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Two-dimensional joint inversion of Magnetotelluric and local earthquake data: Discussion on the contribution to the solution of deep subsurface structures

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ABSTRACT

Joint inversion of data sets collected by using several geophysical exploration methods has gained importance and associated algorithms have been developed. To explore the deep subsurface structures, Magnetotelluric and local earthquake tomography algorithms are generally used individually. Due to the usage of natural resources in both methods, it is not possible to increase data quality and resolution of model parameters. For this reason, the solution of the deep structures with the individual usage of the methods cannot be fully attained. In this paper, we firstly focused on the effects of both Magnetotelluric and local earthquake data sets on the solution of deep structures and discussed the results on the basis of the resolving power of the methods. The presence of deep-focus seismic sources increase the resolution of deep structures. Moreover, conductivity distribution of relatively shallow structures can be solved with high resolution by using MT algorithm. Therefore, we developed a new joint inversion algorithm based on the cross gradient function in order to jointly invert Magnetotelluric and local earthquake data sets. In the study, we added a new regularization parameter into the second term of the parameter correction vector of Gallardo and Meju (2003). The new regularization parameter is enhancing the stability of the algorithm and controls the contribution of the cross gradient term in the solution. The results show that even in cases where resistivity and velocity boundaries are different, both methods influence each other positively. In addition, the region of common structural boundaries of the models are clearly mapped compared with original models. Furthermore, deep structures are identified satisfactorily even with using the minimum number of seismic sources. In this paper, in order to understand the future studies, we discussed joint inversion of Magnetotelluric and local earthquake data sets only in two-dimensional space. In the light of these results and by means of the acceleration on the three-dimensional modelling and inversion algorithms, it is thought that it may be easier to identify underground structures with high resolution.

1. Introduction

Magnetotelluric and local earthquake tomography are generally used for relatively deep crustal investigation, in order to explore main tectonic zones, basin depth, faults and geothermal reservoirs. Accordingly, seismic travel time tomography (Aki et al., 1977; Sambridge, 1990; Zelt and Barton, 1998; Rawlinson et al., 2001; Husen and Kissling, 2001; Rawlinson and Sambridge, 2003; Koulakov, 2009) and Magnetotelluric (MT) (Sasaki, 1989; Uchida, 1993; deLugão et al., 1997; Rodi and Mackie, 2001; Uchida and Sasaki, 2006; Candansayar, 2008; Lee et al., 2009) two-dimensional algorithms have been developed.

In the last few decades with the increasing of computer processing capabilities, determination of subsurface structures by using multiple geophysical data sets became applicable. Hence simultaneous interpretation of different geophysical data sensitive to the same (Sasaki, 1989; Candansayar and Tezkan, 2008) or different physical parameters (Colombo and Stefano, 2007; Bedrosian et al., 2007; Munoz et al., 2010; Cardarelli et al., 2010; Falgàs et al., 2011) has become a popular research topic in last decade. However, during the geological interpretation of geophysical data sensitive to different physical parameters, the interpreter must deal with any incompatible physical model boundaries obtained with the different geophysical data, which may result in meaningless interpretations. To overcome such challenge, the use of sequential (Vernant et al., 2002; Venisti et al., 2004; Saunders et al., 2005; Wang et al., 2011) or joint (Haber and Oldenburg, 1997;

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Gallardo and Meju, 2003, 2007; Linde et al., 2006; Candansayar and Tezkan, 2008; Infante et al., 2010; Moorkamp et al., 2011; Gallardo et al., 2012; Bennington et al., 2015) inversion methods has gained importance.

During the development of joint inversion algorithms that use different physical parameters, two different procedures have been followed. First, a relationship between geophysical properties can be formulated (e.g. empirical, physical, statistical) based on petro-physical properties (e.g. saturation, porosity, etc.). In the last decade, there are a number of developments that have followed this approach (Tiberi et al., 2003; Kozlovskaya et al., 2004; Hoversten et al., 2006; Harris and MacGregor, 2006). However, it is clearly said that a single petro-physical relationship may not always be suitable for the whole model. The second idea for joint inversion algorithms is that different physical parameters are combined under structural constraints and can be jointly solved, although definition and determination of structural boundaries is a challenging task in multi-dimensional space.

In recent years, many efforts have been devoted to the definition of multidimensional structural links. The first announcement of joint inversion was made by Haber and Oldenburg (1997). In this first approach, it is assumed that there are common structural limits spatially shared by different physical parameters. Nowadays the most widely accepted joint inversion approach is the cross-gradient method proposed by Gallardo and Meju (2003). The Cross-gradient method seeks subsurface images with parallel parameter changes without restricting the actual parameter values or the magnitude of their variations (Gallardo, 2007). In subsequent developments, many efforts have been devoted for structure-based joint inversion of seismic travel time and magnetotelluric data (Gallardo and Meju, 2007; Moorkamp et al., 2011; Gallardo et al., 2012; Bennington et al., 2015). In these studies, seismic methods with active source have been used. Structure-based joint inversion of passive source seismic travel time data has been considered by Tryggvason and Linde (2006). In their algorithm, they inverted P- and S- wave velocities using structural constraints. However, 2D joint inversion of MT and local earthquake data set has not been studied, yet.

