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A framework for three-dimensional coupled seismic-electromagnetic inversion

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SUMMARY

We present a three-dimensional (3D) coupled seismic-electromagnetic (EM) imaging workflow and apply it to subsalt exploration. Our coupled seismic-EM imaging workflow is characterized as follows. First, seismic data are transformed into the Laplace domain. Because the transformation changes the modeling of seismic fields from wave to diffusion, seismic and EM data are governed by the same physics of diffusion. Accordingly, seismic and EM resolutions are better matched, leading to robust coupling of velocity and resistivity models via structural constraints and petrophysical methods. Second, we separate the full joint seismic-EM inversion into three simple inversion components: seismic inversion, EM inversion and cross-gradient inversion for structure. This separation helps us mitigate non-convergence issues that frequently arise when an objective function of the joint inverse problem has multiple data, regularization terms and constraints. The cross-gradient inversion and resistivity-velocity cross-plots are used to infuse structural information from velocity to resistivity models and vice versa as described below.

Keywords: 4-6 keywords, coupled seismic-EM inversion, cross gradients, sub-salt exploration, matched resolution

INTRODUCTION

Joint inversion methods aim to integrate complementary geophysical data, thereby producing more consistent and reliable geophysical models of the subsurface with improve overall resolution. Joint seismic-EM inversion methods have recently gained attention and are now being applied to a wide range of geophysical problems from near-surface geophysics to subsalt imaging. Joint inversion methods are mainly grouped into two approaches (Hu et al., 2009). One approach is based on a petrophysical relationship between seismic velocity and electrical resistivity attributes (e.g. Hoversten et al., 2006; Harris and MacGregor, 2006). The other approach utilizes the structural similarity between seismic velocity and electrical resistivity attributes via the cross-gradient technique in the course of the inversion (e.g. Gallardo and Meju, 2003; Gallardo and Meju, 2007; Moorkamp et al., 2010). Colombo and Stefano (2007), Colombo and Keho (2010), Colombo et al. (2012[a] and 2012[b]) incorporate both petrophysical relationships and structure constraints using the cross-gradient method, into a single inversion process.

The goal of joint seismic-EM inversion methods is to combine seismic and EM inverse modeling into a single integrated inversion process which improve overall consistency and resolution in the final velocity and resistivity models. However, the joint inversion methods also introduce new challenges in inverse modeling. For example, petrophysical relationships for the joint inversion may not be uniquely determined, but frequently show a large range of uncertainty (Rubin and Hubbard, 2005; Hu et al., 2009). When an objective function includes multiple data terms, model regularization terms and additional constraints, it can be highly non-linear. In such cases the inversion process frequently fails to find an acceptable solution, often times getting stuck at local minima. It is our experience that this non-linearity is further aggravated especially when the cross-gradient-based joint inversion is applied to large-scale industrial-size 3D exploration problems. Another major obstacle in joint seismic-EM inversion is the mismatch in the resolution at which seismic and EM methods sense the subsurface. The resolution of seismic imaging is an order of magnitude finer in scale than that of EM imaging. The superior resolution of seismic imaging results from the fact that its governing physics is based on wave phenomena, whereas the EM methods are based on the diffusion phenomena. For consistent joint imaging, their resolutions need to be matched (Newman and Commer, 2010; Newman et al., 2011).

Here we present a coupled seismic-EM imaging workflow that can effectively mitigate the problems mentioned above. We use a term, 'coupled' rather than 'joint' in order to indicate that our imaging workflow is not classified by a true joint inversion approach where both seismic and EM misfit terms are simultaneously minimized in the course of the inversion iterations. In contrast, our approach might be viewed as similar to a sequential approach where one set of geophysical data are inverted and the resulting model is used to constrain the starting model for the other geophysical inversion.

However, our imaging workflow is distinguished from the traditional sequential approach due to the following features. First, we split the full joint inverse problem into more manageable inversion components, where the cross-gradient method is used to exchange structural information between the velocity and resistivity starting models. As will be described in detail later, the cross-gradient method is used to precondition starting resistivity models for successive inversion of EM data, where no other coupling between the resistivity and velocity attributes are provided. A petrophysical relationship that is estimated from cross-plots is used for a similar purpose for deriving better velocity starting models in the workflow. The proposed approach effectively mitigates convergence issues with full joint inversion of large scale 3D type problems and improves the overall consistency and resolutions in the velocity and resistivity models.

