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Application of Inversion Modeling in Geothermal and Hydrothermal Reservoirs

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ABSTRACT

In geothermal reservoir studies we often have to draw conclusions and make decisions using uncertain or incomplete data sets. Reservoir studies includes modeling of all relevant geological structures, populating the model with physical and hydraulic properties and examining their evolution due to changes in pressure, temperature and applied stress.

The Berlin study area is placed in the North German Basin (NGB) and its present topographic relief is the result of Pleistocene glaciations. The groundwater in the sedimentary units below Berlin is characterized by freshwater in loose sediments at shallow depth and a salty brackish to saline groundwater within the deeper sediments. Between these two different groundwater compartments a natural hydrogeological boundary is provided by the presence of an impervious clay-enriched layer, separated by a Rupel clay layer.

We are using an inversion analysis approach to estimate parameters relevant for coupled heat and transport processes and to quantify the uncertainty associated while using available local data within the regional city context. The result of this study would provide a geologically consistent model useful for the assessments of the physical hydro-thermal and mechanical process occurring in the subsurface. Such a model would therefore serve as a tool to attempt a detailed study of the potential of geothermal energy application in the sedimentary units beneath Berlin.

To accomplish this task we couple a commercial finite element hydro-geological code (FEFLOW) to a parameter estimation package (PEST) and we use them to characterize the uncertainty and to estimate hydraulic parameters of interest. PEST not only can be used to calibrate the model but also to analyze the spectrum of the possible solution and consequently uncertainty range. A special algorithm (Gauss-Levenberg-Marquardt algorithm, GLMA) is used to alter the model parameters such that to improve its fit to observed data, iteratively.

1. INTRODUCTION

Determining physical and hydraulic properties of sedimentary and crustal rocks is crucial in modeling geothermal reservoirs performance. Generally, THMC coupled simulations of a geothermal reservoir consist of five physical and chemical processes that are required to be solved numerically: (1) mechanical deformation, (2) fluid flow, (3) heat transfer, (4) multi species transport, and (5) chemical reactions. In addition, understanding of these processes and their interrelations requires a method to quantify the range of their applicability and limits of prediction. The overall goal of this study is to consider all processes contributing to the internal heat budget of the study area (hydrothermal modeling), to properly predict pressure and temperature distribution at depths, and to provide a quantitative analysis of the dynamics interaction between these physical process. Furthermore, we are addressing at the same time the effects of the different parameters involved and the uncertainty associated with.

2. GEOLOGY OF BERLIN AREA

The previous study by Sippel et al. (2013) derived the thermal model and calculated the internal heat budget in Berlin area, while quantifying the effects of different processes involved. The structural model included shallow and deep aquifers below the city of Berlin and different crustal units reaching down to lithospheric mantle (see Figure 1 and Sippel et al. 2013). Moreover for the upper part, the model boundary was set to surface topography and at base down to Lithosphere – Asthenosphere Boundary (LAB). Within the sedimentary succession, key geological features such as regional aquifers and aquitards as well as distribution of salt structures are represented in particular by Tertiary Rupelian Clay aquitard.

The latter aquitard is of specific relevance for the groundwater dynamics in the subsusrface, since it separate hydro-geologically, the fresh Tertiary aquifers from the deeper brackish to saline Mesozoic aquifers. That is, the hydraulic connections between the upper and lower aquifers do exist in areas where the Rupelian Aquitard is missing (hydrogeological windows). Hydrogeological windows act as preferential domains of hydraulic interconnectivity between the different aquifers at depth and likely result in across-aquifer heat and mass transport, which might lead to mixing of warm and saline groundwater with cold and freshwater within both aquifers. This may result in buoyant upward groundwater flow transporting heat and mass to shallower levels within the same Mesozoic Aquifer.

