A grid-search approach for 4D pressure-saturation discrimination

Hung Nho Dinh, Mirko van der Baan
Department of Physics, University of Alberta

Summary

In reservoir management it is important to understand changes in reservoir parameters instead of seismic attributes. Recent 4D inversion methods for estimating pressure and saturation changes have challenges addressing true uncertainty since they are generally based on solving linearized approximations. A new simple grid-search-based inversion scheme is introduced to discriminate pore pressure and fluid saturation from time-lapse seismic attributes. Two examples show the promise of this novel method.

Introduction

In reservoir management, the final objective is to quantitatively observe reservoir parameter variations over time. Hard constraints are either obtained at a limited number of wells, or soft constraints are required from indirect observations such as time-lapse changes in reflection seismic data. Recent studies have introduced techniques to discriminate pore pressure and fluid saturation changes in the reservoir from time-lapse seismic data. There are three main challenges with current approaches. Firstly, most inversion schemes are based on the Hertz-Mindlin rock physics model to link pressure effects to seismic observations. This model involves complex calculations, heavy parameterizations and possibly unrealistic assumptions (Dinh et al., 2016). This complicates its implementation since results will strongly depend on appropriate parameterization. Secondly, current least-squares (Blanchard, 2011) or quadratic polynomial (Landrø, 2001) solutions involve a linearization step. Since the rock physics models are usually non-linear, this step transforms the inversion problem and introduces the possibility of systematic biases to obtained solutions. Lastly, the two most widely used input attributes, namely AVO response and time shifts, are interconnected since both depend on velocity changes. This violates the requirement that input parameters are ideally independent.

We avoid these challenges by using a different way to solve the inverse problem. First of all, we use a simpler rock physics model to solve the forward model which depends on fewer parameters. In particular we will use the pore-space-stiffness-based model (Mavko and Mukerji, 1995) for relating dry and saturated rock moduli to pore pressure and the random-patchy-saturated model (Müller and Gurevich, 2004) for computing corresponding P-wave velocities and attenuation. We then predict seismic parameters for a pre-defined range of solutions using these combined models. Finally we use independent time-lapse attributes as the input and use the grid-search method to find the global solution and its true uncertainties.

Rock physics model for seismic modelling

In order to perform a meaningful inversion, it is important to use appropriate rock physics models for solving the forward problem. The Gassmann equation predicts the effect of fluid saturation on velocities and densities well in many cases. The Hertz-Mindlin model is often used to describe pore-pressure effects but it depends on many parameters. In this paper, we use the Pore space stiffness model (PSS) to link pressure with the dry rock modulus. This model also has an intuitive relationship with the saturated rock modulus after introducing fluids into the pore space (Dinh et al., 2016a). The saturated rock modulus will serve as the input for the Random patchy saturation model (RPS) to get seismic velocities and attenuation (Figure 1). Here we consider fluids composed of two phases, ie. brine and gas, and compute the effective fluid modulus using the Reuss average. The two-phase modulus is governed by the Batzle-Wang relationship (BW) and depends on pressure.

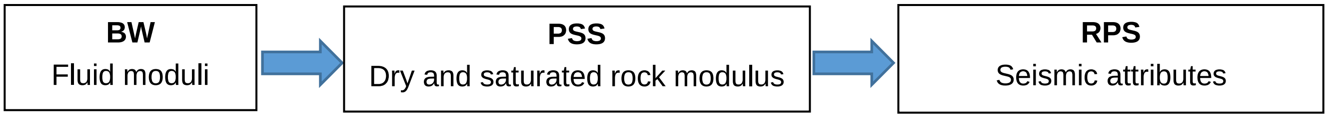

Figure 1: Rock physics template using the pore space stiffness concept and the random patchy saturation model

a) Pore space stiffness concept and its relation to the Gassmann equation

Pore space stiffness (modulus) describes the ability of the pore space to resist volumetric changes under external pressure (Mavko and Mukerji, 1995). The bulk moduli of pore space K_ϕ and rock matrix K_m determine the dry rock bulk modulus K_d given a porosity ϕ:

