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Inverting for Pressure Using Time-Lapse Time-Strain – Application to a Compacting GOM Reservoir

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SUMMARY

Quantitative estimation of dynamic reservoir properties from time-lapse seismic is becoming increasingly widespread. In compacting reservoirs however, the 4D seismic signal is complex due to stress and strain redistribution in reservoir and non-reservoir rocks. Several authors have reported observing measurable time-shifts in the overburden on time-lapse seismic data. A method for using these overburden time-lapse time-shifts to invert for reservoir pressure change is presented. This method requires minimal constraints and is computationally fast, when compared with more complex geomechanical modelling. Results are shown after the application of the technique to the Genesis Field in the Gulf of Mexico.

Introduction

The quantitative use of 4D seismic for dynamic reservoir management is becoming increasingly widespread. In particular, multi-attribute 4D seismic inversion for pressure and saturation has proven successful for certain classes of reservoir (Floricich et al., 2006). However, in compacting reservoirs the reservoir level attributes are complicated by stress and strain changes in both reservoir and non-reservoir rocks. Indeed, there are increasing numbers of published examples where significant 4D time-shifts have been observed in the overburden above producing reservoirs (Hatchell and Bourne, 2005, Rickett et al., 2006). Seismic travel-times in the overburden differ because the overburden stress and strain fields change in response to reservoir compaction, which in turn changes the seismic velocity. Whilst these non-reservoir 4D seismic changes make interpretation of the seismic response difficult, they could also be used to provide information on the pressure changes in the reservoir, hence complementing well measurements or other 4D seismic-based approaches. Following this idea, several authors have presented methods to invert surface deformation measurements for reservoir volume or pressure change (Vasco et al., 2000, Du and Olson, 2001). Here, we present work that extends this approach further by focusing on the inversion of 3D strain deformation estimates for the overburden derived directly from the 4D seismic.

Method

A perturbation formula relating changes in vertical travel time t, velocity v, and vertical layer thickness z, assuming small changes in thickness and velocity, was given by Landrø and Stammeijer (2004);

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

Hatchell and Bourne (2005) went on to make the assumption that changes in thickness and velocity can be linearly related by a constant of proportionality, R, which relates the fractional change in velocity and vertical strain so that $\Delta v/v = -R\varepsilon_{zz}$, resulting in the following relationship

$$\Delta t/t = -(1+R)\varepsilon_{zz} \qquad (2)$$

where we have replaced $\Delta z/z$ by ε_{zz}, signifying the vertical component of the strain tensor. The left-hand side of Eq. (2) is the derivative of the time-shift field, which we term time-strain. A fast method of obtaining time-strains from 4D seismic data is described by Rickett et al. (2006). For a complete analysis of the vertical and lateral strain deformation from 4D seismic, 3D warping as described by Hall (2005) could be used. If we have knowledge of the magnitude of R we can obtain estimates of vertical strain directly from 4D seismic observations.

With estimates of vertical strain for the overburden we present a linearised inversion for pressure using the 4D seismic vertical strain observations. Segall (1992) shows that the displacement in a poroelastic medium can be given by the distribution of centers of dilatation with a magnitude proportional to $\alpha\Delta p(x,t)$. The i th component of displacement tensor u_i at an observation point x in the subsurface is given by

$$u_i(x,t) = \frac{\alpha}{\mu}\int_v \Delta p(\zeta,t) g_i(x,\zeta) dV_\xi \qquad (3)$$

where α is Biot's coefficient, μ the shear modulus, Δp is the change in pore pressure, $\zeta = (\zeta_1,\zeta_2,\zeta_3)$ are the integration coordinates over the volume V, and $g_i(x,\zeta)$ is the Green's function (Figure 1). We consider the pressure at two discrete times so that the time t in Eq. (3) is irrelevant. Using Eq. (3) we can calculate the displacement due to the pressure change in the whole reservoir by using a superposition of N elements of volume V_k, which undergo a constant pressure change p_k. The strain is found by differentiating the displacement Green's function.

$$\frac{\partial u_i}{\partial x_j} = \frac{\alpha}{\mu} \sum_{k=1}^{N} \Delta p_k \int_{V_k} \frac{\partial g_i(x,\zeta)}{\partial x_j} dV_k \tag{4}$$

