

## **A downscaling strategy from FWI to micro-scale reservoir properties from high resolution images**

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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 geological interpretation. An on-going 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. Here We describe a step towards this goal. We assume a generic rock physics model which upscales micro-scale rock physics properties to meso-scale (effective medium) poroelastic quantities to be recovered from macro-scale estimates of seismic attributes. We show on simple synthetic examples that quantitative multi-parameter reconstruction, when it is possible, can dramatically reduce ambiguities in meso-scale parameter estimation, using a semi-global 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, we show that estimating the P wave quality factor along with P wave velocity from full waveform inversion can significantly change our estimation of meso-scale parameters, assuming that the upscaling of the rock physics model and the recovered macro-scale parameters are well constrained. Also, we show that shear-wave information is crucial for pressure-saturation discrimination. The inferred information at the reservoir level resulting from full waveform inversion and subsequent meso-scale estimation can be useful for reservoir characterization.

**Key words: High resolution seismic imaging, multi-parameter reconstruction, rock mechanics, reservoir interpretation**

## 1 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<sub>2</sub> storage ; and hydrogeological interpretation. In spite of dramatic improvements in the seismic imaging resolution provided by better acquisition and processing, the micro-scale 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-phasic media at a scale broader than the micro-scale we consider for rock physics analysis but still below the seismic scale. Homogenization allows us to still extract sub-seismic scale information without involving the intrinsic complexities related to detailed rock physics description (Chopra and Marfurt 2007; Mavko et al., 2009; Dupuy et al., 2015a,b).

We envision the meso-scale 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 meso-scale quantities important for improving our micro-scale 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 dramatically improve the meso-scale characterization, but remains an ill-posed problem with cross-talk 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 micro-scale information from seismic is ambitious (to say the least) but, as we show, recovering parameters at the meso-scale is possible at least in principle. To accomplish this in a meaningful fashion, we need to link rock physics at the micro-scale and homogenized parameters at the meso-scale (see the book of Pride(2005) for extensive review on this subject). At this meso-scale, various theoretical and empirical models for poroelasticity have been proposed. Pride (2005) identifies connections between effective parameters at the meso-scale and macro-scale seismic parameters obtained by seismic imaging. These connections provide the basis for our reconstructions of meso-scale 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 can also be upscaled from multi-phase micro-scale rock physics. We next mention our inversion scheme, based on a semi-global search (Sambridge, 1999). Then, two examples will illustrate difficulties and trade-offs in constructing meso-scale parameters for restricting micro-scale rock physics interpretation. These examples consider a steam injection configuration and a fluid substitution (monitoring). The first attempts to provide a fluid characterization, assuming we know the solid frame skeleton. the second uses a partially saturated medium to illustrate the

importance of multi-parameter 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 in order to provide a significant contribution at the micro-scale. Our knowledge of the macro-scale parameters relevant for meso-scale parameter inversion, which will be useful for parametric rock physics description, will help narrow the gap between seismic imaging and reservoir monitoring.

## 2 Upscaling rock physics and semi-global inversion

A good introduction to the deterministic description of rocks as complex porous media is provided in the book by Pride (2005). At the meso-scale, intermediate between the macro-scale related to seismic waves and the micro-scale 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  $\phi$  is the ratio between void volume  $V_v$  and total volume  $V_T$ : in saturated media, the proportion of fluid phase is the porosity  $\phi$  while the proportion of the solid phase is  $1 - \phi$ . The fluid is characterized by a bulk modulus  $K_f$ , a density  $\rho_f$  and a viscosity  $\eta$ . For partially saturated media, we need more advanced techniques for homogenization of these three parameters where dispersion and attenuation should also be described. The solid frame is entirely described by the combination of grains with a bulk modulus  $K_s$ , a shear solid modulus  $G_s$  and a solid density  $\rho_s$ . Again, various effective medium theories exist for expressing the effective mechanical moduli  $K_D$  and  $G_D$  and the density  $\rho_D$  of the porous frame (Pride, 2005; Mavko et al., 2009).

The forward problem, taking meso-scale parameters into macro-scale quantities, comes from the Biot poroelastodynamic theory. The inverse problem takes macro-scale quantities into meso-scale parameters. Pride (2005) presents analytical expressions for slownesses (data) of P, S and Biot waves in terms of the effective parameters (model) at the meso-scale: 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 semi-global inversion: an oriented Monte-Carlo method known as the Neighborhood Algorithm (NA), based on random exploration and guided towards 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 10000 models generated per FWI grid point for the meso-scale inversion. Specifically, the pixel density is 2.5 times denser than the FWI half-wavelength resolution. The optimal size of the meso-scale grid depends on the correlation length of the effective medium parameters; determining this is an ongoing research problem.