Second, the coupled seismic-EM imaging workflow employs the Laplace inversion method (Shin and Cha, 2008) where an acoustic wave equation is transformed into an acoustic diffusion equation. The benefit of the Laplace inversion for the work presented here is that seismic and EM imaging experiments are better matched in spatial resolution at low wave numbers since both are now in the diffusion domain. Unlike conventional frequency-domain seismic inversion, the Laplace inversion robustly recovers low wave number velocity structures. Brown et al. (2005) used a similar approach for elastic wave fields to avoid local minima issues discussed by Pratt (1999) in full waveform imaging (FWI) of seismic data. To avoid local minima in FWI, the strategy is to recover the low wave numbers of the velocity model first using lower frequency data and subsequently recover higher wave number components by adding higher frequency data in the imaging process. Throughout the paper, we demonstrate our coupled seismic-EM imaging workflow using the SEG salt velocity model (Aminzadeh et al., 1997) and its corresponding electrical resistivity model.

RESULTS

We introduce the coupled imaging workflow in Figure 1 for seismic and EM data and apply it to synthetic data arising from the SEG salt velocity model and its corresponding resistivity model. We first perform standalone seismic and magnetotelluric (MT) inversion with layered starting models and realistic 3D measurement configurations. In the given inversion example (Figure 2), the resulting velocity model better defines the flanks and the bottom of the salt than the resistivity model. Thus, via the cross-gradient inversion, the structural information of the velocity model is infused into the resistivity model. The resulting resistivity model is then used as a new starting model for the subsequent MT/EM inversion. By repeating the cross-gradient inversion and the subsequent MT inversion, the flanks and the bottom of the salt are increasingly recovered and closely resemble those of the true salt. As the EM refinement process makes velocity-resistivity cross-plots clustered well, petrophysical relationships between velocity and resistivity values are estimated for constructing a new starting velocity model. The starting model has some new features that are not imaged by the standalone seismic inversion. Along with the new improved starting model, the subsequent seismic inversion yields a more accurate delineation of the salt structure's bottom and flanks. Figure 2 shows the progressive improvement in the velocity and resistivity attributes arising from the proposed inversion framework illustrated in Figure 1.

