A downscaling strategy from FWI to microscale reservoir properties from high-resolution images

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Abstract

Extracting detailed earth information from an ensemble of seismic traces is a challenge facing full-waveform inversion. So far, success on synthetic and real data has been accomplished primarily for the twin purposes of complex structural imaging and geologic interpretation. An ongoing issue for the seismic-imaging community, in addition to building high-resolution images, is the reliable extraction of acoustic and shear velocities, anisotropic parameters, quality factors, and density. Such extractions, performed at the seismic resolution scale, should help greatly with quantitative interpretation and estimation of rock properties. A step toward this goal is described here. A generic rock-physics model is assumed, which upscales microscale rock-physics properties to mesoscale (effective-medium) poroelastic quantities to be recovered from macroscale estimates of seismic attributes. It is shown on simple synthetic examples that quantitative multiparameter reconstruction, when it is possible, can reduce ambiguities in mesoscale parameter estimation dramatically, using a semiglobal search. Successful estimation of these effective-medium quantities will narrow the range of possible rock-physics estimations to be considered for seismic imaging target zones. For example, estimating the P-wave quality factor along with P-wave velocity from full-waveform inversion is shown to change the estimation of mesoscale parameters significantly, assuming that the upscaling of the rock-physics model and the recovered macroscale parameters are well constrained. In addition, shear-wave information is shown to be crucial for pressure-saturation discrimination. The inferred information at the reservoir level, resulting from full-waveform inversion and subsequent mesoscale estimation, can be useful for reservoir characterization.

Introduction

Successful estimation of quantitative rock-physics properties from seismic data will be useful for problems as diverse as reservoir characterization to enable enhanced oil recovery, site determination for CO_2 storage, and hydrogeologic interpretation. In spite of dramatic improvements in the seismic imaging resolution provided by better acquisition and processing, the microscale for deterministic or stochastic description of rocks is still well below the seismic scale. However, one can hope to infer some information or constraints on average properties of rocks by considering homogenized two-phase media at a mesoscale, broader than the microscale we consider for rock-physics analysis but still below the seismic scale. Homogenization allows us to extract subseismic-scale information without involving the intrinsic complexities related to detailed rock-physics description (Chopra and Marfurt, 2007; Mavko et al., 2009; Dupuy et al., personal communication, 2015a; Dupuy et al., personal communication, 2015b).

We envision the mesoscale to be the bridge between high-resolution seismic and rock characterization scales. We then ask: what parameters do we need to reconstruct at the seismic imaging scale in order to infer mesoscale quantities important for improving our microscale description for reservoir monitoring?

Since the revival of full-waveform inversion (FWI) a decade ago, thanks to dramatic improvements in both data acquisition and computer power, the standard application of FWI is imaging the acoustic-velocity structure (Operto et al., 2013). This velocity model is mainly used as an improved background model for depth migration. Multiple-parameter reconstruction (often obtained by modeling elastic propagation) can improve the mesoscale characterization dramatically but remains an ill-posed problem with crosstalk among parameters resulting from the imperfect illumination of the target and from the limitations of optimization theory (Operto et al., 2013).

In this short paper, we do not use FWI to reconstruct all possible parameters but rather a subset ranging from acoustic and shear velocities to acoustic and shear attenuation factors. In fact, we may consider only a subset of these parameters while keeping others fixed, depending on the data available to us.

Extracting microscale information from seismic is ambitious (to say the least), but, as we show, recovering parameters at the mesoscale is possible, at least in principle. To accomplish this in a meaningful fashion, we need to link rock physics at the microscale and homogenized parameters at the mesoscale (see Pride [2005] for extensive review on this subject). At the mesoscale, various theoretical and empirical models for poroelasticity have been proposed. Pride (2005) identifies connections between effective parameters at the mesoscale and macroscale seismic parameters obtained by seismic imaging. These connections provide the basis for our reconstructions of mesoscale effective-medium parameters from FWI-inverted velocities and attenuation values. That is, we assume that effective two-phase parameters can be reconstructed from seismic velocities and attenuation values and that these quantities also can be upscaled from multiphase microscale rock physics.

