Feasibility of inverting compaction-induced traveltime
shifts for reservoir pressure

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ABSTRACT

Pore-pressure variations inside producing reservoirs result in excess stress and strain that cause time shifts of reflected waves. Inversion of seismic data for pressure changes requires better understanding of the dependence of compaction-induced time shifts on reservoir pressure reduction. Here, we investigate pressure-dependent behavior of P-, S-, and PS-wave time shifts from reflectors located above and below a rectangular reservoir embedded in a homogeneous half-space. Our geomechanical modeling algorithm generates the excess stress/strain field and the stress-induced stiffness tensor as linear functions of reservoir pressure. Analysis of time shifts obtained from full-waveform synthetic data shows that they vary linearly with pressure for reflectors above the reservoir, but become nonlinear for reflections from the reservoir or deeper interfaces. Time-shift misfit curves computed with respect to noise-contaminated data from a reference reservoir for a wide range of pressure reductions display well-defined minima. We also evaluate the influence of the reservoir width and third-order stiffness coefficients on time shifts because these parameters will be fixed in the inversion for reservoir pressure. Our results indicate that stable pressure estimation requires including multicomponent time shifts from reflectors below the reservoir and applying a nonlinear global inversion algorithm.

Key words: geomechanics, seismic modeling, inversion, stress-induced anisotropy, converted waves, shear waves, time-lapse, compacting reservoir, transverse isotropy, VTI

Introduction

Compaction-induced seismic traveltine shifts can potentially be inverted for pressure and fluid distributions inside a producing reservoir. Such an inversion contributes to the understanding of how fluids are moving (sweeping) through a reservoir, of levels of intercompartment pressure communication, and whether fluid is produced away from wells (Greaves and Fulp, 1987; Landro, 2001; Lumley, 2001; Calvert, 2005; Hodgson et al., 2007; Wikle, 2008). Knowledge of reservoir pressure can also be used to estimate stress and strain variations outside the reservoir (Herwanger and Horne, 2005; Dusseault et al., 2007; Scott, 2007). Identifying those stress patterns helps guide drilling decisions and reduce the cost of repairing or replacing wells snapped or sheared by high stresses.

Conventional methodologies employ poststack data and compaction-induced vertical stress/strain to estimate time-lapse velocity and volume changes (Hatchell and Bourne, 2005; Janssen et al., 2006; Roste, 2007). However, migration and stacking of data represents a complex filtering process that can corrupt phase rela-
tionships and arrival times. Further, velocity/strain estimation from field data using this approach rarely produces results that agree with laboratory experiments (Bathija et al., 2009). Additionally, it has been shown that shear (deviatoric) strains generate significant time shifts, requiring the use of triaxial geomechanical interpretation of time-lapse data (Schutjens et al., 2004; Sayers and Schutjens, 2007; Herwanger, 2008; Sayers, 2010; Smith and Tsvankin, 2011b).

Estimation of compaction-related time shifts requires geomechanical computation of excess strains, strain-induced stiffnesses, and modeling of time-lapse wavefields. Fuck et al. (2009, 2011) develop a modeling methodology based on triaxial strain formulation and nonlinear theory of elasticity, and estimate P-wave shifts using anisotropic ray tracing. Smith and Tsvankin (2011b) confirm the P-wave results of Fuck et al. (2009) and analyze time shifts for S- and PS-waves using finite-difference elastic modeling. These studies demonstrate that both volumetric (hydrostatic) and deviatoric (shear) strains generate significant time-shift contributions for all three (P, S, and PS) modes. According to their results, sensitivity of time shifts to reservoir pressure strongly varies with wave type and reflector location.

Here, we use the geomechanical and seismic modeling methodology of Smith and Tsvankin (2011b) to study the dependence of P-, S-, and PS-wave time shifts on reservoir pressure. For a set of reflectors located above and below the reservoir, we examine the linearity of time shifts expressed as a function of reservoir pressure for different noise levels in the data. We also examine time-shift misfits with respect to a reference reservoir for a realistic range of pressure reductions. Further, we estimate time-shift variations for a range of the third-order stiffness coefficients and reservoir widths - parameters that will be assumed to be known during the inversion.