The Green's function in Eq. (4) could be calculated in various ways. There is a trade-off between the advantages of simple solutions, such as the simplified nucleus of strain method for an elastic whole-space (Fjær et al., 1992) or the semi-analytical solution for a disk shaped reservoir Geertsma (1973), which are easy to implement, computationally fast and require less parameterization, and the complexity of more sophisticated techniques which require a greater number of parameters and are computationally expensive. Here, we use the solution for a point source in elastic whole-space with bulk compressibility C_b is given by

$$g_i(x,\zeta) = \frac{C_b}{4\pi} \frac{(x_i - \zeta_i)}{S^3} \tag{5}$$

where S = $[(x_1 - \zeta_1)^2 + (x_2 - \zeta_2)^2 + (x_3 - \zeta_3)^2]^{1/2}$ (Fjær et al., et al., 1992), which is found to be adequate for our current work. In practice we can write Eq. (4) as a linear system of equations. First the Green's function integral, derived with respect to x_3 to give the vertical component of strain, is pre-computed to form a matrix of coefficients **G**, which describes the strain at a given subsurface observation point due to a unit pressure change in a volume of reservoir V centered at ζ. This gives a linear matrix equation of the form

$$\varepsilon_{zz,M} = \sum_{n=1}^{N} \Delta p_n G_{n.M} = \Delta \mathbf{pG} \tag{6}$$

where $\varepsilon_{zz,M}$ is the M_{th} observation given by Eq. (2), and $\Delta\mathbf{p}$ are our unknown pressure changes.

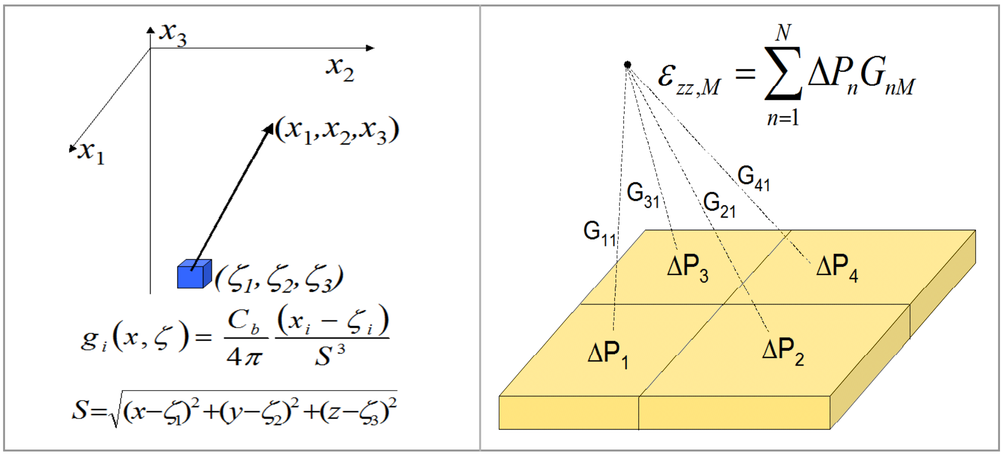

Figure 1 (a) Geometry for equations (4-6), also showing the Green's function for a point source in an elastic whole-space (b) The strain at a given observation point is given by the linear sum of contributions from *N* cuboids which describe the entire reservoir.

Application to the Genesis field

The inversion method is applied to data from the Genesis field in the Gulf of Mexico. Hudson et al. (2006) give a comprehensive overview of the 4D project at Genesis. The field consists of turbidite reservoirs lying between 3000m and 5000m. We concentrate on the three main producing intervals, the N1, N2 and N3L sands, which have average thicknesses of 21m, 14m and 20m respectively. These are unconsolidated Lower Pleistocene aged sands with initially high porosities of between 23 and 32% and high permeability of between 600 and 900mD. The field has been depleted significantly and sands have undergone substantial compaction since first oil in 1999; furthermore, several wells have been lost due to compaction related shear failure. The monitor survey was acquired in 2001, three years after first oil, with the same orientation as the baseline. The two surveys were carefully coprocessed and cross-equalized to maximize repeatability (Magesan et al., 2005). Large time-shifts are observed in the data in both reservoir and non-reservoir zones. These time-shifts were converted to time-strains, as described by Rickett et al. (2006), and the time-strains then depth converted using a velocity model, ready for input into the inversion.