We next mention our inversion scheme, based on a semiglobal search (Sambridge, 1999). Then, two examples will illustrate difficulties and trade-offs in constructing mesoscale parameters for restricting microscale rock-physics interpretation. These examples consider a steam-injection configuration and a fluid substitution (monitoring). The first example attempts to provide a fluid characterization, assuming we know the solid-frame skeleton. The second example uses a partially saturated medium to illustrate the importance of multiparameter FWI imaging in extracting information on frame parameters and fluid saturation.

We conclude by discussing which target parameters should be estimated by FWI at the seismic scale to provide a significant contribution at the microscale. Our knowledge of the macroscale

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parameters relevant for mesoscale parameter inversion, which will be useful for parametric rock-physics description, will help to narrow the gap between seismic imaging and reservoir monitoring.

Upscaling rock physics and semiglobal inversion

A good introduction to the deterministic description of rocks as complex porous media is provided in Pride (2005). At the mesoscale, intermediate between the macroscale related to seismic waves and the microscale related to rock physics, we may consider an effective medium where only one solid phase and one fluid phase are combined based on homogenization strategies. The effective porosity ϕ is the ratio between void volume V_v and total volume V_T: in saturated media, the proportion of fluid phase is the porosity ϕ while the proportion of the solid phase is 1-ϕ. The fluid is characterized by a bulk modulus K_f, a density ρ_f, and a viscosity η. For partially saturated media, we need more advanced techniques for homogenization of these three parameters where dispersion and attenuation also should be described. The solid frame is described entirely by the combination of grains with a bulk modulus K_s, a shear solid modulus G_s, and a solid density ρ_s. Again, various effective-medium theories exist for expressing the effective mechanical moduli K_D and G_D and the density ρ_D of the porous frame (Pride, 2005; Mavko et al., 2009).

The forward problem, taking mesoscale parameters into macroscale quantities, comes from the Biot poroelastodynamic theory. The inverse problem takes macroscale quantities into mesoscale parameters. Pride (2005) presents analytical expressions for slownesses (data) of P, S, and Biot waves in terms of the effective parameters (model) at the mesoscale: here, we shall recover the effective-medium parameters (model) from the data, which are velocities and attenuations obtained by FWI. Because the forward calculation of these analytical expressions is rapid, we use a semiglobal inversion: an oriented Monte Carlo method known as the neighborhood algorithm (NA), based on random exploration and guided toward the best models through a sampling around low misfit values (Sambridge, 1999).

This strategy relies on two control parameters: number of models generated at each iteration and resampling size of Voronoï cells corresponding to values of each model parameter. In our examples, for each pixel in our FWI computational grid, we compute 1000 iterations and we choose a resampling of 10, leading to 10,000 models generated per FWI grid point for the mesoscale inversion. Specifically, the pixel density is 2.5 times denser than the FWI half-wavelength resolution. The optimal size of the mesoscale grid depends on the correlation length of the effective-medium parameters; determining this is an ongoing research problem.

Simple illustrations: Fluid substitution and solid skeleton evolution

As a first illustration, we consider a 2D synthetic example named "Dai" (Dupuy et al., personal communication, 2015a). The medium is layered, with eight horizontal sand layers in which the consolidation degree increases with depth (parameters are given in Table 1). The sixth layer is the reservoir layer saturated with oil before the steam injection. Other porous layers are saturated with water.

Acquisition consists of 22 sources placed every 25 m on a horizontal line at 75 m depth, 45 receivers on the same line, and 45 receivers in vertical wells located at both ends of the horizontal

Table 1: Mesoscale and macroscale parameters of the Dai reservoir model. The velocities and the quality factors of P-, S-, and Biot waves (V_P, V_S, V_{Biot}, Q_P, Q_S, and Q_{Biot}) are computed at 20 Hz.