## 3 Simple illustrations: fluid substitution and solid skeleton evolution

As a first illustration, we consider a 2D synthetic example named “Dai” (see Dupuy et al (2015a) for this steam injection benchmark). 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 line are spaced with a 12.5 m interval. Figure 1 (left panel) shows the reconstruction by FWI of the macro-scale acoustic velocity. 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 1 (right panel) shows successful reconstruction of meso-scale porosity from velocity.

		Sand layers								Reservoir layer (6)		
		1	2	3	4	5	7	8	Oil	Steam	Heated oil	
Meso-scale 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	
	$\rho_s$ (kg/m <sup>3</sup> )	2250	2300	2400	2490	2211	2670	2700	2650	2650	2650	
	$K_f$ (GPa)									1.7	0.0014	1.2
	$\rho_f$ (kg/m <sup>3</sup> )									985	10	900
	$\eta$ (Pa.s)									150	$2.2 \cdot 10^{-5}$	0.3
	$m$									1.5		
	$\phi$	0.25	0.1	0.05	0.03	0.01	0.02	0.05	0.33	0.33	0.33	
	$k_0$ (m <sup>2</sup> )	$10^{-12}$	$10^{-13}$	$10^{-13}$	$10^{-13}$	$10^{-16}$	$10^{-13}$	$10^{-14}$	$10^{-12}$	$10^{-12}$	$10^{-12}$	
	$cs$									20		
Macro-scale 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	$+\infty$	$+\infty$	$+\infty$	$+\infty$	$+\infty$	$+\infty$	
	$Q_S \cdot 10^3$	14.33	160	172	180	$1.62 \cdot 10^5$	194	1925	$2.58 \cdot 10^6$	3114	6108	
	$Q_{Biot}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
	$\rho$ (kg/m <sup>3</sup> )	1948	2174	2332	2445	2200	2637	2617	2100	1779	2073	

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

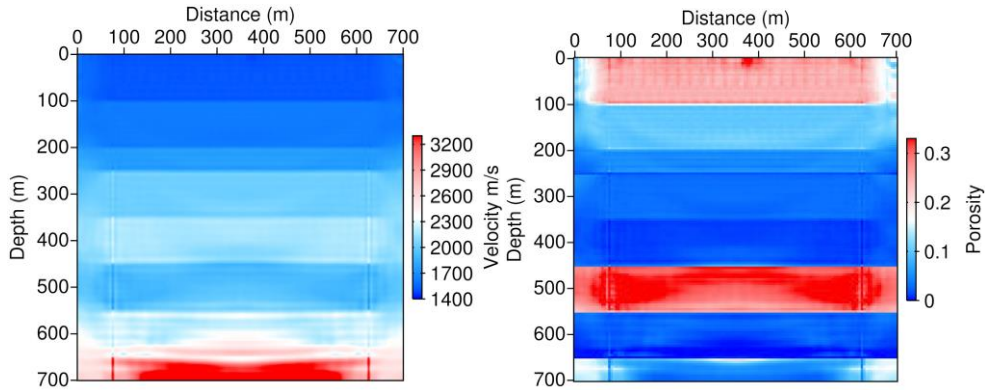
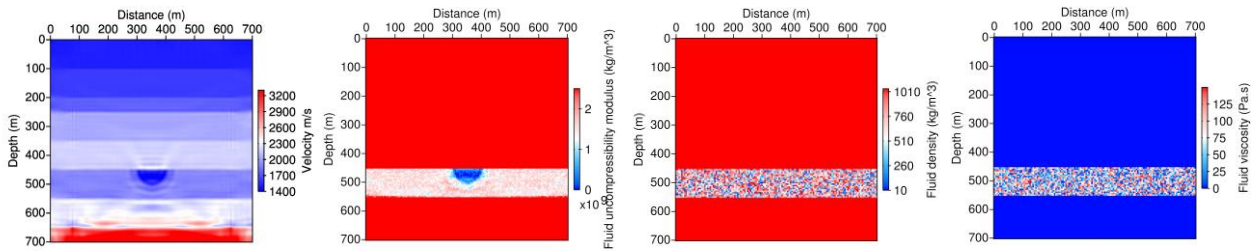


Figure 1: Left panel: macro-scale reconstructed  $V_P$  baseline model by FWI nearly identical to the true model, except at borders where illumination is missing in spite of the information from the vertical wells near the left and right edges. Right panel: meso-scale reconstruction of effective  $\phi$  porosity by independent point inversion.

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 macro-scale velocities and attenuations, and should affect the high resolution seismic imaging provided by full waveform inversion. 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 meso-scale parameter inversion.



*Figure 2: Left panel: macro-scale 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. Other panels: meso-scale effective fluid parameters estimated using pointwise meso-scale inversion. From left to right, fluid bulk modulus, fluid density and fluid viscosity, with good reconstruction only of bulk modulus.*

In this fluid substitution monitoring case, the fluid phase inversion reconstructs the effective-medium bulk modulus  $K_f$ , density  $\rho_f$  and viscosity  $\eta_f$  (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 meso-scale image of fluid bulk modulus  $K_f$ , we can possibly infer reliable information on fluid nature at the micro-scale level.

