

Integration of seismic and fluid-flow data: a two-way road linked by rock physics

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Abstract

Geologic model building of the subsurface is a complicated and lengthy process. Seismic data are usually inverted at the beginning of this process and discarded after inversion and interpretation. Modifications from the seismic inversion results are almost never validated due to the one-way information flow towards reservoir properties. In this paper, we propose to include the production data and the inverted reservoir properties back in the seismic inversion during the next iteration of geologic model updates. The elastic properties and the fluid-flow properties are connected and cross-updated based on the underlying rock physics models. The statistical approach we propose in this paper not only provides a single Earth model that best satisfies both types of data, but also has the potential to properly quantify the uncertainty associated with this model. We show preliminary results from the proposed framework on a synthetic gas-pocket identification example.

Introduction

Traditionally, the practice of geological model building has been sequential from seismic imaging to lithological inversion, and eventually to reservoir properties and production. As more information is acquired with field development, the geological model will be modified and updated away from the initial seismic inversion results. Should we model the seismic data using the final geologic model, the chances of reproducing the field measurements are very low. The lack of cross validation is due to the lack of a channel that links the reservoir properties back to the seismic data (Li, 2014 and Gray, 2014).

In this paper, we formulate a statistical inversion framework that integrates seismic, rock physics and fluid-flow data. The goal is to resolve a reliable geological model whose elastic properties (seismic velocity, attenuation, and reflectivity) and fluid-flow properties (porosity, permeability, and saturation) are consistent with all available information and all principles in different disciplines. The proposed workflow (Figure 1) starts by generating rock physics models based on the regional geological information. These rock physics models are used to generate plausible lithological scenarios, with corresponding elastic and fluid-flow properties. Seismic data are investigated first to provide spatial distributions of the elastic properties. Possible lithological scenarios with these particular elastic properties are then tested against the fluid-flow data. Consequently, the resulting lithological scenarios and geologic models are consistent with both seismic and fluid-flow data. We demonstrate the preliminary results following the proposed workflow on a synthetic shallow gas pocket model.

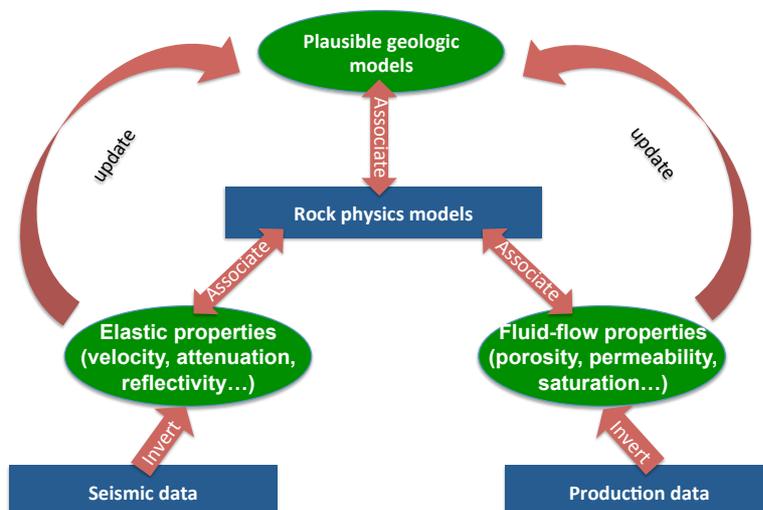


Figure 1 Flowchart for the integrated model building. Inversion results from the production data are introduced back to seismic inversion through the corresponding rock physics models.

Geologic and rock physics model

Shallow gas pockets widely exist in the subsurface. These geological features pose serious imaging challenges (e.g. Billette and Brandsberg-Dahl, 2005) and safety concerns while drilling. It is difficult to accurately identify the gas pockets from seismic data due to its attenuation effects on the seismic waves. Consequently, the accuracy of the elastic properties estimated from the seismic data is degraded, which further challenges the identification of the gas pockets.

Many rock physics models have been developed to model the dispersion and attenuation effects from the fluid properties (e.g. Muller et al., 2010). Based on the classic model (White 1975) of the mesoscopic dispersion and attenuation, we model the elastic properties (P-wave velocity, attenuation) of the unconsolidated sandstone when the fluid-flow properties (porosity, permeability, gas saturation) are uniformly sampled in given ranges. Figure 2 shows the modeling results. For an unconsolidated sandstone, elastic properties (given combinations of quality factor and P-wave velocity) are very sensitive to porosity, less sensitive to saturation, and least sensitive to permeability. Therefore, unique determination of a geologic model is hardly possible based on only seismic data, even if we could accurately resolve the elastic properties from it.