			Sand layers							Reservoir layer (6)		
			1	2	3	4	5	7	8	Oil	Steam	Heated oil
Mesoscale parameters	K_s	(GPa)	5.2	5.3	5.8	7.5	6.9	9.4	26	37	37	37
	G_s	(GPa)	2.4	2.9	3.3	4.2	3.6	5.6	17	4.4	4.4	4.4
	ρ_s	(kg/m^3)	2250	2300	2400	2490	2211	2670	2700	2650	2650	2650
	K_f	(GPa)	2.5							1.7	0.0015	1.2
	ρ_f	(kg/m^3)	1040							985	10	900
	η	(Pa.s)	0.001							150	$2.2\ 10^{-5}$	0.3
	m		1.5							1.5	1.5	1.5
	K_D	(GPa)	0.65	1.59	2.76	4.54	5.69	6.58	12.35	3.21	3.21	3.21
	ϕ		0.25	0.1	0.05	0.03	0.01	0.02	0.05	0.33	0.33	0.33
	k_0	(m^2)	10^{-12}	10^{-13}	10^{-13}	10^{-13}	10^{-16}	10^{-13}	10^{-14}	10^{-12}	10^{-12}	10^{-12}
Macroscale parameters	V_P	(m/s)	1505	1613	1749	2019	2179	2265	3281	1900	1428	1768
	V_S	(m/s)	330	548	733	936	1116	1140	1571	359	390	361
	V_{Biot}	(m/s)	7.8	4.2	6.2	8.8	0.4	11.7	3.5	0.03	3.5	0.6
	Q_P		948	413	$+\infty$	1054	$+\infty$	$+\infty$	$+\infty$	$+\infty$	$+\infty$	$+\infty$
	Q_S	$*10^3$	14.33	160	172	180	$1.62\ 10^5$	194	1925	$2.58\ 10^6$	3114	6108
	Q_{Biot}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	ρ	(kg/m^3)	1948	2174	2332	2445	2200	2637	2617	2100	1779	2073

line spaced with a 12.5 m interval. Figure 1a shows the reconstruction by FWI of the macroscale acoustic velocity performed by Asnaashari et al. (2015). This FWI used prior information from wells containing receivers, and it reconstructed velocity values very close to those of the exact synthetic model. The lithology and fluid phase were assumed to be known. Figure 1b shows successful reconstruction of mesoscale porosity from velocity.

During steam injection from a single location at the top of layer 6, simulating a horizontal injection well directed perpendicular to the plane containing the porous medium becomes saturated with steam inside an internal disk (Figure 2). On a thin external wider disk, only heated oil is present. Away from the warming zone, values are the same as before the injection. We assume that the oil has been drained outside the internal disk and has been heated by the steam, increasing its mobility in the external disk. These changes in fluid properties affect the macroscale velocities and attenuations and should affect the high-resolution seismic imaging provided by FWI. These slight changes are visible on arrival times and amplitudes of reflected seismic waves between the baseline and monitor acquisitions (not shown).

A second FWI produced velocity reconstruction for the monitor, which was used for effective-medium property prediction (Figure 2). Again, lithology and fluid phase are assumed to be known. We recognize the oversimplified nature of our inversion of V_P-only FWI for fluid bulk modulus after steam injection, but it gives a flavor of the potential for mesoscale parameter inversion.