$$\frac{1}{K_d} = \frac{1}{K_m} + \frac{\phi}{K_\phi}. \qquad (1)$$

When fluid is substituted, the saturated pore space stiffness $\widehat{K_\phi}$ is related to the fluid modulus K_f as:

$$\widehat{K_\phi} = K_\phi + \frac{K_m K_f}{K_m - K_f}, \qquad (2)$$

and yields the saturated bulk rock modulus K_s:

$$\frac{1}{K_s} = \frac{1}{K_m} + \frac{\phi}{\widehat{K_\phi}}, \qquad (3)$$

Equation 3 shows the intuitive link between the pore space stiffness concept and the fluid substitution theory as the Gassmann equation can be derived by substituting equations 1 and 2 into equation 3.

We use an empirical relationship between two dry rock moduli and linear effective pressure (Dinh et al., 2016a), yielding a simple way to obtain these moduli from pressure information:

$$\begin{cases} K_d = \dfrac{K_m}{1 + \dfrac{\phi}{A + 0.001 P_e}}. \\ \mu_d = B + 0.08 P_e \end{cases} \qquad (4)$$

where A and B are free intercepts and need to be calibrated for every case study.

b) Random Patchy Saturation model (Müller and Gurevich, 2004)

The random patchy saturation theory uses the complex P-wave modulus $\widetilde{H}$:

$$\widetilde{H} = H\left[1 + \frac{s}{1 + \frac{2i}{kd}}\right], \qquad (5)$$

where H is regular (real-valued) P-wave modulus, ie. $H = K_s + {}^4/_3\mu$, and variables s and k are functions of the bulk modulus of dry rock, matrix and fluid phase, porosity, permeability, viscosity and typical correlation lengths in parameter fluctuations. P-wave velocity Vp and quality factor Q then become

$$Vp = \sqrt{\frac{\Re(\widetilde{H})}{\rho}}, \qquad (6)$$

$$Q = \frac{\Re(\widetilde{H})}{\Im(\widetilde{H})}. \qquad (7)$$

where $\Re$ and $\Im$ represent real and imaginary parts, respectively.

c) Example of seismic properties

The combination of the pore space stiffness concept and the random patchy saturation model creates a new rock physics template that does not only predicts reasonable P-wave velocities (Dinh et al., 2016a) but also provides an estimate for seismic attenuation, which is an independent input parameter, thus stabilizing the inversion (Dinh et al., 2016b).

Methodology

We solve for the time-lapse inversion problem by first predicting a series of possible monitoring attributes by varying pore pressure and water saturation using a simple grid search (Figure 2, step 1). Possible monitoring attributes include attenuation, impedances, time shifts and AVO attributes. Possible time-lapse changes are calculated by subtracting predicted attributes from initial attributes for the base data assuming known initial reservoir conditions (step 2). We then find the differences between these predicted attributes and the actual measured time-lapse attributes given the monitoring data (step 3). After weighting them properly, we sum misfits (step 4) and minimize this cost function to display the global solution (step 5).