Theoretical Background

Modeling travelttime shifts caused by production-induced changes in a reservoir is a three-step process. First, changes in reservoir parameters (here, pressure reduction) result in excess stress and strain in and around the reservoir. Second, the excess stress/strain perturbs the stiffness coefficients (C_{ij}) that govern the velocities and traveltimes of seismic waves. Third, the stress-induced stiffnesses are used to model seismic data and compute the time shifts between the baseline and monitor surveys. Note that time shifts are generally nonlinear in the relevant stiffness coefficients even when the model is homogeneous and isotropic (Figure 1). In the following tests, we compute time shifts for the reflectors shown in Figure 2.
Strain, stiffness, and ray-based time shifts

We employ a simplified, 2D rectangular reservoir model after Fuck et al. (2009, 2011) (Figure 1), comprised of isotropic Berea sandstone that follows standard Biot-Willis compaction theory (Hofmann et al., 2005; Zoback, 2007). The effective pressure in the reservoir (P_{eff}) changes according to a reduction of the pore fluid pressure (P_{fluid}):

\[ P_{eff} = P_c - \alpha P_{fluid}, \]  

where (P_c = \rho g z) is the confining pressure of the overburden, and \( \alpha \) is known as the effective stress coefficient (Biot-Willis coefficient for “dry” rock, where air is the only pore infill). Pressure changes occur only in the reservoir block. The resulting displacement, stress, and strain changes throughout the section can be computed from analytic equations discussed by Hu (1989), Downs and Faux (1995), and Davies (2003). However, here we perform geomechanical modeling using the finite element, plane-strain solver from COMSOL (COMSOL AB, 2008), which can handle more complicated models. For isotropic background material (Figure 1), COMSOL solves the linear system

\[ \sigma = D\epsilon_o + \sigma_o - \Delta P, \]

where the geomechanical model has zero initial stress and strain (\( \sigma_o, \epsilon_o \)), and \( D \) are the stiffness coefficients. Typical modeled volumetric and deviatoric strains for the range of pressures used in our study are shown in Figure 3 (next page) for reflector A (Figure 2) and for a horizontal line through the vertical center of the reservoir. The modeled strains are linear in the pressure drop, and 1-2 orders of magnitude higher inside the reservoir than in the overburden.

The strain-induced variations of the stiffness tensor can be expressed using the so-called nonlinear theory of elasticity (Hearmon, 1953; Thurston and Brugger, 1964; Fuck et al., 2009):

\[ c_{ijkl} = c^0_{ijkl} + \frac{\partial c_{ijkl}}{\partial \epsilon_{mn}} \Delta \epsilon_{mn} = c^0_{ijkl} + c_{ijklmn} \Delta \epsilon_{mn}. \]

where \( c^0_{ijkl} \) is the second-rank stiffness tensor of the background (unperturbed) medium, \( c_{ijklmn} \) is a sixth-order tensor containing the derivatives of the second-order stiffnesses with respect to strain, and \( \Delta \epsilon_{mn} \) is the excess strain. Despite the term “nonlinear,” which applies to Hooke’s law, equation 3 expresses the stiffnesses \( c_{ijkl} \) as linear functions of the strain \( \Delta \epsilon_{mn} \).

Wave propagation through the stressed medium may then be modeled using Hooke’s law with the stiffness tensor \( c_{ijkl} \). For our 2D models, we need only two stiffnesses from the sixth-order tensor, and employ empirical values of \( c_{ijklmn} = C_{oij} \) measured by Sarkar et al. (2003) (the matrix \( C_{oij} \) is obtained by the Voigt convention (Tsvankin, 2005; Fuck and Tsvankin, 2009)). Values of the stiffnesses \( C_{111} \) and \( C_{112} \) for different samples of Berea sandstone are displayed in Figure 4.