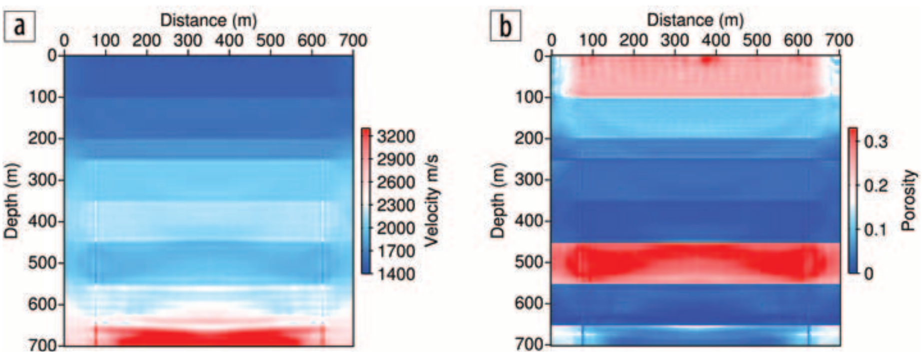

Figure 1. (a) Macroscale reconstructed V_P baseline model by FWI nearly identical to the true model, except at borders where illumination is missing in spite of the information from the vertical wells near the left and right edges. (b) Mesoscale reconstruction of effective ϕ porosity by independent point inversion.

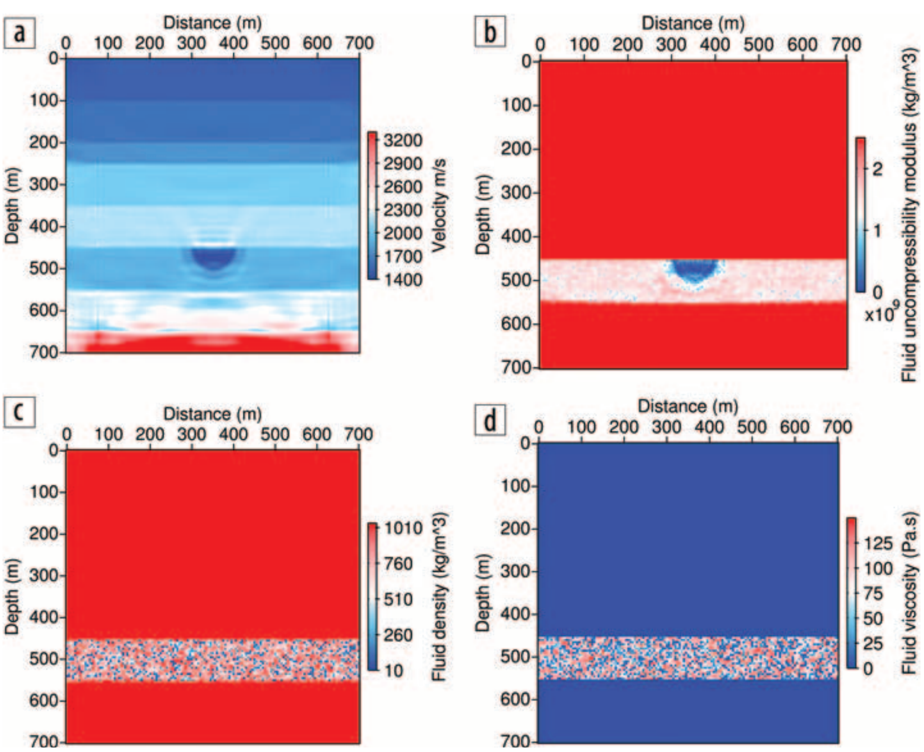

Figure 2. (a) Macroscale reconstructed V_P monitor model by time-lapse FWI with excellent reconstruction of the true monitor model (not shown here, but nearly identical to the FWI reconstruction), especially around the steam injection. Mesoscale effective fluid parameters estimated using pointwise mesoscale inversion: (b) fluid bulk modulus, (c) fluid density, and (d) fluid viscosity, with good reconstruction only of bulk modulus.

In this fluid substitution monitoring case, the fluid phase inversion attempts to reconstruct the effective-medium bulk modulus K_f, density ρ_f, and viscosity η_f (Figure 2). This inversion focuses only on fluid changes, so we assume that neither the solid phase nor the properties of the overburden have changed; again, this is an ideal, not usually realistic, situation. The fluid bulk modulus is well reconstructed both for the steam and for the heated oil as shown by concentric half-circle imprints (left), while density (middle) and viscosity (right) are poorly constrained. From the mesoscale image of fluid bulk modulus K_f, we can possibly infer reliable information on fluid nature at the microscale level.