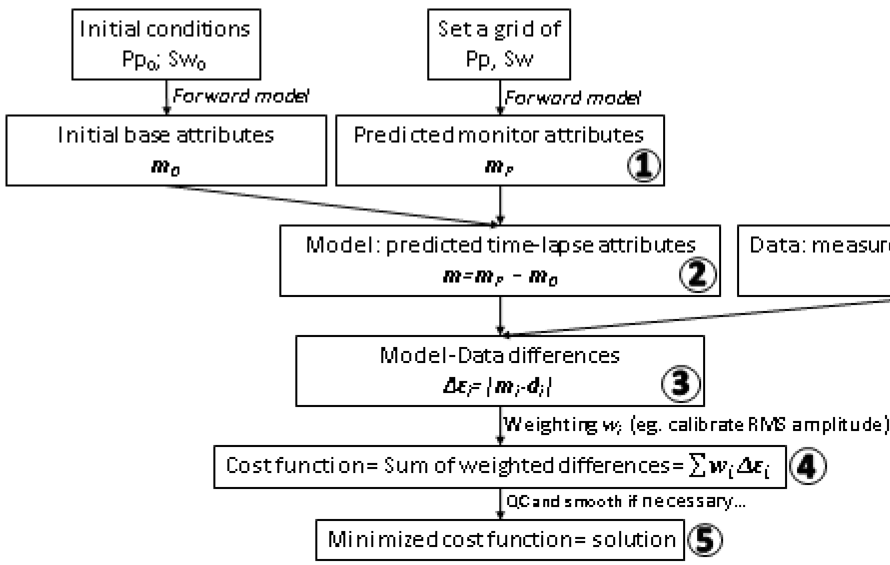

Figure 2: Inversion scheme

An example of pre-defined predicted monitor attributes is shown in Figure 3. The three attributes (density, P-wave velocity and attenuation) are largely independent. In step 4, weighting depends on the data confidence and/or uncertainty as well as the attribute ranges. In the simplest case, weighting coefficients can be the RMS amplitude scalars between predicted attributes to prevent that the absolute magnitude of a single attribute dominates the cost function. This inversion scheme allows for integrating many time-lapse attributes in a single step. This is useful to investigate sensitivity of individual attributes.

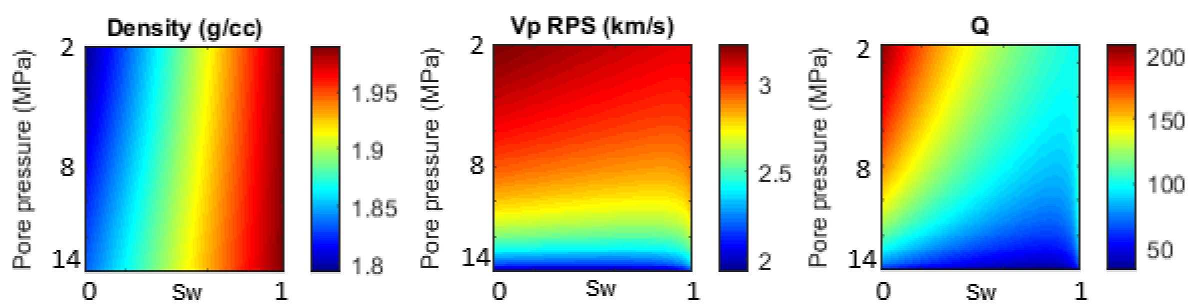

Figure 3: Example of predicted monitor attributes (step 1): density (left), p-wave velocity (middle) and Q factor (right)

Examples

a) Synthetic example

We first create a 3-horizontal-layers model. Changes occur in the middle layer only. Initial conditions are set as fully brine saturated and pore pressure = 10 MPa. We assume an increase of 2MPa for pore pressure and 20% for gas saturation to mimic a gas injection (blowout) instead of a depletion scenario. This leads to two sets of seismic parameters (Table 1). The top and the bottom layers have little attenuation compared with the middle one. The predicted seismic stacked trace is displayed in Figure 4a. We use two time-lapse attributes, namely time shifts measured at top of layer 3 and changes in effective attenuation measured in layer 2. Attenuation changes are estimated using a spectral ratio method as described in Dinh et al., 2015.

	Base (Vp, Vs: km/s, ρ: g/cc)				Monitor (Vp, Vs: km/s, ρ: g/cc)			
	Vp	Vs	ρ	Q	Vp	Vs	ρ	Q
Layer 1	2.6	1.2	2	100,000	2.6	1.2	2	100,000
Layer 2	2.85	1.88	1.99	123	1.94	1.53	1.83	51.5
Layer 3	2.6	1.2	2	100,000	2.6	1.2	2	100,000

Table 1: Synthetic data model

The grid-searched minimum in the cost function map (Figure 5b) is located at Pp=12 MPa and Sw=0.8. This corresponds to an increase of 2MPa and 20% in pore pressure and gas saturation, respectively. The uncertainties in fluid saturation and pore pressure are around ±10% and ±1 MPa, respectively.