Synthetic modelling has shown that the inversion is stable where the reservoir is confined to a single layer. A problem arises when attempting to resolve closely spaced vertical layers; there may be a trade-off between pressure changes in layers at different depths. In this example we make a single composite layer representing the three sand units, as the average vertical extent of the sands (including inter-sand shale) is not more than 80m. The composite layer is split into a regular grid composed of 114×46 cuboids of dimension 100×100×T metres, where T is the combined thickness of the three sands at any given location. For noisy data, using as many observations as possible helps to ensure the robustness of the inversion solution. When choosing the number of data points we are limited only by the sampling interval of the time-strain volume (in *x, y, z*) and by the computational power needed to solve the large matrix equation Eq. (6). We use data from 9 depth-slices in the overburden separated by 100m vertically on a grid 300×300 m (approximately 7000 data points). Eq. (6) is solved using a least squares objective function with a smoothing constraint (using a Laplacian finite difference operator) and constraining all areas with $NTG = 0$ to have zero pressure change.

We compare the inverted pressure depletion with a map determined using reservoir simulator predictions (Figure 2). To produce the composite pressure change map for the N1, N2 and N3 intervals from the simulator, we weight the pressure from each interval by thickness and porosity, so that the reservoir simulation pressure is given by

$$\Delta P_{comp} = \sum_{n=1}^{N} \Delta p_n T_n \phi_n \bigg/ \left\langle \sum_{n=1}^{N} T_n \phi_n \right\rangle \tag{7}$$

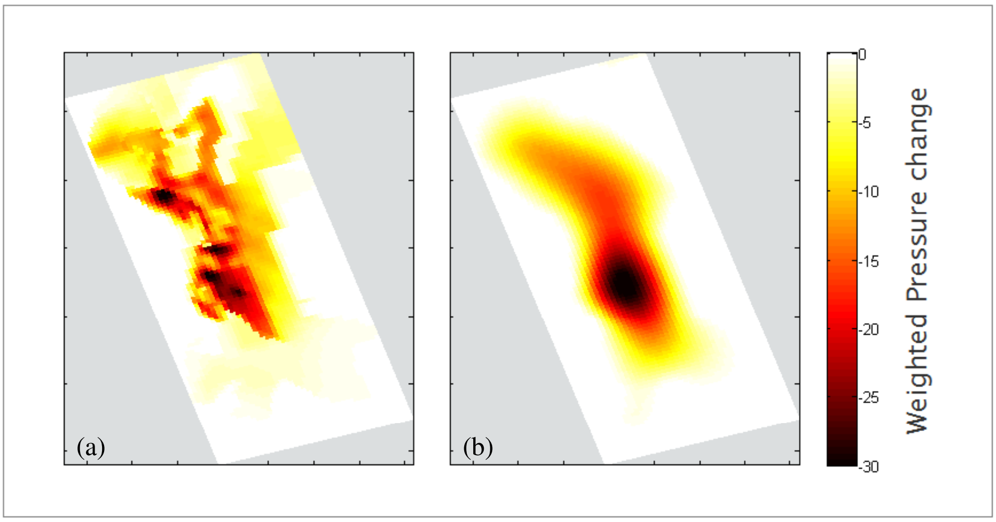

Figure 2 (a) map of composite pressure map made from the N1, N2 and N3 intervals taken from reservoir simulator predictions as given by Eq. (7). (b) pressure change inverted from 4D derived time-lapse time strain.

The agreement between the two maps is favourable. The inversion correctly recovers the long wavelength features of the pressure distribution, most noticeably the main area of depletion in the central area. As expected, the inverted pressure is considerably smoother than the composite simulation prediction. This is partly due to our smoothness constraint but it may also be related to the ultimate limit of resolution given the nature of the data that the time-lapse time-strain cubes provide.

Conclusions

A method for using time-lapse overburden time-shift measurements to invert for reservoir pressure change is presented based on linear elastic theory. This method requires minimal *a priori* information and is computationally fast and straightforward to implement when compared with more complex numerical modelling. Results are presented after the method has been applied to the Genesis field in the Gulf of Mexico. Because of the difficulties of inverting closely spaced vertical layers we invert for a single composite layer. The problem of vertical resolution is one that is consistent for most problems related with turbidites. Further work is envisaged to address this issue, such as including more information in the inversion such as amplitude data from the reservoir interval and well-based constraints as suggested by Corzo and MacBeth (2006). This may also help improve the lateral resolution of the solution. Surface deformation data may also help to constrain the inversion, especially the other components of the strain tensor that are produced as a product of 3D warping.

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