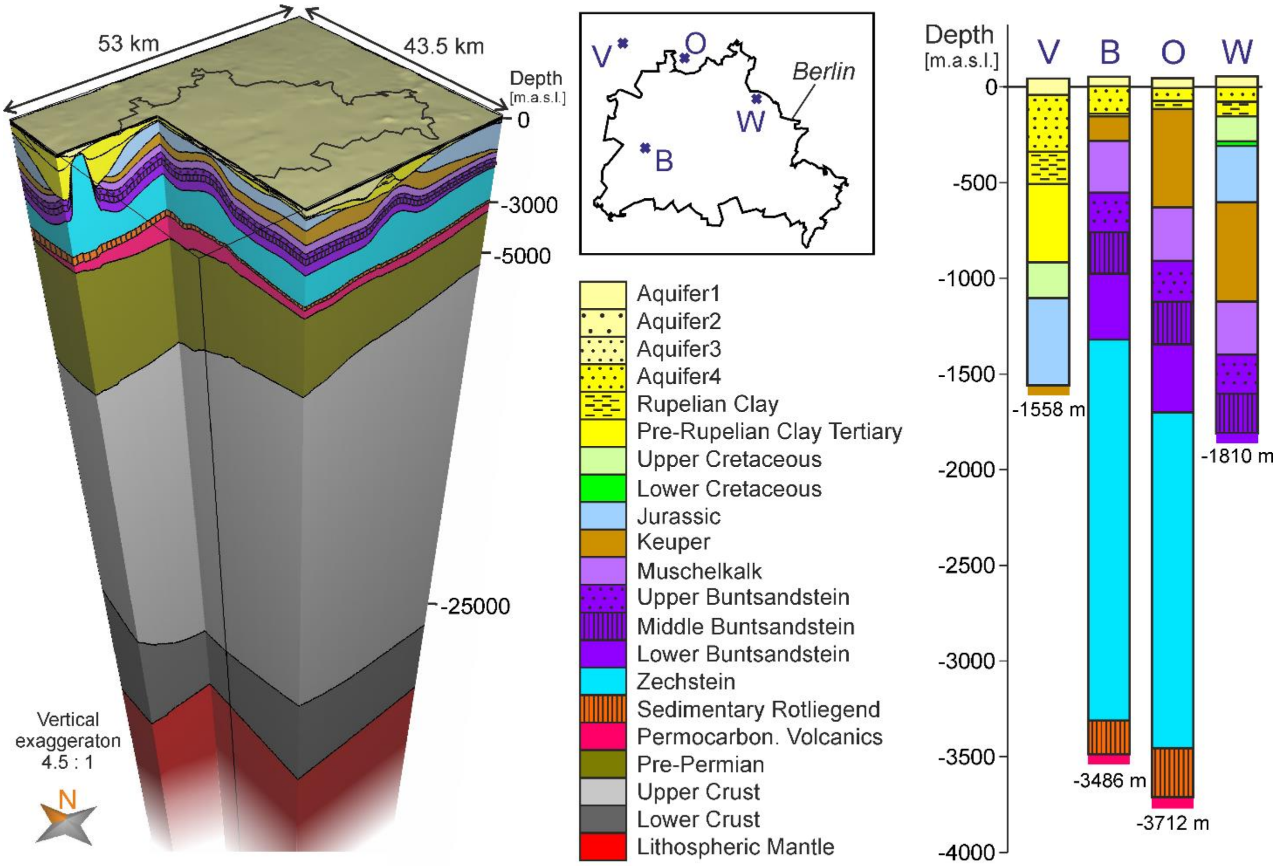

Figure 1: 3D structural model of Berlin with differentiated geological units and drilled boreholes (named as V, B, O and W) from Sippel et al. (2013).

The present relief of earth's surface in Berlin is the result of inland glaciations that has determined the morphology of the city. The geological map of Berlin includes Warsaw-Berlin Glacial Spillway with its Panke Valley branch in the middle, Barnim Plateau to the north, and the Teltow Plateau with the Nauen Plate to the south (see Figure 2).

