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Exploring the Groß Schönebeck (Germany) geothermal site using a statistical joint interpretation of magnetotelluric and seismic tomography models

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ABSTRACT

Exploration for geothermal resources is often challenging because there are no geophysical techniques that provide direct images of the parameters of interest, such as porosity, permeability and fluid content. Magnetotelluric (MT) and seismic tomography methods yield information about subsurface distribution of resistivity and seismic velocity on similar scales and resolution. The lack of a fundamental law linking the two parameters, however, has limited joint interpretation to a qualitative analysis. By using a statistical approach in which the resistivity and velocity models are investigated in the joint parameter space, we are able to identify regions of high correlation and map these classes (or structures) back onto the spatial domain. This technique, applied to a seismic tomography-MT profile in the area of the Groß Schönebeck geothermal site, allows us to identify a number of classes in accordance with the local geology. In particular, a high-velocity, low-resistivity class is interpreted as related to areas with thinner layers of evaporites; regions where these sedimentary layers are highly fractured may be of higher permeability.

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1. Introduction

The non-uniqueness of the inverse problem in geophysics, together with an incomplete knowledge of the subsurface and the varying spatial resolution of derived models, makes it difficult to interpret geophysical data directly in terms of geological units. The inversion models provide the spatial distribution of a physical parameter (e.g. electrical resistivity, seismic velocities, magnetic susceptibility), which is then commonly used as a proxy for a rock property in the area under investigation (e.g. porosity, mineral composition, fracture density). This interpretation is not always straightforward, because the physical parameters do not depend on a single property but on a (possibly complex) combination of several properties. For example, seismic velocity is not only controlled by mineral composition but also by temperature, pressure, pore space geometry and other rock properties, while electrical resistivity depends on rock porosity, fluid saturation, salinity, temperature, etc. (It is assumed hereunder that the cause of low resistivity is the presence of saline fluids, but it could be due to the existence of ore minerals, partial melt, or conductive clays.)

Therefore, it is common to use a combination of geophysical methods to obtain the distribution of independent physical properties over the area of interest in order to discriminate between the different possible geologic/lithologic units. This kind of study, however, is usually limited to a qualitative comparison of the different models, which may – or may not – yield a relation between the parameters in certain regions.

Quantitative approaches are usually based on either joint inversion of two independent data sets or on empirical or constitutive relations between the physical parameters. Approaches to joint inversion often include geometrical constraints, such as the requirement of coincident interfaces (e.g. Moorkamp et al., 2007) or the use of physical properties gradients (cross gradients inversion) to characterize the geometrical features of the models (Gallardo and Meju, 2007). Combined interpretations, and some joint inversion approaches, commonly link different geophysical parameters through rock property models. These models assume that a certain relation between the modelled physical parameters and the properties of interest (porosity, water saturation, etc.) is valid under particular conditions and, therefore, require local calibration, e.g. with borehole data. These local relationships can then be used, for example, as constraints for a joint inversion (Colombo et al., 2008) or to derive reservoir parameters via Bayesian inversion (Hoversten et al., 2005).

The magnetotelluric (MT) and seismic methods are the only geophysical exploration techniques that can yield reliable images at depths greater than the km-scale. The MT and seismic tomography techniques provide images of electric resistivity (ρ) and seismic velocity (V_p, V_s), respectively, with similar spatial resolution (e.g. Jones, 1987; Unsworth and Bedrosian, 2004) and are

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Nomenclature

$\mathrm{pdf}(\rho, V_\mathrm{p})$	joint probability density function of the resistivity–seismic velocity distribution
V_p	P-wave seismic velocity (m/s)
m	number of parameter points in the joint parameter space
$\mathrm{pdf}_i(\rho, V_\mathrm{p})$	probability density function of the ith parameter pair (ρ, V_p) of the joint resistivity–seismic velocity distribution
$V_{\mathrm{p},i}$	seismic velocity of the ith element of the parameter space (m/s)
$\delta\log(\rho_i)$	error of the electrical resistivity of the ith element of the parameter space
$\delta V_{\mathrm{p},i}$	error of the P-wave seismic velocity of the ith element of the parameter space (m/s)
$C_{\log(\rho)}$	mean error of $\log(\rho)$
s_i	normalized sensitivity of the electrical resistivity of the ith element of the parameter space
$\overline{\log(s)}$	average of the sensitivity of the electrical resistivity over all m parameters of the parameter space
C_{V_p}	mean error of V_p (m/s)
n_i	hit counts (number of rays crossing a particular cell) in the cell corresponding to the ith element of the parameter space
$\overline{\log(n)}$	average of the hit counts over all m parameters of the parameter space
$f(\mathbf{x})$	function representing the best fit to $\mathrm{pdf}(\rho, V_\mathrm{p})$, is a sum of n bivariate Gaussian peaks
$\mathbf{x} = [\log(\rho), V_\mathrm{p}]$	vector representing a pair resistivity–seismic velocity in the joint parameter space
n	number of bivariate Gaussian peaks in f
a_j	amplitude of the jth Gaussian function composing f