We show the importance of amplitude information at the macroscale level with another example. We assume we are able to reconstruct various sets of parameters, ranging from single parameter (V_P) to the most complete isotropic parameter set (V_P, V_S, Q_P, Q_S, ρ). Anisotropic parameters are disregarded in this example, as their high-resolution estimation by FWI is still a challenge at the macroscale level. We consider the reconstruction of frame parameters, namely porosity ϕ and consolidation parameter cs, from known macroscale reconstructed values. Fluid and solid-phase parameters are assumed to be known.

We emphasize that we have not actually performed FWI to get these macroscale values, because reconstructing multiple parameters from FWI remains an ongoing challenge; instead we assume that the macroscale values have been obtained, without error, by some future implementation of FWI or some other method. Figure 3 illustrates the benefits of considering multiple parameters at the

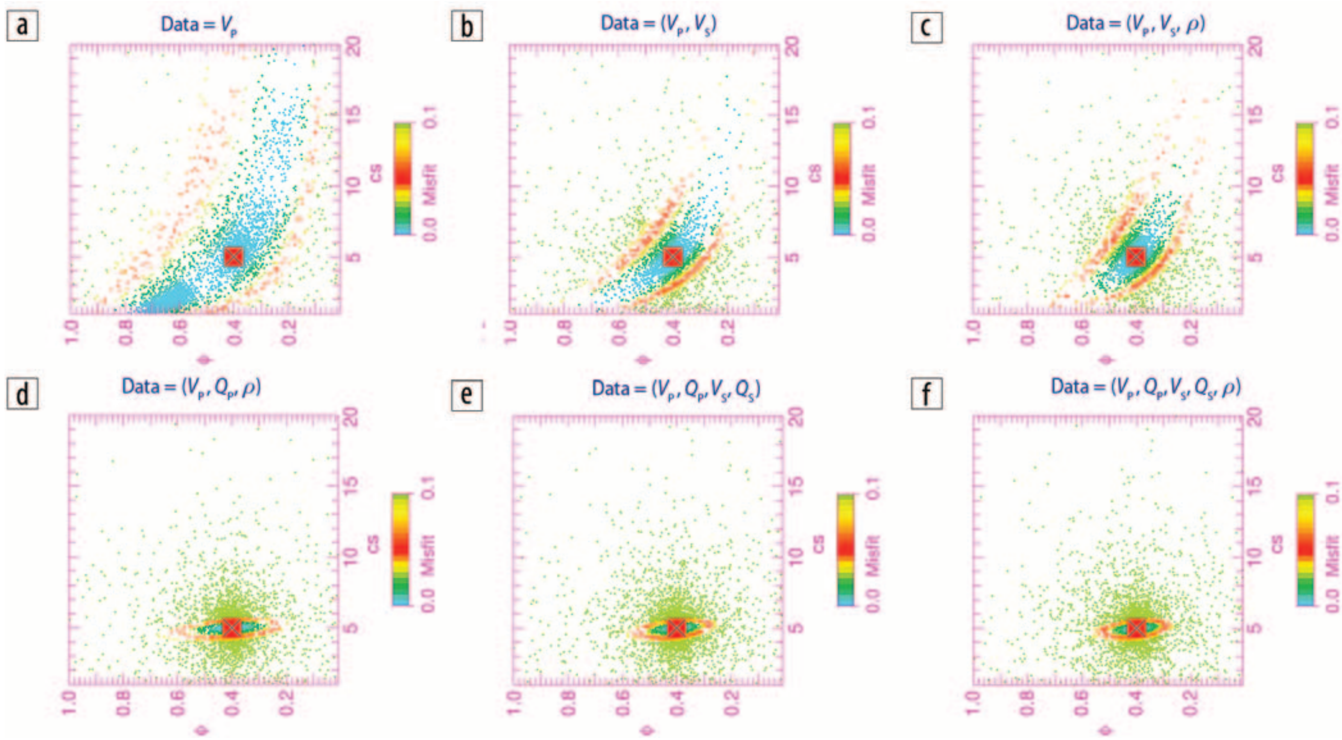

Figure 3. Reconstruction of porosity ϕ and consolidation coefficient cs (true values = red crosses). From (a) to (f), the misfit shape changes considerably with scatter decreasing the most from (c) to (d).

macroscale level as input data. When using only V_P (Figure 3a), the misfit function is broad; therefore porosity and consolidation parameters are not well constrained. As we increase the number of available inputs, we see improved focusing of the misfit function. The greatest improvement occurs between Figure 3c (estimation from macroscale velocities and density) and 3d (estimation from P-wave velocity, P-wave quality factor, and density). As one might expect, the availability of attenuation estimates is crucial when performing a two-step inversion. In another example, we noticed also that the fluid saturation parameter depends strongly on attenuation estimation at the macroscale level. This leads to the conclusion that inversion that does not consider attenuation will likely produce incorrect reconstruction at the mesoscale and, therefore, incorrect microscale inference.

These oversimplified examples indicate the possible benefits of FWI multiple-parameter reconstruction in estimating mesoscale properties. Dupuy et al. (personal communication, 2015a, 2015b) show other examples in more complex contexts. In general, we expect improvement in effective-medium estimates in the future, when multiple-parameter FWI can be achieved with high resolution, especially for time-lapse targets.