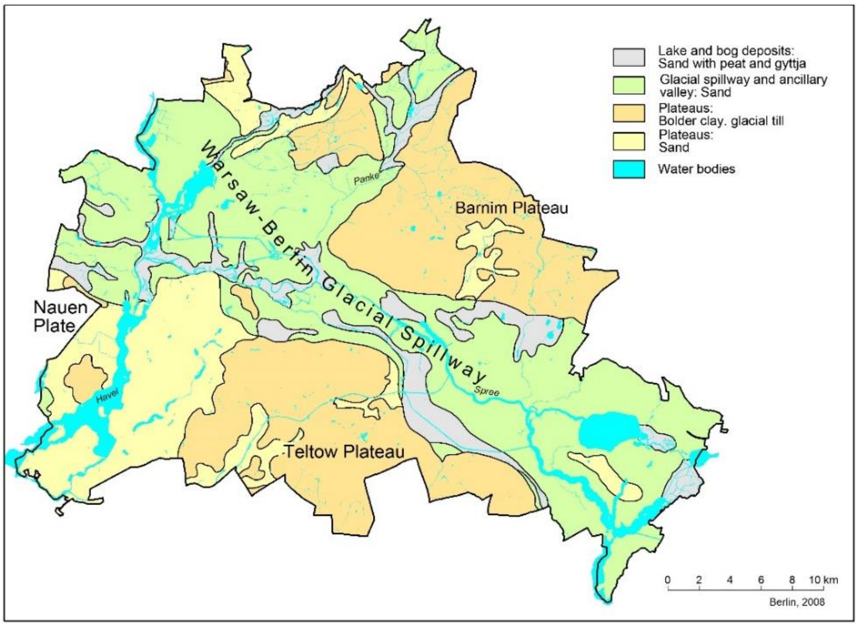

Figure 2: The geological map of Berlin includes Warsaw-Berlin Glacial Spillway with its Panke Valley branch in the middle, Barnim Plateau to the north, and the Teltow Plateau with the Nauen Plate to the south (Berlin Environmental Atlas 2013).

2. MODDELING APPROACH

A finite element commercial software (FEFLOW) is employed to simulate the heat and fluid flow in porous media (Diersch 2014) and to quantify the impact of uncertainty associated with input parameters in geothermal potential of Berlin area. The FEFLOW models represent a necessary level of reduction and idealization where the most important processes are emphasized and the uncertainty within the input parameters would not be considered. Similarly, the previous studies, for example Sippel et al. (2013), considered homogeneous input parameters and did not investigate on a range of possible values for different parameters and therefore, the model prediction uncertainty was not determined. In our modeling approach, first we estimate the range of thermal and hydraulic conductivity for Rupelian clay aquitard and hydrogeological windows, connecting fresh and salty water. Then, we determine the spatial distribution of the thermal and hydraulic conductivities by an iterative model fit between calculated and observed parameters (temperature and hydraulic heads). Based on a starting 3D coupled heat and transport model we test the variability of the assigned thermal and hydraulic properties using a parameter estimation tool, PEST.

3. PARAMETER ESTIMATION (PEST)

PEST is using the Pilot points to bridge the gap between estimating a parameter value in every cell of a model and subdividing models into a small number of homogeneous zones (Dohrety 2002). The goal of pilot points is to provide an intermediate approach for characterizing heterogeneity in groundwater models between direct representation of cell-by-cell variability and reduction of parameterization to few homogeneous zones. Pilot points serve as surrogate parameters at which values are estimated in the inverse-modeling process, and their values are interpolated onto the modeling domain in such a way that heterogeneity can be represented at a much lower computational cost than trying to estimate parameters in every cell of a model. Pilot points can be useful for any model parameter or boundary condition, but are most commonly applied to aquifer hydraulic conductivity. The solution space is the portion of parameter space that is informed by the observations while the null space accounts for parameters (or combinations of parameters) that are unknown and not informed by observations. A special algorithm (Gauss-Levenberg-Marquardt algorithm, GLMA) is used to alter the model parameters such that to improve its fit to observed data, iteratively.

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