To illustrate our integrated model building workflow, we build a synthetic geologic model based on the shallow unconsolidated sand reservoir model (model III) in Wang et al., (2013). A shallow gas pocket with 70% gas saturation is located in the upper part of the second layer. Properties of the “true” geologic model are shown in Figure 3.

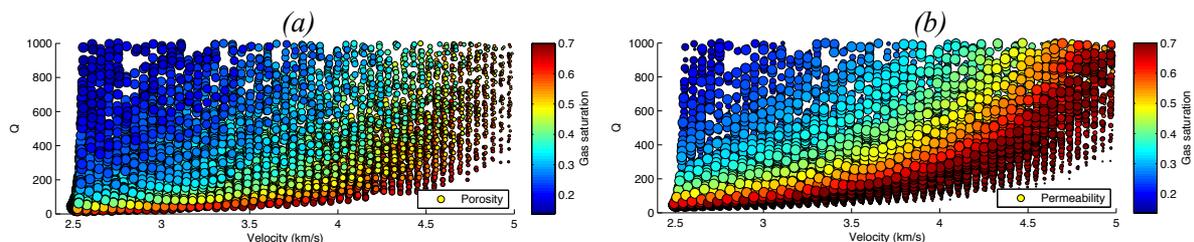


Figure 2 Elastic properties and fluid-flow properties modelled for the unconsolidated sand reservoir. Size of the bubble indicates porosity in (a) and permeability in (b). Both plots are color-coded by the gas saturation.

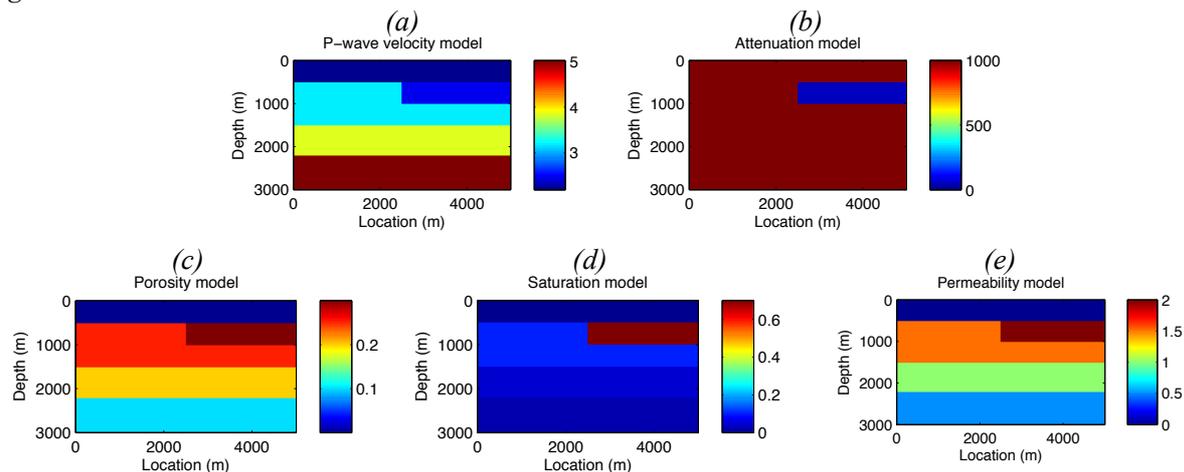


Figure 3 The “true” geologic model. Top row shows the elastic properties. Bottom row shows the fluid-flow properties.

Seismic data and the elastic properties

Seismic data are modeled based on visco-acoustic assumptions. Without the knowledge of the gas pocket, we obtain the seismic image in Figure 4(a) using a background velocity field in Figure 4(b). The image shows distorted and attenuated events below the gas pocket, due to the inaccuracy in the

elastic properties. These misplaced reflection events could lead to severe consequences during production.