Fuck et al. (2011) estimate the P-wave time shifts \( \delta t \) along a certain raypath using a Fermat integral with the integrand linearized in the excess strains:

\[ \delta t = \frac{1}{2} \int_{t_1}^{t_2} \left[ B_1 \Delta \epsilon_{kk} + B_2 \left( n^T \Delta \epsilon \ n \right) \right] d\tau, \]

where \( \epsilon_{kk} \) is the volumetric strain (1/3 of the trace of strain tensor), \( \epsilon \) is the deviatoric strain, \( n \) is the slowness vector, and

\[ B_1 = \frac{C_{111} + 2C_{112}}{3C_{33}}, \quad B_2 = \frac{C_{111} - C_{112}}{C_{33}}. \]

Here, \( C^0_{33} \) is the background stiffness coefficient, and \( C_{111} \) and \( C_{112} \) are the “third-order” stiffness coefficients from equation 3. Equation 4 is valid only for small stiffness perturbations. Clearly, the time shifts described by equation 4 are linear in excess strains and the pressure drop inside the reservoir. In general, however, time shifts are nonlinear in the stiffness coefficients. Indeed, even the P-wave velocity in homogeneous, isotropic media is given by \( \sqrt{C_{33} / \rho} \), and traveltime over distance \( R \) is

\[ t = R \sqrt{\frac{\rho}{C_{33}}}. \]

Therefore, the issue is the range of \( \Delta \epsilon_{mn} \) and \( \Delta C_{ij} \) for which traveltime shifts can be accurately described as linear functions of \( C_{ij} \)'s and therefore, reservoir pressure reduction.
Time-shift trends vs reflector location

Smith and Tsvankin (2011b) employ an elastic finite-difference algorithm to compute time shifts of P-, S-, and PS- reflections for the model in Figure 1. Figure 5 shows typical time shifts for a reservoir at 1.5 km depth with a pressure drop of 20%. For P-waves (Figure 5a) the results are close to those obtained by ray tracing (Fuck et al., 2009). Strain-induced P-wave velocity anisotropy around the reservoir causes offset-dependent traveltime shifts. Laterally varying P-wave time-shift patterns below the reservoir are due to elevated shearing (deviatoric) strains at the reservoir endcaps.

Spatial distributions of time shifts show that specific wave types/reflector combinations exhibit different sensitivities to reservoir pressure changes. P-waves both above and below the reservoir exhibit distinct time-shift variations with offset due to changing deviatoric stress around the reservoir (Figure 5a). The combination of increased volumetric and deviatoric strains inside the reservoir generates large S- and PS-wave time shifts from reflectors beneath it (Figures 5b,c). These...
trends provide useful guidance for designing a pressure-inversion procedure. For this study, the reflectors shown in Figure 2 are used to measure time shifts of P-, S- and PS-waves for a range of pressure drops and evaluate the linearity of the pressure dependence of time shifts.

**Dependence of time shifts on reservoir depressurization**

The character of the variation of time shifts from specific reflectors with pressure can determine the methodology used to invert for reservoir pressure changes. If time shifts change linearly with pressure, they can be represented by a system of linear equations for a multi-compartment reservoir:

\[ A \Delta P = \Delta t, \]

where \( \Delta P \) is a vector containing pressure drops in all reservoir compartments, and \( \Delta t \) is a vector of P-, S-, and/or PS-wave time shifts for a range of receiver offsets. Elements of matrix \( A \) are the pressure-dependent time-shift gradients \( (dt_i(x, z)/dP_j) \) (i denotes offset and j reservoir compartment) of reflections for specific source-receiver pairs. Therefore, for small perturbations in \( C_{ij} \), the coefficients of \( A \) can be computed using standard linear inversion techniques (e.g., Gubbins, 2004) for a combination of reservoir geometry, source location, and reflector coordinates.

**Methodology**

**Modeling and assumptions**

We employ the modeling methodology described by Smith and Tsvankin (2011b) to investigate the behavior of time shifts for the reflectors shown in Figure 2. The initial reservoir pressure corresponds to a state of stress/strain equilibrium. Thus, the initially homogeneous stiffness/velocity field across the section becomes heterogeneous as reservoir pressure is reduced. Following geomechanical finite-element modeling of pressure-induced strain \( (\Delta \epsilon_{mn}(x, z)) \), changes in the stiffnesses are computed from equation 3. These stiffnesses are used by an elastic finite-difference code (Sava et al., 2010) to generate shot records.

