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Direct elastic FWI updating of rock physics properties

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Summary

Quantitative estimation of rock physics properties is of significant interest in reservoir characterization, and most current workflows in this field are based on amplitude variation with offset (AVO) techniques. To improve inversion results, we propose to directly estimate rock physics properties using elastic full-waveform inversion (FWI). We do this by incorporating the rock physics model, which builds a link between elastic and rock physics properties, directly into the FWI workflow by parameterizing the inversion procedure with rock physics parameters. We formulate the inversion with a model parameterization of porosity, clay content, and water saturation (P-C-S), and their link to elastic properties is formulated using each of the three rock physics models: the Han empirical model, the Voigt-Reuss-Hill (VRH) boundary model, and the Kuster and Toksöz (KT) inclusion model. Numerical examples illustrate that our method can outperform a sequential approach, which first inverts for elastic attributes and then determines rock physics properties from them.

Introduction

Current seismic techniques usually go beyond inverting for elastic attributes (e.g., velocity, density, and modulus) and try to infer rock physics properties of interest, such as lithology, porosity, and fluid information (Bosch et al., 2010). The estimation of rock physics properties can be achieved either in a sequential workflow, where seismic inversion for elastic attributes is followed by the rock physics inversion that transforms those elastic attributes to rock physics properties (Grana 2016), or in a joint workflow, where seismic data are directly inverted for rock physics properties (Buland et al., 2008). Whether deterministic or stochastic, seismic inversions in the two workflows are commonly performed using the amplitude variation with offset (AVO) techniques. However, AVO inversion suffers from inherent problems, in particular, it operates only with the amplitudes of reflection waves, and the migrated gathers are sensitive to errors in the velocity model (Kamath et al., 2017a). Full-waveform inversion (FWI), which employs waveforms and avoids migration-related amplitude errors, offers the likelihood of enhanced accuracy for estimating elastic and rock physics parameters.

Method

Three parameters are needed to describe the isotropic-elastic medium, and the simplest choice is the density and Lame constants, which appear in the wave equation. Many other parameterizations in terms of a combination of three elastic attributes can be viewed, and once the parameterization is selected, the parameter classes involved can be directly updated during the inversion. In this part, we consider parameters beyond elastic attributes, and illustrate how to formulate the inversion with a parameterization of rock physics properties.

In the frequency-domain multiparameter FWI, a new parameterization **q** can be calculated from the reference parameterization **p** using the chain rule. Here we consider **q** as a parameterization of rock physics properties. To calculate the partial derivatives of the impedance matrix with respect to **q** (with **p** still being an elastic parameterization) , we need to introduce a rock physics model that links the parameter classes in **q** with those in **p**. Three classic rock physics models are studied in the paper: the Han empirical model (Han, 1987), the Voigt-Reuss-Hill (VRH) boundary model (Hill, 1952), and the Kuster and Toksöz (KT) inclusion model (Kuster and Toksöz, 1974). We consider three rock physics properties that are widely used for reservoir characterization: porosity ϕ, clay content C, and water saturation S_{w}. We parameterize our inversion in terms of these variables, which we refer to as porosity, clay content, and water saturation (P-C-S) parameterization, in contrast to the P- and S-wave velocity and density (D-V) parameterization we use as our elastic benchmark.

Direct vs Indirect Inversion

We assume a rock type of gas-bearing shaly sand, where the solid phase is composed of quartz and clay, and the fluid phase composed of water and gas. Frequencies from 2 to 25 Hz are assumed to be available, and the source is considered to have a uniform amplitude spectrum over this range. We adopt a multiscale approach by proceeding iterations on five frequency bands, each contains three evenly spaced frequencies, beginning at 2 Hz and ending at a frequency that grows as iterations progress. We mimic an acquisition geometry of surface seismic + VSP (vertical seismic profile) by deploying a line of sources on the top and three lines of receivers on the top and lateral sides of the domain.

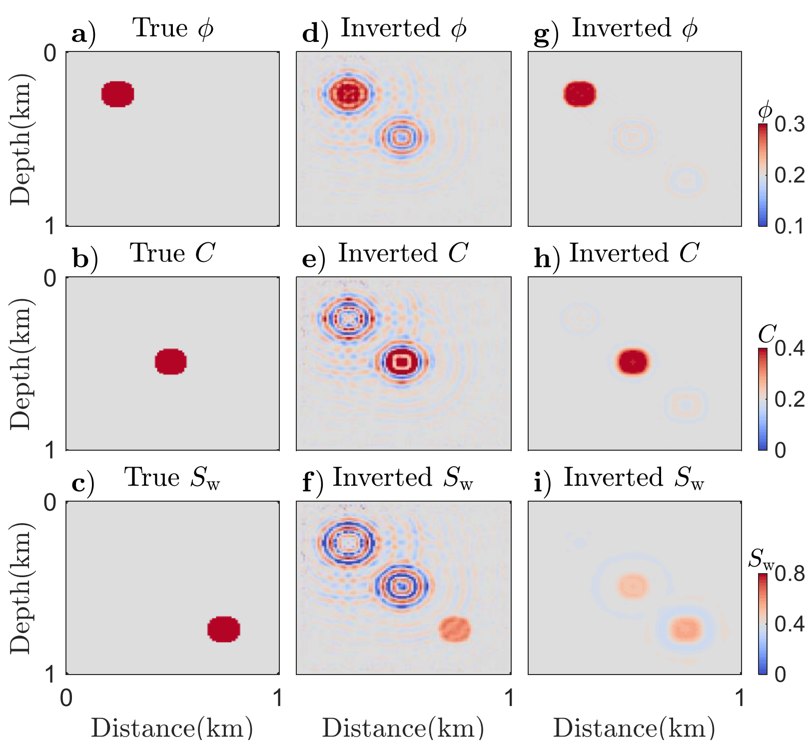

Figure 1. (a-c) True models of ϕ, C, and S_{w}.The corresponding inverted models in the (d-f) velocity-density parameterization and (g-i) rock physics parameterization.