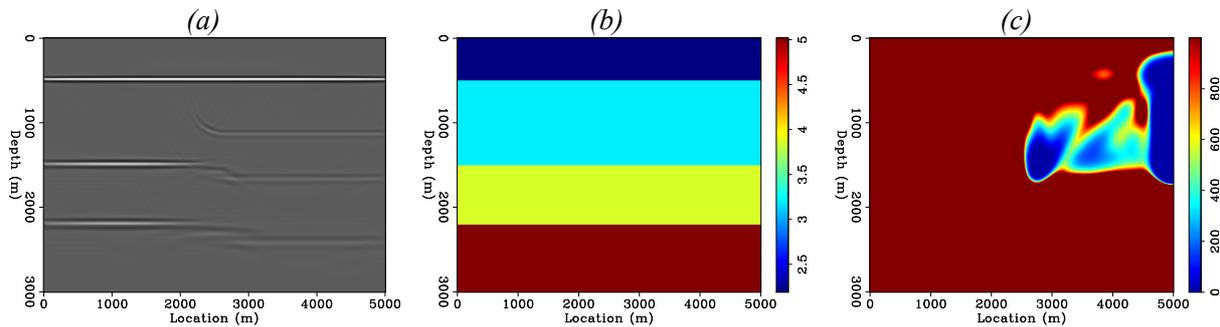


Figure 4 The Inverted elastic properties from the seismic data. In (a), reflectivity model; In (b), velocity model; In (c), Q model.

Based on the migration image in Figure 4(a), we invert for the attenuation model using wave-equation migration Q analysis (Shen et al., 2014), without updating the background velocity. The inverted Q model in Figure 4(c) highlights the area that possibly has high attenuation due to the high saturation of gas. However, the low amplitudes of the seismic events as well as an inaccurate velocity model limit the resolution of the Q model, especially in the vertical direction.

Given the inverted Q model and the seismic image, it is reasonable that we divide the study area into 8 different geologic blocks (Figure 5b). In each block, we estimate numerical distributions of the elastic properties from the seismic data.

Fluid-flow data and the reservoir model estimation

Since fluid-flow data are sensitive to gas saturation, porosity and permeability, we now utilize fluid-flow related data to better constrain the reservoir model. We generate fluid-flow response by studying a simple but realistic flow setting: a no-flow condition at the top and bottom boundaries of the domain, and fixed pressure values at the left and right boundaries with the higher pressure value on the left boundary. Therefore, mean flow direction is from left to right (Figure 5). We assume Darcy's law for the fluid flux with gas saturation-dependent relative permeability (C. S. Land, 1968). Imposing mass conservation at each grid block and assuming incompressible flow, leads to a linear system of equations, which is solved for the pressure values simultaneously at all the nodes. Once the fluxes are known, transport velocities can be obtained by dividing fluxes with porosity values and we simulate transport of a passive tracer by particle tracking (L. Moreno et al., 1988). For fluid-flow data set, we take four flux values and one breakthrough curve (first-passage time distribution) at the production well (Figure 5).

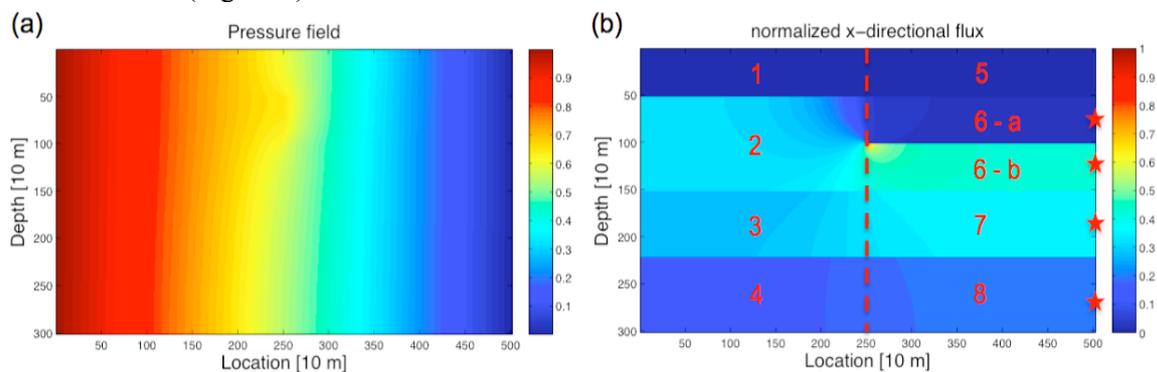


Figure 5 (a) Fluid pressure field obtained by solving mass conservation constraint with Darcy's law. (b) Normalized x -directional flux field. Four flux values marked at four different locations at the production well (marked with red stars) and a tracer breakthrough at the production well are taken as fluid flow data. The reservoir zonation is marked by numbers.