Reflectors A, B, and C shown in Figure 2 are inserted in the model to sample travel times and estimate time shifts for each shot. Then, the multicomponent synthetic data are processed to isolate arrivals from the specific reflector, and time shifts between the reference (baseline) and monitor reservoir models are computed by cross-correlation. P-wave time shifts are measured from the vertical displacement, while S- and PS-shifts are measured on the horizontal component. Additional smoothing is applied to reduce interference-related distortions. For all models discussed below, the reservoir

**Figure 5.** Typical time-shift surfaces for (a) P-waves, (b) S-waves, and (c) PS-waves, measured using 22 reflectors around the reservoir (white box) of Figure 1 (Smith and Tsvankin, 2011b). The time shifts correspond to hypothetical specular reflection points at each \( (X,Z) \) location in the subsurface. Positive shifts indicate lags where monitor survey reflections arrive later than the baseline events; negative shifts are leads. Source location is indicated by the white asterisk at top.
depth is 1.5 km, and the source is located above the center of the reservoir at X=0 km.

Measurements and misfits

In the tests below, we individually vary reservoir pressure, stiffness coefficients $C_{111}$ and $C_{112}$, and reservoir width. A pressure drop of at least 30% is typical for most reservoirs, while the coefficients of $C_{111}$ and $C_{112}$ are measured with significant uncertainty (Figure 4) (Sarkar et al., 2003). Reservoir depth is usually well known, but the reservoir width may be estimated with an error. Shear (deviatoric) strains concentrate at the endcaps of the reservoir model (Smith and Tsvankin, 2011b), and changes in width will move the location of these anomalies and change the ratio of volumetric-to-deviatoric strain across the reservoir.

Misfits for P-, S-, and PS-waves time shifts between a given reservoir and a reference reservoir model are computed as the L2-norm,

$$\mu = \sqrt{\sum_{k=1}^{N} (\Delta t_{\text{ref}} - \Delta t_{k})^2},$$

where $k = 1, 2, ..., N$ are the individual traces in the shot record. When computing the time-shift misfit between a modeled (test) reservoir and the reference reservoir, both reservoirs have been depressurized from a zero-stress/strain initial state. Joint misfit is the sum of the L2-norms for all wave types at a specific reflector. Misfits shown below have not been normalized in order to facilitate comparison of results for different wave types at specific reflectors.

ANALYSIS

Time shifts and sensitivity to reservoir pressure

Figure 6 shows measured time shifts of P-, S-, and PS-waves (columns) reflected from interfaces A, B, and C (rows) of Figure 2 for a set of 20 reservoir pressure drops ranging between 0.01% and 30% of the initial reservoir fluid pressure. Positive shifts indicate lags where monitor survey reflections arrive later than baseline survey reflections, while negative shifts are leads. Data for S- and PS-waves do not include time-shift estimates at X=0 due to the low amplitudes of the horizontal displacement at small offsets.

In general, P-wave time shifts at reflector A (top row) are linear lags in pressure drop, caused by a P-wave velocity reduction above the reservoir. S-waves at reflector A experience small velocity increases and time shift leads due to changes in the stiffness $C_{55}$ in the overburden. PS-wave shifts above the reservoir are close to zero, because P-lags are almost canceled by S-leads (Smith and Tsvankin, 2011b). At reflector B (middle row) all time shifts exhibit slightly nonlinear behavior with increasing pressure drop. Time shifts for all wave types from reflector C are clearly nonlinear as a function of pressure because of large stiffness perturbations inside the reservoir. Therefore, we can invert for time shifts at reflectors above the reservoir using the linear system of equation 7. While reflections from beneath the reservoir may be approximated as linear for small pressure drops, they become nonlinear after 10-20% pressure reduction, which necessitates application of a nonlinear inversion algorithm.

As a second aspect of our 4D inversion feasibility study, we evaluate the sensitivity of “compound” time shifts for a certain mode and a given reflector to a range of reservoir depressurizations. For this discussion, the term “higher sensitivity” indicates a combination of high time-shift values with respect to reservoir pressure variation, and a steeply-sloped misfit curve with a distinct minimum misfit at the reference (true) pressure value (Figure 7c, for example). L2-norm time-shift misfits (equation 8) for 20 pressure drops between 0.01% and 30% were computed against a reference reservoir in Figure 1, which has a pressure drop of 15%. The results for P-, S-, and joint misfits (equation 8) at reflectors A, B, and C (Figure 2) are shown in Figure 7. Misfit curves correlate well with the time-shift magnitudes for each wave type and reflector depth in Figures 2 and 5. At reflector A, PS-wave time shifts at larger offsets provide greater sensitivity to lower pressure drops than time shifts of P- and S-waves. At the top of the reservoir (reflector B), P-wave time shifts change most rapidly with pressure deviation from the reference value. S-wave shifts clearly provide the largest sensitivity for all pressure drops beneath the reservoir at reflector C. However, in all cases, the joint misfit is more sensitive to pressure than the misfit for any single wave type.