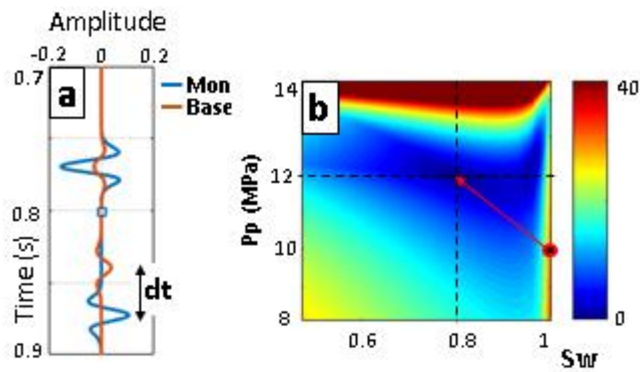

Figure 5: (a) Time shifts from synthetic traces (b) Cost function indicates optimal solution (red arrow)

b) Real-data example

We look at an internal underground blowout where gas has leaked into a shallow sand and caused time-lapse effects in the observed time-shifts and attenuation changes prior and after the blowout (Dinh et al., 2015, 2016b). Various measured 2D attributes are shown in Figure 6a. Assuming a hydrostatic pressure, we set initial conditions as a fully saturated brine saturated sand and a pore pressure of 5.1 MPa. At every CDP, we then perform a similar inversion as in the synthetic data.

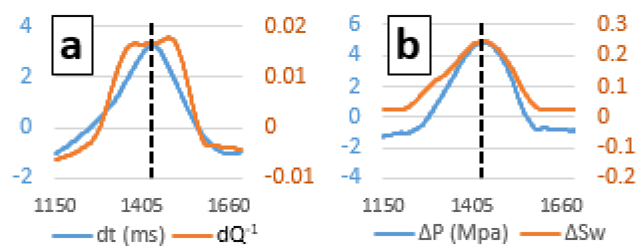

Figure 6: (a) Input data: time shifts and attenuation changes. (b) Inversion results: changes in gas saturation and pore pressure. Horizontal axis is CDP number, vertical dashed line is the blowout well location.

The results in Figure 6b show an increase of 25% gas saturation and 5 MPa pore pressure. Both inverted pressure and gas content peaks are located around the blowout well. This results match very well with the observed time-lapse anomalies (Figure 6a). Qualitatively, the inversion results show gas extend and its pressure effect in the area. They also indicate a pressure reduction zone of about -1 MPa beyond the gas front where no changes in gas saturation are observed.

Conclusions

We describe a new time-lapse inversion scheme to solve for changes in pore pressure and fluid saturation. The process is based on a grid search method in which we use a combination of pore space stiffness and random patchy saturation models to predict various time-lapse attributes within a predefined solution space. This inversion scheme is easy to implement, can integrate multiple time-lapse attributes and provide visible solutions to the problem, thus making it easy to investigate solution uncertainties.

Acknowledgements

The authors acknowledge CGG GeoSoftware for its donation of the HampsonRussell software products. We also thank NSERC and LOSEM sponsors for their financial supports.

References

Blanchard, T., 2011: Time-lapse seismic attenuation as a tool for monitoring hydrocarbons and CO2 in geological materials: PhD thesis, The University of Leeds.

Dinh, N. H., M. van der Baan, and M. Landrø, 2015: Time-lapse Processing Strategies for Detecting 4D Attenuation Changes and Shallow Gas Movement: 77th Annual International Conference and Exhibition, EAGE, Extended Abstracts,Th N101 08.

Dinh, N. H., M. van der Baan, and B. H. Russell, 2016a: Pore space stiffness approach for a pressure-dependent rock physics model: 86th Annual International Meeting, SEG, Expanded Abstracts, 3226–3230.

Dinh, N. H., M. van der Baan, and M. Landrø, 2016b: Processing and quality-control strategies for consistent time-lapse seismic attributes: A case history on an internal blowout using vintage data: Original submitted to Geophysics on August 2016, revised on December 2016.

Landrø. M., 2001: Discrimination between pressure and fluid saturation changes from time-lapse seismic data: 69th SEG International Exposition and Annual Meeting, Expanded Abstract, 1651–1654.

Mavko. G., and T. Mukerji, 1995: Seismic pore space compressibility and Gassmann's relation: Geophysics, 60, no. 6, 1743–1749.

Müller, M., and B. Gurevich, 2004: One-dimensional random patchy saturation model for velocity and attenuation in porous rocks, Geophysics, 69, no. 5, 1166–1172.