Conclusions

We showed that combining high-resolution FWI with rock-physics upscaling into a mesoscale inversion provides valuable information about reservoir properties. Using multiparameter input data obtained from FWI (and other sources of information), especially shear-wave properties and attenuation data, helps constrain the estimation of fluid properties. This two-step inversion improves our quantitative estimations and narrows the gap between seismic imaging (which assumes, in effect, a one-phase medium) and reservoir characterization (multiphase medium) by introducing a mesoscale effective medium (two-phase medium). Attenuation plays a significant role in these reconstructions, suggesting that we should concentrate our attention on high-resolution seismic-imaging techniques. For multiparameter inversion, time lapse appears to be an ideal application for this work, because it allows us to consider only specific differential changes. TLE

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References

Asnaashari, A., R. Brossier, S. Garambois, F. Audebert, P. Thore, and J. Virieux, 2015, Time-lapse seismic imaging using regularized full waveform inversion with prior model: which strategy?: Geophysical Prospecting, **63**, no. 1, 78–98, http://dx.doi.org/10.1111/1365-2478.12176.

Chopra, S., and K. J. Marfurt, 2007, Seismic attributes for prospect identification and reservoir characterization: SEG Geophysical Developments Series No. 11, http://dx.doi.org/10.1190/1.9781560801900.

Mavko, G., T. Mukerji, and J. Dvorkin, 2009, The rocks physics handbooks, tools for seismic analysis in porous media, 2nd ed.: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511626753.

Operto, S., R. Brossier, Y. Gholami, L. Métivier, V. Prieux, A. Ribodetti, and J. Virieux, 2013, A guided tour of multiparameter full waveform inversion for multicomponent data: from theory to practice: The Leading Edge, **32**, no. 9, 1040–1054, http://dx.doi.org/10.1190/tle32091040.1.

Pride, S., 2005, Hydrogeophysics: Water Science and Technology Library, Springer, 253–290, http://dx.doi.org/10.1007/1-4020-3102-5_9.

Sambridge, M. S., 1999, Geophysical inversion with a neighbourhood algorithm — I. Searching a parameter space: Geophysical Journal International, **138**, no. 2, 479–494, http://dx.doi.org/10.1046/j.1365-246X.1999.00876.x.