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Shape Optimization Methods Locating Layer Interfaces in Geothermal Reservoirs

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Abstract

Subsurface structures have a strong influence on fluid flow and heat transport in geothermal systems. We examine whether the position and shape of an interface between two lithological bodies can be detected based on temperature-depth measurements. We use a level set function to describe the interface, and a shape optimization method in combination with the adjoint variable based on the heat transport equation to invert for position and shape. Specifically, we investigate how advective heat transport affects the identification of the interface and show that the method successfully retrieves interface positions in synthetic 2D cases of two-layer models.

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Keywords: level set function; adjoint variable; shape optimization; inversion problem; geothermal reservoir; heat transport equation

1. Introduction

Inversion methods are widely applied to determine petrophysical properties, and increasingly also structural elements, of the subsurface. Oliver summarized in [1] the key developments in reservoir history matching including reparameterization of the model variables, computation of sensitivity coefficients, and uncertainty quantification.

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Associated issues and techniques of modeling uncertainty of Earth systems can also be found in [2]. We present here a shape optimization method with level set functions and adjoint variables to infer the position of subsurface geophysical layers, based on temperature data measured in boreholes. We study a synthetic 2D model with two layers of different petrophysical properties (i.e. thermal conductivity and permeability). The goal is to identify the interface position and shape from temperature depth data measured in several boreholes. This task is formulated as an optimization problem. A least-squares function is first established subject to the heat transfer equation governing the temperature field and its temporal variations. Instead of directly computing the gradient of the objective function, we compute the adjoint variable of temperature. A level set method is then used to represent the shape of the geological interface. The change of the level set function describes the evolution of the model during optimization iterations. The level set function follows a Hamilton-Jacobi equation and the zero level set is used to indicate location of the interface. With the adjoint variable and temperatures predicted from forward modeling of conductive and advective heat transport in the model, an artificial velocity is calculated at each grid point. This velocity is subsequently used for a stepwise update of the level set function and, therefore, the position of the layer. This procedure is repeated until a specified tolerance level is obtained and the position of the geological interface is retrieved. In [3], Papadopoulos addressed the reconstruction of geophysical layers with the combination of the adjoint variable and the level set method for the case of heat conduction. We extended this work so that it can be used to compute adjoint variables for both conductive and advective heat transport cases. We describe the theoretical aspects of this extension in the next section, and then test our method in a synthetic case study in several model scenarios.

2. Methods

2.1. Forward Modeling

The forward problem is described by the heat transport equation for the fluid flow, which can be derived by considering the content of heat change of a control volume and applying Darcy's Law and Gauss' theorem [4]. The heat transport equation can be expressed as:

$$\nabla(\lambda \nabla T - \rho_f c_f T v) = \frac{\partial T}{\partial t}(\phi \rho_f c_f + (1-\phi)\rho_m c_m) \tag{1}$$

Where ρ_f is fluid density (kg m^{-3}), c_f is fluid specific heat capacity ($J\ kg^{-1} K^{-1}$), v is Darcy (filtration) velocity (m s^{-1}), ϕ is porosity, $\rho_f c_f$ is volumetric heat capacity of the fluid, $\rho_m c_m$ is volumetric heat capacity of the rock matrix , λ is effective thermal conductivity of the saturated porous medium ($W m^{-1} K^{-1}$). Currently we only take the distribution of conductivity into consideration, assuming other parameters as constant. Also conductivity λ is assumed to be isotropic, so it is treated as a scalar.

2.2. Adjoint Method

In order to do shape optimization of the interface, the problem we are trying to solve here is to minimize the (quadratic) temperature residual under the constraint of the heat transport equation. To avoid directly computing the gradient of the objective function with respect to heat transport, we apply the adjoint method and compute the adjoint variable of temperature instead. Sirkes and Tziperman explained in [5] the process of continuous adjoint approach for deriving the adjoint equations, by considering a simple one dimensional advection-diffusion equation. For our case, similarly, we can first define an objective function: