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Electromagnetic methods for exploration and monitoring of enhanced geothermal systems – A virtual experiment

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ABSTRACT

We present the concept of virtual electromagnetic experiments, which aims at setting up and optimizing the monitoring design for a potential stimulated geothermal energy reservoir. The concept builds on existing 3D geologic models, which are processed, meshed, assigned realistic electrical parameters and used for our finite element simulations on unstructured tetrahedral grids. The available simulation codes are able to cope with the high degree of geometric complexity in close-to-reality scenarios.

To demonstrate the procedure and the capabilities of our method, we show the model preparation and the simulation results for the transient electromagnetic method in the context of a prospective enhanced deep geothermal energy site at the fault ‘Roter Kamm’ near Schneeberg in Saxony/eastern Germany. We show the changes in the measuring signal caused by the stimulated fracture system in more than 5000 m depth for a range of electrical resistivity contrasts, which represent different porosity, pore connectivity or fluid resistivity variations. When a borehole receiver is advantageously placed at depth, percentage changes in the measuring signal of 25% can be expected. Our study demonstrates, that the optimal positioning of source and receiver is crucial for a successful monitoring and may only be achieved with advanced simulation techniques.

1. Introduction

Electromagnetic methods are suitable for monitoring the subsurface in the context of geotechnological projects such as geothermal energy or CO_2 sequestration (Streich et al., 2010; Börner et al., 2013). Based on the principles of current flow and electromagnetic induction, numerous methods are available to determine the electrical properties of the subsurface (see Fig. 1). Several studies have shown the capabilities of electromagnetic methods for the exploration, structural and thermal characterization of geothermal reservoirs (see the overviews given by Meju, 2002; Spichak and Manzella, 2009). Recently enhanced geothermal systems and their monitoring come into focus (e.g. Peacock et al., 2013).

In deep enhanced geothermal energy, there are several specific aspects to be considered besides the mere spatial reconstruction of the subsurface. In addition to the structural mapping of the potential geothermal reservoir, knowledge about the degree of fracturing, porosity, water content and water composition is of great importance. The shape and the pore content of the stimulated fracture system need to be described and its stability requires permanent monitoring. For this purpose, electromagnetic methods are ideally suited because of their high sensitivity to connected pore fluids. They are therefore an important addition to seismics. The monitoring design highly depends on the particular method used and the site to be monitored (e.g. Muñoz et al., 2010).

Other than inversion studies reported in the literature (see e.g. Árnason et al., 2010; Carbajal et al., 2012; Wamalwa and Serpa, 2013) the methodology we introduce in this study helps to understand the complex and site-specific behavior of electromagnetic fields in a 3D geological environment. Therefore, our virtual EM experiments allow the evaluation of the sensitivity pattern for an individual scenario and, consequently, facilitate the optimization of the field setup prior to the actual field campaign. To achieve this and to obtain robust and realistic results, the following three aspects have to be addressed (Börner and Spitzer, 2013):

- Is the geology represented sufficiently accurate in the 3D geologic model?
- Do we have adequate knowledge about the petrophysical parameters and the processes causing the contrasts in conductivity?
- Are the numerical simulation techniques sufficiently powerful to simulate the underlying physics in complex spatial environments with acceptable accuracy?

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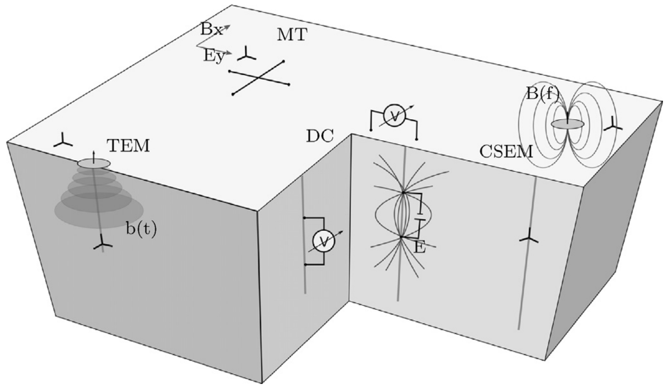

Fig. 1. Electromagnetic (EM) methods come in a wide variety of different configurations: surface, borehole, surface-to-borehole and cross-borehole methods generate different current and sensitivity patterns. The electromagnetic fields may be of natural origin (magnetotellurics MT) or generated by artificial sources. They are quasi-static (DC resistivity) or time-dependent. The latter are processed either in the time domain (transient electromagnetics TEM) or in the frequency domain (controlled-source electromagnetics CSEM). A virtual experiment serves for identifying the appropriate EM method and a suitable experimental design for resolving the desired target.

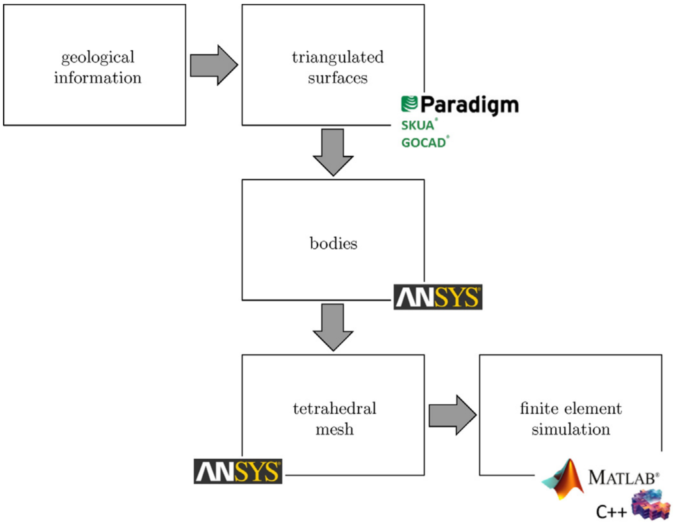

Fig. 2. Generalized workflow for the incorporation of 3D geologic models into finite element simulations. The tools used in this study are represented by their logograms.

In order to demonstrate the benefit of performing virtual experiments, we have chosen the transient electromagnetic method applied to a prospective deep geothermal energy site near Schneeberg in Saxony/Germany. Transient electromagnetic methods have already been used for crustal characterization in geothermal areas (see e.g. Strack et al., 1990). In the following, we outline the procedure of how to set up the virtual scenario from describing and incorporating the geologic model, to creating an appropriate mesh for the simulation and assigning realistic resistivities, to finally run the simulation and interpret the results in terms of feasibility.

2. Methods

2.1. Incorporating and meshing 3D geologic models

During the last decade several 3D geologic models of the subsurface of Germany have been developed (GeoMol, 2014; ISONG, 2014; NIBIS, 2014). These models describe both the geological features and the potential hydrological and geothermal resources of Germany. They are commonly developed and distributed in geomodeler software formats such as Paradigm Gocad® or Paradigm Skua® (Paradigm, 2011).

In the geomodeler software, a geologic horizon (i.e., the boundary between two adjacent geological features) is commonly represented as a triangulated 3D surface (see Fig. 2). Such triangulated surfaces are, however, problematic if the mesh employed for the simulation requires local refinements in particular regions. Therefore, we export the horizons to a computer aided engineering (CAE) tool using a plugin (e.g., Zehner, 2011) and subsequently transform them into freeform representations using non-uniform rational B-splines (NURBS) (De Casteljau, 1959). Then, each geological feature is turned into a 3D solid. All solids yield the complete 3D geologic model which is finally handed over to a meshing operator (e.g. Schöberl, 1997; Si, 2013).

Our finalized mesh is an unstructured tetrahedral grid with a local refinement depending on the geological features, the material characteristics and the chosen geophysical method. Local refinements might be necessary at sources and receivers, which can be placed on the surface or in boreholes. Electrical resistivities are then assigned to the tetrahedrons and the mesh is passed on to the finite element software for geophysical simulation.

2.2. Electrical rock properties

The electrical resistivity of a water bearing porous medium ρ_{rock} can be described by Archie's law (Archie, 1942):

$$\rho_{\text{rock}} = \frac{1}{\Phi^m S^n}\rho_{\text{water}} \tag{1}$$

It describes the direct proportionality of the electrical resistivity of a porous rock to the electrical resistivity of the water content of the pore space ρ_{water}. The proportionality factor depends on the porosity Φ, the water saturation S, and the empirical factors m (cementation exponent) and n (saturation exponent, for solid rocks m and n can be assumed to be close to 2).

Of course, Archie's law is very general and the individual conditions should be inferred from accompanying laboratory experiments or from analyzing drill cores.

2.3. Finite element simulation of transient electromagnetic fields

The virtual experiment presented here employs the transient electromagnetic method (TEM) in the time domain. A direct current flows in a conductor loop at the surface and is switched off at a defined time t_0 (Fig. 3). A mainly horizontal, ring-shaped eddy current system – represented by the electric field $\mathbf{e}$ – is induced in the subsurface (red rings $t_0, t_1 \ldots$ in Fig. 3). This current system spreads laterally and downwards with time and looses in magnitude. A magnetic field $\mathbf{h}$ is associated with the current flow at all times (denoted green in Fig. 3). The magnetic field $\mathbf{h}$ is related to the magnetic flux density $\mathbf{b}$ via a constitutive relation:

$$\mathbf{b} = \mu\mathbf{h} \tag{2}$$

Here, μ denotes the magnetic permeability and may be assumed to be a scalar value for this study. The decay of the electromagnetic field is measured using a three-component receiver located at the earth's surface or in a borehole. The characteristic behavior of the transient field contains information on the distribution of the electrical resistivity within the subsurface.

We calculate the 3D transient electromagnetic field using a Krylov subspace finite element code developed by our group