We show the importance of amplitude information at the macro-scale 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 ( $V_p, V_s, Q_p, Q_s, \rho$ ). Anisotropic parameters are disregarded in this example, as their high-resolution estimation by FWI is still a challenge at the macro-scale level. We consider the reconstruction of frame parameters, namely porosity  $\phi$  and consolidation parameter  $cs$ , from known macro-scale reconstructed values. Fluid and solid phase parameters are assumed to be known.

We emphasize that we have not actually performed FWI to get these macro-scale values, because reconstructing multiple parameters from FWI remains an on-going challenge; instead we assume that the macro-scale 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 macro-scale level as input data. When using only  $V_p$  (panel a), 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 panel (c) (estimation from macro-scale velocities and density) and panel (d) (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 macro-scale level. This leads to the conclusion that inversion that does not consider attenuation will likely produce incorrect reconstruction at the meso-scale and, therefore, to incorrect micro-scale inference.

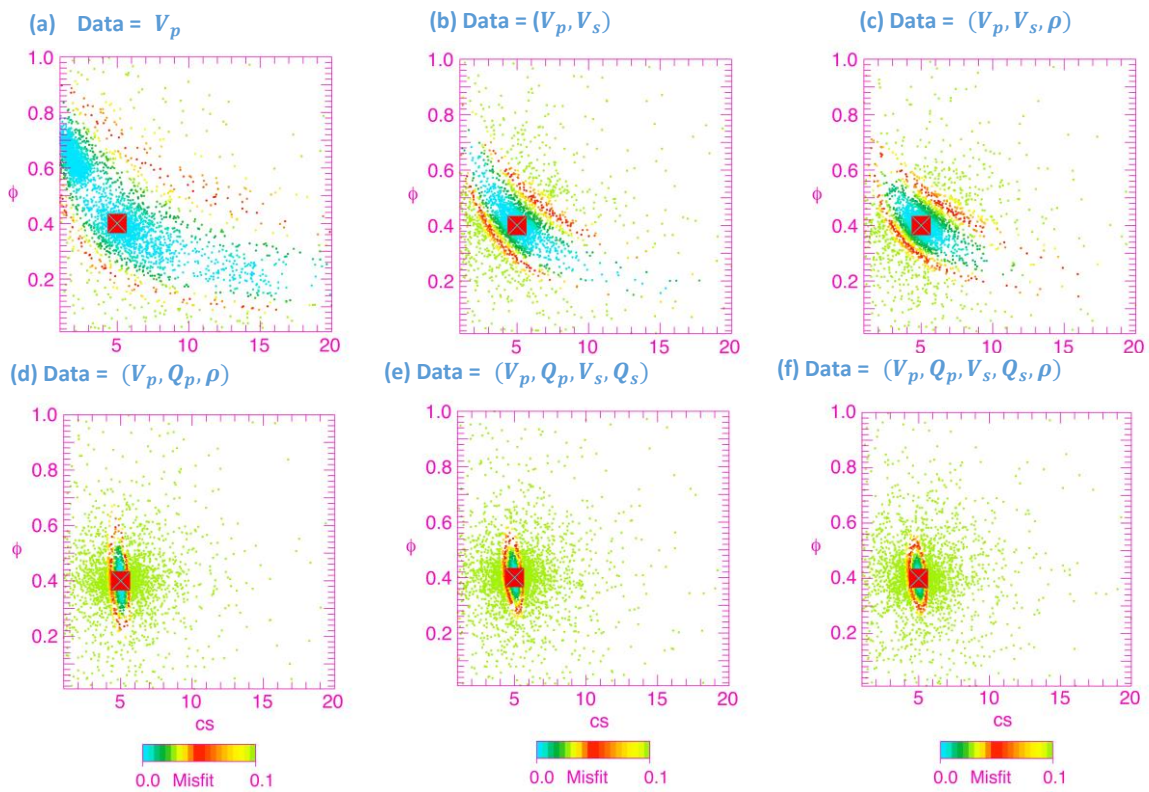


Figure 3: Reconstruction of porosity  $\phi$  and consolidation coefficient  $cs$  (true values = red crosses). From left top panel to right bottom panel, the misfit shape changes considerably with scatter decreasing the most from (c) to (d).

These oversimplified examples indicate the possible benefits of FWI multiple parameter reconstruction in estimating meso-scale properties. Dupuy et al. (2015a,b) 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.

#### 4 Conclusions

We showed that combining high-resolution FWI with rock physics upscaling into a

meso-scale inversion provides valuable information about reservoir properties. Using multi-parameter 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 characterisation (multi-phase medium), by introducing a meso-scale 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 multi-parameter inversion, time-lapse appears to be an ideal application for this work, because it allows us to consider only specific differential changes.

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