Influence of the coefficients $C_{111}$ and $C_{112}$

The third-order stiffnesses $C_{111}$ and $C_{112}$ control the magnitude of the second-rank stiffness tensor $c_{ijkl}$ computed from excess strain (equation 3). Due to large variations of $C_{111}$ and $C_{112}$ over small stress/pressure ranges (Sarkar et al., 2003; Bathija et al., 2009), scarcity of available data, and because they are part of a linearized equation, these coefficients may represent a source of significant error in time shifts. Equation 5 shows that the value of $C_{112}$ controls the relative contributions of the volumetric and deviatoric strains to time shifts in equation 4.

Variations of both $C_{111}$ and $C_{112}$ produce smaller time-shift magnitudes above the reservoir at reflector A than those for pressure variations (having a maximum of approximately 4 ms). The largest time shifts due to both coefficients occur at reflector C, ranging up to -20 ms for P-waves, -30 to -40 ms for S-waves, and -20 to -30 ms for PS-waves. Misfit sensitivity curves for variations in both coefficients are shown in Figure 8. With the exception
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Figure 6. Time shifts for reservoirs with pressure drops ranging from 0.01% and 30%. The source is located above the center of the reservoir at $X=0$. (a,b,c) reflector A, (d,e,f) reflector B, and (g,h,i) reflector C. Columns correspond to (a,d,g) P-wave, (b,e,h) S-wave, and (c,f,i) PS-wave. Plot legends indicate receiver (surface) coordinate between $X=0$ km and $X=2.0$ km.

Figure 7. L2-norm misfits of time shifts for reservoir pressure drops ranging from 0% to 30%. The reference reservoir is maintained at a pressure drop of 15%. (a) reflector A, (b) reflector B, and (c) reflector C.

Influence of reservoir width

While reservoir depth is typically well known from borehole data, the true width of the reservoir may be estimated with an error. Shear (deviatoric) stresses are largest at the endcaps of the reservoir, even for reser-
Figure 8. L2-norm misfits of time shifts as functions of the third-order stiffnesses $C_{111}$ (top row), and $C_{112}$ (bottom row) (see Figure 4). Reservoir pressure drop is 15%. (a,d) Reflector A, (b,e) reflector B, (c,f) reflector C. Both stiffnesses vary by ± two standard deviations around their mean values.

Sensitivity to noise in time shifts

The influence of Gaussian noise with standard deviations of 2, 5, and 10 ms added to the reference time shifts (Figures 6 and 7) is shown in Figure 11. Time-shift misfits for 2-ms noise (left column) do not differ significantly from the corresponding noise-free estimates in Figure 7. Substantial degradation in sensitivity is observed for reflectors A and B (above reservoir) for 5-ms noise (Figures 11b,e). The misfit curves develop local minima, indicating that a linear inversion algorithm may fail at moderate noise levels. For strong noise reaching 10 ms (approximately 2/3 of the maximum P-wave time shifts for noise-free data), the misfit curves for reflectors A and B are significantly distorted. However, time shifts of all wave types for reflector C are sufficiently large to provide smooth sensitivity curves with a clear global minimum and minimal degradation. In general, as noise levels increase, the sensitivity of individual wave types/reflectors to pressure reduction declines, but joint sensitivity at reflectors B and C remains reasonably high. These results suggest that in the presence of substantial noise, joint and S-wave time shifts for reflectors below the reservoir provide the most reliable input data for pressure inversion.

Conclusions

We have used a simple, 2D rectangular reservoir model to study the dependence of P-, S- and PS-wave time shifts on reservoir pressure with the goal of assessing the feasibility of pressure estimation. The model is comprised of a single homogeneous block of Berea sand-voirs of elliptical shape (Smith and Tsvankin, 2011b). The distance between these shear-strain anomalies will vary with reservoir width, thus changing the strain field near and around the reservoir.