In reality, fluid-flow data alone is not enough to construct accurate geologic models for porosity, permeability and saturation. In this study, we utilize seismic interpretation and rock physics model to construct ensemble of plausible reservoir models. In addition to the reservoir zonation information (8 geologic blocks) that has been interpreted from the seismic image, the distributions of porosity, permeability and saturation values for each zone come from rock physics models that link elastic properties with fluid-flow properties (Figure 6). We further divide zone 6 into two zones so that accurate targeting of gas pocket location is possible by incorporating the fluid-flow data.

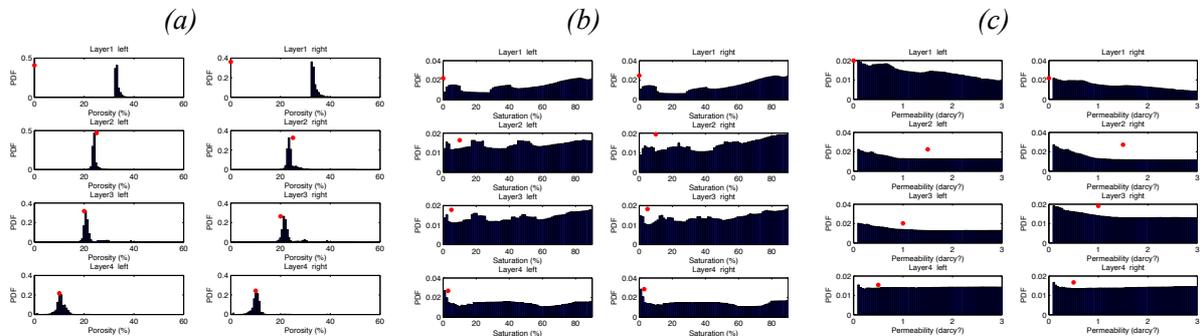


Figure 6 Numerical distributions (blue bars) in each geologic block for (a) porosity, (b) gas saturation, and (c) permeability. The red dot in each plot denotes the “real” fluid-flow properties in each block. These models are tested against the fluid-flow data.

To estimate most plausible reservoir model, we run Monte Carlo simulations on the ensemble of reservoir models and find a model that minimizes error with the actual flux and breakthrough curve measurements. The estimation from fluid-flow modelling successfully identified the location of gas pocket from the inverted saturation map (Figure 7a).

Joint evaluation and cross-updates

The updated fluid flow models provide the shape and location of the gas layer, which could confine the seismic updates (e.g. attenuation) within the indicated gas pocket. Therefore, we redistribute the updates in the attenuation model while preserving the seismic amplitude. The resulting updated Q model is shown in Figure 7(b). Evidently, we have improved the identification of the gas pocket by utilizing both seismic and fluid-transport data. In the next iteration of seismic inversion, these models will be used to update the velocity model and to produce a clearer seismic image.

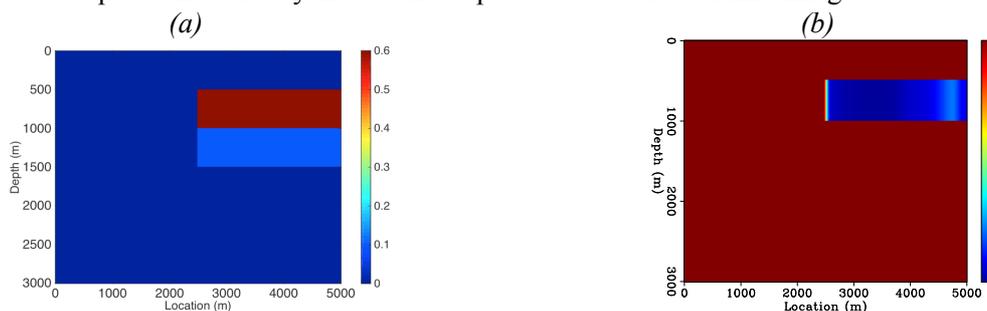


Figure 7 (a) Gas saturation map obtained from fluid flow modelling and estimation. (b) Updated Q model based on the fluid flow information in (a). Both models successfully reveal the exact location and the accurate properties of the gas pocket.

Conclusions and Discussions

We propose an integrated model building workflow that links seismic and production data with geologic and rock physics models. To perform the joint inversion, inversion of each dataset provides not only the most probable model but also a numerical distribution for each parameter. These models are jointly evaluated against the plausible geologic scenarios and rock physics models. The preliminary results in this paper show that the joint inversion can improve the identification of the gas pocket and the definition of the geologic model. Eventually, we hope to produce a consistent geologic

model whose elastic and fluid-flow properties satisfy the field data and whose uncertainty is properly quantified.

Acknowledgements

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