} = R^{-} = 5$ and in this case the timeshift at top and base reservoir is equal and opposite and the timeshift far beneath the reservoir is zero. The middle plot shows the case where $R^{+} =5$, $R^{-} =1$ and in this case the timeshift at the base reservoir event is smaller than that at the top reservoir although still positive. The right-most plot shows the case where the velocity response inside the reservoir is insensitive to compaction ($R^{-} =0$). In both of the last two examples there is a net positive timeshift far beneath the reservoir.

The asymmetry that occurs in the reservoir complicates the interpretation of time-lapse timeshifts. Restricting the timeshift analysis to the interval above the reservoir avoids this complexity. Figure 5 shows a comparison between the timeshifts that are measured at the top reservoir event in the Valhall oil field compared to the net thickness change due to compaction predicted by the reservoir simulation over the time period captured by the time-lapse survey. The agreement between these pictures shows that the time-lapse timeshift is measuring the reservoir compaction.

Conclusions

Compaction-induced timeshifts result from changes in layer thickness and velocity that occur both inside and outside of the reservoir interval. A model that relates the changes in seismic velocity to the vertical strain explains many features that are observed in real data and predicts that the timeshift observed at the top reservoir event is proportional to the reservoir compaction. The model developed in this paper also predicts that if the velocity-strain response is symmetric between elongation and contraction that positive timeshifts will never be observed below the reservoir due to reservoir compaction. This is not consistent with time-lapse data and so it is proposed that the velocity-strain response is asymmetric.

References

Barkved, O., Kommedal, J., Thomsen, L., 2004, The role of multi-component seismic data in developing the Valhall field, 66th Mtg.: Eur. Assn. Geosci. Eng., E040.

Geertsma, J., 1973, A basic theory of subsidence due to reservoir compaction: The homogeneous case, Verhandelingen Kon. Ned. Mijnbouwk. Gen., v 28, p 43-62.

Hall, S.A., MacBeth, C. and Barkved, O. I., 2003, Interpreted Warping for 4D Monitoring of Production-Induced Subsidence at Valhall, 65th Mtg.: Eur. Assn. Geosci. Eng., P183.

Hatchell, P., van den Beukel, A., Molenaar, M., Maron, K., Kenter, C., Stammeijer, J., van der Velde, J. and Sayers, C., 2003, Whole earth 4D: Monitoring geomechanics, 73rd Ann. Internat. Mtg.: Soc. of Expl. Geophys., 1330-1333.

Hatchell, P.J., Kawar, R.S, Savitski, A.A. 2005, Integrating 4D seismic, geomechanics, and reservoir simulation in the Valhall Oil field, 67th Mtg.: Eur. Assn. Geosci. Eng., C012.

Landro, M. and Stammeijer, J., 2004, Quantitative estimation of compaction and velocity changes using 4D impedance and travel time changes, Geophysics, **69,** 949-957**.**

Sarkar, D., Bakulin, A. and Kranz, R. L., 2003, Anisotropic inversion of seismic data for stressed media: Theory and a physical modeling study on Berea Sandstone: GEOPHYSICS, Soc. of Expl. Geophys., **68,** 690-704.

Sayers, C., 2004, Monitoring production induced changes using seismic wave, 74th Ann. Internat. Mtg.: Soc. of Expl. Geophys..

Stammeijer, J.G.F., van der Velde, J.J., Hatchell, P.J., Van den Beukel, A., Molenaar, M.M., 2004, Integrating 4D Seismic and geomechanics: a case study, 66th Mtg.: Eur. Assn. Geosci. Eng., A038.

Wang, Z., 2002, Seismic anisotropy in sedimentary rocks, part 2: Laboratory data: GEOPHYSICS, **67,** 1423-1440.

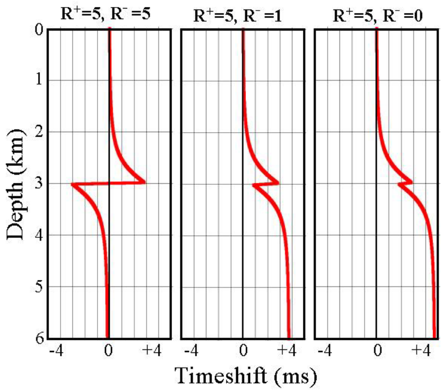

Figure 4. Timeshifts calculated along a vertical profile through the center of the block-shaped reservoir of Fig. 1 for three different choices of the strain velocity-coupling parameters indicated at the top of each plot.

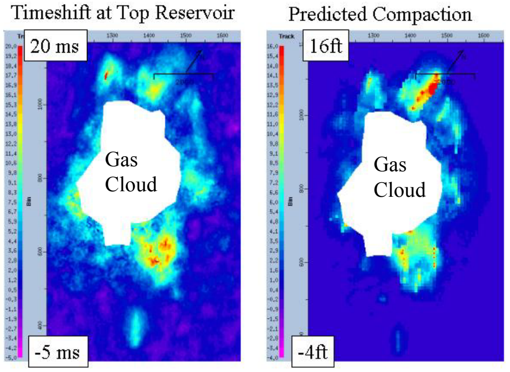

Figure 5. Left side shows timeshifts measured at top reservoir between streamer surveys measured 10 years apart. Right side shows predicted net feet of compaction based on a reservoir simulation over the same time interval.

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