When the Han's linear relations are assumed, we compare our method with the indirect approach, where velocity and density are estimated directly and then converted to rock physics properties. As shown in Figure 1d-1f, the converted rock physics properties are exposed to obvious parameter crosstalk. The estimate of water saturation is extremely contaminated and has nonphysical negative values. On the other hand, as a direct approach for updating rock physics properties, the P-C-S parameterization correctly recovers the porosity and clay content (Figure 1g-1i). Although crosstalk remains present in the recovered water saturation, it is of a lower degree than that in the indirect inversion.

Experiments with different rock physics relations

We test the P-C-S parameterized inversions, formulated with each of the Han, VRH, and KT models, on a plausible model that includes hydrocarbon units. As shown in the leftmost column of Figure 2, the gas sand, centered at a depth of 0.38 km and a position of 0.4 km, is distinguished by a higher porosity, a lower clay content, and a lower water saturation. The initial models are smoothed versions of the true models. The three rightmost columns show the recovered models when assuming different rock physics relations. We note that in each experiment, the rock physics properties can be resolved to some extent. With Han's relation, the results are especially satisfactory that almost all layers are recovered.

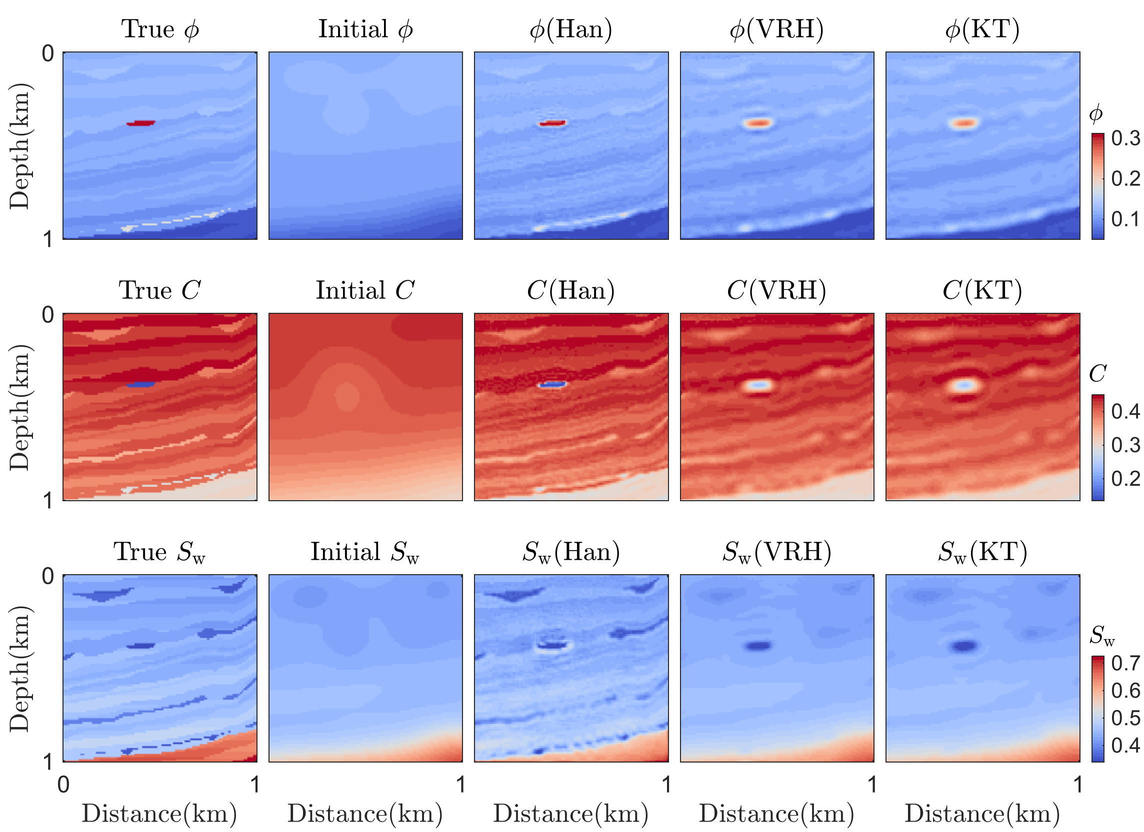

Figure 2. True, initial and inverted models of ϕ, C, and S_w.

Conclusions

We supplement FWI with the rock physics model to achieve a direct estimation of rock physics properties based on seismic data. Three rock physics relations are adopted individually to formulate the inversion with a parameterization of porosity, clay content, and water saturation (P-C-S). When we employ the Han model, our method is shown to be superior to the indirect inversion. We also find that the inverted porosity and clay content are highly compatible with the true models, whereas water saturation is prone to insufficient updating.

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