In this study, we propose that the joint inversion of MT and local earthquake data set yields better underground velocity and resistivity models and we developed a structure-based algorithm for two-dimensional joint inversion of MT and local earthquake dataset. In our joint inversion implementation, the original algorithm of Candansayar (2008) MT inversion was modified using finite difference (FD) method with triangular cell definition (Demirci, 2009; Demirci and Candansayar, 2010) to resource more flexible meshes (Weaver, 1994; Aprea et al., 1997; Erdoğan et al., 2008). We also implemented a travel time tomography algorithm based on a Multi-Stencil Fast Marching Method (MSFM) that includes corner points in the discrete element model (Hassouna and Farag, 2007). This method is especially selected in order to reduce the numerical errors in the propagation in diagonal directions for its use in local earthquake tomography. Detailed information about the adopted approaches can be found in Demirci (2015). In the subsequent sections, the forward modeling of MT and local earthquake tomography (LET) data and the joint inversion used in the identification of subsurface structures are briefly explained. Then, definition and discretization of the computation mesh shared by both MT and LET methods is shown. Next, the results of the developed joint inversion algorithm are discussed showing solutions on synthetic models.

2. Forward solution

2.1. Traveltime computation in seismic tomography

In an asymptotic approach for wave propagation, the time T for a deformation to travel from the source (s) to the receiver (r) along the ray path for a medium of propagation velocity field $v(\xi)$ is given by the integral:

$$T = \int_s^r \frac{1}{v(\xi)} dl. \tag{1}$$

where $v(\xi)$ denotes the wave velocity at ξ and dl is the integral unit along a ray path. Alternatively, the travel times can be obtained by solving the corresponding eikonal equation given below:

$$(\nabla T)^2 = \frac{1}{v(\xi)^2}. \tag{2}$$

A widely popular numerical solution of Eq. (2) was developed by Vidale (1988) for two and three-dimensional spaces. In the following decades, several other approaches have been developed by many researchers (e.g. Qin et al., 1992; Cao and Greenhalgh, 1994; Sethian, 1996; Rawlinson and Sambridge, 2003; Hassouna and Farag, 2007; Sun et al., 2011). Almost all of the researchers solved Eq. (2) by using various finite difference operators. The most widely accepted approach is Fast Marching Method (FMM) developed by Sethian and Popovici (1999). FMM is the most stable and compatible method currently used in the solution of Eikonal equation. However, the calculation errors especially at diagonal node points are quite large. Therefore, to eliminate the calculation errors for the diagonal directions, Hassouna and Farag's (2007) proposed a new approach named as Multi-Stencil Fast Marching (MSFM). In this study, we used MSFM approach, which uses directional derivatives and higher order finite difference schemes as:

$$\max(D_{ij}^{-x}T, -D_{ij}^{+x}T, 0)^2 + \max(D_{ij}^{-z}T, -D_{ij}^{+z}T, 0)^2 = \frac{1}{v_{ij}^2} \tag{3}$$

where v_{ij} denotes the velocity value at (i,j) nodal point in the computation mesh, T is travel time, D^- and D^+ are backward and forward difference operators, respectively. In the solution of Eq. (3), the diagonal node points are included as done by Hassouna and Farag (2007). In this approach, diagonal node points were only added to calculation of travel time with conventional FMM method.

2.2. Forward solution in Magnetotelluric method

The frequency domain Maxwell equations are used to derive Transverse Electric (TE) and Transverse Magnetic (TM) mode Helmholtz equations for the two-dimensional forward solution of the MT method. The Helmholtz equations for the TE and TM modes are given as:

$$(\nabla \times \nabla \times \overrightarrow{E})_y = \nabla^2 E_y = -i\omega\sigma\mu_0 E_y \tag{4}$$

and

$$(\nabla \times \rho \nabla \times \overrightarrow{H})_y = \nabla . \rho \nabla H_y = -i\omega\mu_0 H_y \tag{5}$$

where μ_0 is the magnetic permeability of the free space, $\overrightarrow{E}$ and $\overrightarrow{H}$ indicate electric and magnetic fields, respectively. ω is the angular frequency and σ is conductivity. In the solution of the Helmholtz equation the most common numerical techniques are Finite Element (FE) and FD methods. Although the solution of Eqs. (4) and (5) by using FE method has advantages in shaping largely heterogeneous resistivity models and can easily incorporate topography into the model, the solution and programming of the problem with FD method are easier (Erdoğan et al., 2008; Demirci et al., 2012). Because of that, many researchers have preferred to use FD method in order to solve the two-dimensional forward MT problem (Jones and Price, 1970; Brewitt-Taylor and Weaver, 1976; Smith and Booker, 1991; Weaver, 1994; deLugão et al., 1997; Aprea et al., 1997; Candansayar, 2008). In this study, we used the FD method to obtain apparent resistivity and impedance phase values. Triangular cell definition was used not only to improve the stability of the algorithm but also to incorporate surface topography in the solution (Demirci, 2009; Demirci and Candansayar, 2010).