Figure 9 shows estimated time shifts of P-, S- and PS-waves (columns) at reflectors A, B, and C of Figure 2 (rows) for reservoir width ranging from 0.5 km to 4 km, in 0.5 km intervals. The reference reservoir width for misfit measurements is 2 km. Time shifts above reflector A do not vary significantly with reservoir width, except when shearing strains from the reservoir endcaps are close to one another. However, directly above the reservoir at reflector B, P-waves time shifts change by up to 10 ms. At reflector C, maximum time shifts occur for larger widths, and are similar to those of the reservoir with $\Delta P = 20\%$ shown in Figure 5. L2-norm sensitivity curves for P-, S-, and PS-wave data shown in Figure 10 are reasonably smooth, with the exception of S-wave misfit on reflector B for a reservoir width of 3 km. Joint misfit data from reflector C are most sensitive to variations in reservoir width.
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Figure 9. Time shifts for reservoirs with widths ranging from 0.5 km to 4 km. Pressure drops for all reservoirs are 15%. (a,b,c) reflector A, (d,e,f) reflector B, and (g,h,i) reflector C. (a,d,g) P-wave, (b,e,h) S-wave, and (c,f,i) PS-wave. Plot legends indicate receiver (surface) coordinate between X=0 km and X=2.0 km.

Figure 10. L2-norm misfits of time-shift data for reservoir widths ranging from 0.5 km to 4 km computed with respect to a 2 km-wide reference reservoir (Figure 1). The pressure drop for all reservoirs is 15%. (a) Reflector A, (b) reflector B, and (c) reflector C (see Figure 2).

stone, where pore pressure changes inside the designated reservoir block induce heterogeneous stress/strain and stiffness fields throughout the medium. Geomechanical modeling is implemented with a finite-element solver that generates excess stress and strain as a linear function of reservoir pressure. Multicomponent seismic data are modeled by an elastic finite-difference code, and resulting time shifts are computed by specialized post-processing. While the stress-induced stiffness tensor is
Figure 11. L2-norm misfits for noise-contaminated reference time shifts as a function of reservoir pressure drop (compare with corresponding noise-free misfits in Figure 7). Reference reservoir pressure drop is 15%. (a,b,c) reflector A, (d,e,f) reflector B, and (g,h,i) reflector C. Standard deviation of noise in time shifts increases by column: (a,d,g) ±2 ms, (b,e,h) ±5 ms, and (c,f,i) ±10 ms.

linear in excess strain, traveltime shifts generally depend on the stiffness coefficients in a nonlinear fashion.

In the regions with relatively small strain, pressure-related perturbations in the stiffnesses are not sufficiently large to cause nonlinearity of time shifts. For example, time shifts are linear in pressure reduction for reflector A above the reservoir. However, strains inside the reservoir are much larger than those in the surrounding medium, creating large stiffness changes. Thus, waves reflected from points at and below the reservoir exhibit nonlinear time-shift dependence on pressure.

L2-norm misfits of time shifts computed with respect to a reference reservoir show that S-wave time shifts from reflectors located beneath the reservoir are generally most sensitive to pressure. Misfit curves for S-wave shifts from deep reflectors provide robust indicators of pressure change even for reference time shifts contaminated with 10-ms noise. Therefore, inversions for reservoir pressure with noisy data need to operate with reflections from beneath the reservoir. Variations of the third-order stiffness coefficients (C_{111} and C_{112}) and reservoir width perturb the stress/strain fields around the reservoir, but do not cause distortions that could seriously impede pressure inversion.

Based on our findings, for cases of small pressure changes, a linear inversion method could be sufficient for pressure estimation. However, nonlinear time shifts at pressure drops above 10% should be inverted by a global algorithm.

Ongoing work using the modeling methods discussed here includes the investigation of multicompart- ment reservoirs with interacting stress and strain fields. To estimate reservoir pressure, we are devising a nonlinear global/gradient-hybrid inversion based on the nearest-neighbor algorithm of Sambridge (1999). After testing on the simple reservoir model discussed here, this algorithm will be extended to multicompartment reservoirs.
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