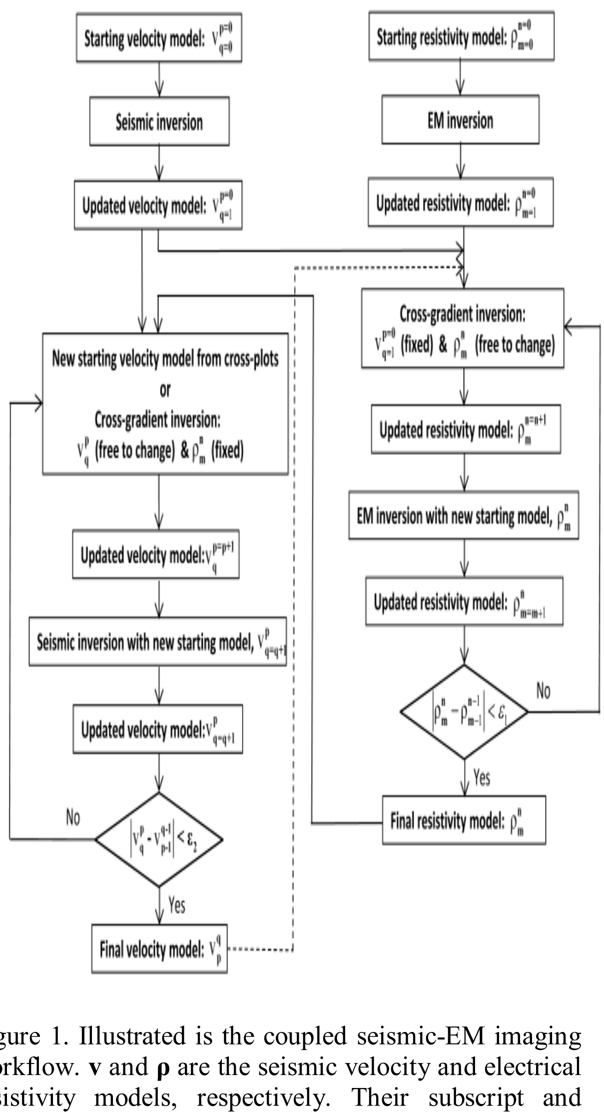

Figure 1. Illustrated is the coupled seismic-EM imaging workflow. **v** and **ρ** are the seismic velocity and electrical resistivity models, respectively. Their subscript and superscript represent the number of standalone inversion and cross-gradient inversion, respectively. ε_1 and ε_2 are tolerances that determines whether two successive models(velocity or resistivity) have converged.

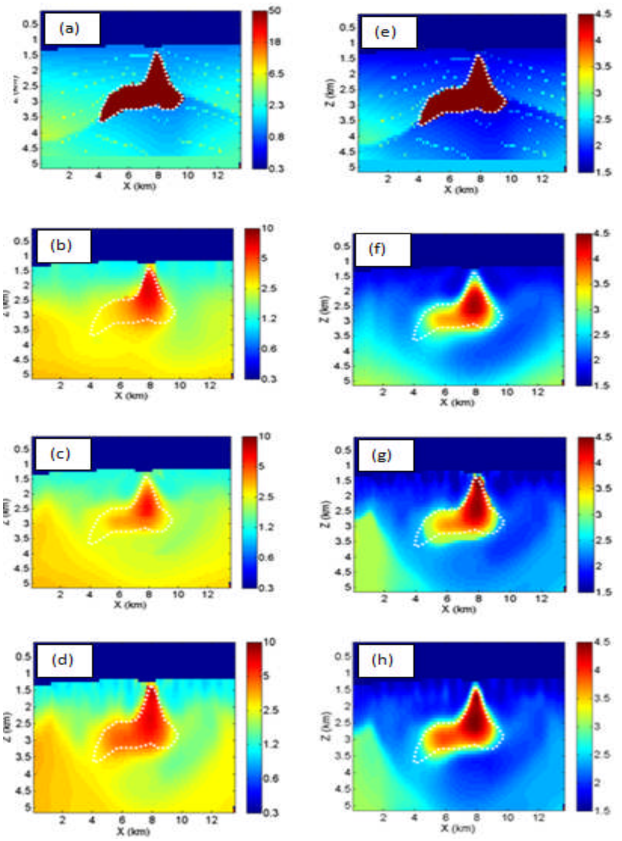

Figure 2. Evolution of the resistivity (the first column) and velocity (the second column) images through the coupled seismic-EM inversion framework. The xz cross-sectional views at y=5 km for the SEG salt model are compared. (a) the true resistivity model. (b) the resistivity model from standalone MT inversion. (c) the starting resistivity model obtained from the cross-gradient inversion. (d) the resistivity model after the five refinements. (e) The true velocity model. (f) the velocity model produced from standalone seismic inversion. (g) the petrophysics-based starting velocity model. (h) the velocity model produced from seismic inversion using the petrophysics-based starting velocity model. The white broken contours represent the boundaries of the true salt.

CONCLUSIONS

We have presented the coupled seismic-EM imaging workflow. The workflow is designed to resolve two major obstacles in 3D large-scale joint geophysical inverse problems: 1) resolution mismatches between seismic and EM imaging and 2) convergence issues of an objective function when it includes multiple data and regularization terms. Through the Laplace seismic inversion, a velocity image is matched with its corresponding resistivity image in terms of spatial resolution. The full joint inversion is split into independent seismic and EM inversion components. The infusion of structural information from seismic to EM inversion and vice versa is effectively achieved by either the cross-gradient inversion or a petrophysical relationship estimated from cross-plots. It is noteworthy that the coupled seismic-EM imaging workflow does not require developing an entire new inversion tool, but can be implemented by using proper subsets of an existing full joint inversion workflow.

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