Greek letters

μ_j	centre of the jth Gaussian function composing f
ρ	electrical resistivity (Ω m)
ρ_i	electrical resistivity value of the ith element of the parameter space (Ω m)
Σ_j	covariance matrix of the jth Gaussian function composing f

often used in combination to derive models of the subsurface (e.g. Jones, 1998; Mechie et al., 2004; Maercklin et al., 2005; Unsworth et al., 2005). Both methods have their characteristic limitations. Magnetotellurics, for example, has an inherent loss of resolution with depth because it is based on diffusive fields. It has particular difficulty resolving structures located below good conductors due to the energy dissipated within them. Seismic refraction has trouble imaging vertical contrasts. By looking at both resistivity and velocity at the same time, we can build on the strengths of both methods and mitigate their weaknesses.

The problem with a joint MT–seismic tomography interpretation is that there is no unique or universal law linking electrical resistivity (ρ) and seismic velocity (V_p or V_s). Roughly speaking, while in a sedimentary environment electrical resistivity is mostly sensitive to the fluid phases present in the rock pores and/or fractures, seismic velocity is mainly imaging rock matrix properties. However, using a statistical analysis of the distributions of both resistivity and velocity, we can find certain areas in the models where a particular relation between physical parameters holds locally, thus allowing us to characterize this region as having a particular lithology.

Here, we use a statistical analysis, as described by Bedrosian et al. (2007) in order to correlate two independently obtained models (a V_p tomography model and an electrical resistivity model) of the Groß Schönebeck geothermal test site.

2. Methodology

The approach of Bedrosian et al. (2007) is based on a probabilistic method developed by Bosch (1999) whose premise is that diverse geophysical parameters are represented as a probability density function (pdf) in the joint parameter space. The coincident velocity and resistivity models are first interpolated onto a common grid. Therefore, a joint parameter space is built, where each point in the modelled area is associated with a velocity–resistivity pair. By plotting one parameter against the other in a cross-plot and including the error estimates we can then construct a joint pdf in the parameter space.

The areas of enhanced probability can be identified as classes that are represented by a certain range in both resistivity and velocity values. By mapping back these classes onto the spatial domain they can be related to particular lithologies and/or geological units. A similar approach has been used in different contexts and with different pairs of physical parameters. Bauer et al. (2003) combined seismic velocity and Poisson's ratio in order to establish a lithologic classification for an igneous complex in Namibia. Haberland et al. (2003) used electrical resistivity and seismic attenuation models to define regions of partial melting beneath the southern Bolivian Altiplano plateau, and Bedrosian et al. (2004) investigated the San Andreas Fault (USA) utilizing a combination of MT and seismic models.

Below we present a brief overview of the methodology; a more detailed analysis can be found in Bedrosian et al. (2007).

2.1. Interpolation

Before the joint pdf for both physical parameters can be assembled, the two sets of model values must be evaluated on a common grid. This is a crucial step because it is important to establish that the estimated and original point distributions are statistically similar. At the same time, one wants to avoid loss of information and creation of artefacts during the interpolation process. As the two models will be, in general, on different model meshes or grids, there are basically three options: the resistivity values can be interpolated onto the velocity grid, the velocity values can be interpolated onto the resistivity grid, or both parameters can be interpolated onto an independent grid. The latter option is rejected, because it involves an additional step, and one wants to keep the number of interpolations to a minimum.

An important difference between MT and seismic models is the discretization of the grids being used. For seismic models, the grids are commonly uniformly spaced. Due to the diffusive nature of the electromagnetic (EM) fields, which decay exponentially with distance (Vozoff, 1987), MT model grids are usually non-uniform, coarsening with depth and distance from the measurement points. In addition, seismic velocity models usually contain more mesh points than electrical resistivity models. Therefore, the interpolation of the velocity values onto the resistivity grid involves a net loss of velocity information. Taking into account that a uniform grid is desirable to ensure that all parts of the model are equally represented, the interpolation of the resistivity values onto the velocity mesh is chosen.

Interpolation of scatter points can be performed in a variety of ways, as described in standard geostatistical texts (e.g. Isaaks and Srivastava, 1989). We used an inverse distance weighted (IDW) interpolation that gives estimates from a weighted average of many

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