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Passive temperature tomography experiments to characterize transmissivity and connectivity of preferential flow paths in fractured media

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SUMMARY

The detection of preferential flow paths and the characterization of their hydraulic properties are major challenges in fractured rock hydrology. In this study, we propose to use temperature as a passive tracer to characterize fracture connectivity and hydraulic properties. In particular, we propose a new temperature tomography field method in which borehole temperature profiles are measured under different pumping conditions by changing successively the pumping and observation boreholes. To interpret these temperature-depth profiles, we propose a three step inversion-based framework. We consider first an inverse model that allows for automatic permeable fracture detection from borehole temperature profiles under pumping conditions. Then we apply a borehole-scale flow and temperature model to produce flowmeter profiles by inversion of temperature profiles. This second step uses inversion to characterize the relationship between temperature variations with depth and borehole flow velocities (Klepikova et al., 2011). The third inverse step, which exploits cross-borehole flowmeter tests, is aimed at inferring inter-borehole fracture connectivity and transmissivities. This multi-step inverse framework provides a means of including temperature profiles to image fracture hydraulic properties and connectivity. We test the proposed approach with field data obtained from the Ploemeur (N.W. France) fractured rock aquifer, where the full temperature tomography experiment was carried out between three 100 m depth boreholes 10 m apart. We identified several transmissive fractures and their connectivity which correspond to known fractures and corroborate well with independent information, including available borehole flowmeter tests and geophysical data. Hence, although indirect, temperature tomography appears to be a promising approach for characterizing connectivity patterns and transmissivities of the main flow paths in fractured rock.

1. Introduction

The accurate prediction of fluid flow in fractured media is a challenging problem, as flow may be localized in few small fractures with heterogeneities at all scales (e.g., Berkowitz, 2002). The classical approach to infer detailed flow properties relies on the identification of the flowing fractures followed by hydraulic testing with packers (e.g., Shapiro and Hsieh, 1998). Recent numerical developments (e.g., Jim and Liu, 2000; Brauchler et al., 2003; Illman et al., 2009; Berg and Illman, 2013) have significantly improved hydraulic tomography methods in fractured media. However, spatial resolution of the inferred tomograms strongly depends on the number of observation intervals (Sharmeen et al., 2012). Furthermore, this approach requires the installation of packers which is often not possible. To avoid these practical issues, we can consider other types of data that can be more easily obtained and that are directly sensitive to ground water flow.

Temperature data meet these conditions as geothermal heat can be considered as a natural tracer of groundwater flow (Anderson, 2005; Saar, 2011). Furthermore, temperature profiles can be obtained easily and continuously in space by logging a temperature probe in the observation borehole. The use of fiber optic technology can also greatly improve the temporal and spatial coverage of borehole temperature measurements (Read et al., 2013). Temperature data have often been used for inferring vertical or horizontal groundwater flow velocities assuming homogeneous

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aquifer properties (Bredehoeft and Papadopulos, 1965; Reiter, 2001; Anderson, 2005; Saar, 2011).

In fractured rocks, abrupt temperature changes are often observed at specific depths (e.g. Ge, 1998; Bense et al., 2008; Chatelier et al., 2011). When groundwater flow occurs within a permeable fracture, it may perturb the temperature profile within and around the fracture due to advected flow carrying either warmer or cooler fluid (Ge, 1998). In large-scale faults, velocities can be large enough to influence the regional heat flux distribution (Deming, 1993; Ge, 1998; Anderson, 2005; Saar, 2011; Garibaldi et al., 2010). Moreover, ambient flow in boreholes themselves, that arises due to the difference in hydraulic heads between fractures intersecting the borehole, affects temperature borehole logs (Bidaux and Drogue, 1993; Pehme et al., 2010; Klepikova et al., 2011). A few studies have considered borehole temperature profiles in fractured rocks under induced fluid flow conditions (Flynn, 1985; Silliman and Robinson, 1989). Among them Silliman and Robinson, 1989 argued that temperature anomalies produced by pumping in adjacent boreholes can be used for initial estimates of fractures connecting a given ‘pumping-observation’ borehole pair. Few of these studies, however, were able to quantify the fracture hydraulic properties or describe how these fractures form different flow paths. This is the objective of this study.

Recently, we have shown how borehole temperature gradients may be sensitive to vertical borehole flow velocities (Klepikova et al., 2011). By applying a fluid flow and heat transfer forward numerical model, we were able to obtain borehole flow profiles under ambient, pumping (while pumping at the top of the borehole) and cross-borehole (while pumping in neighboring boreholes) flow conditions from borehole temperature-depth profiles. Furthermore, such flow profiles can be used to characterize the connectivity and hydraulic properties of the main flow paths in fractured rock (Paillet, 1998; Paillet, 2000; Le Borgne et al., 2006). The method is based on the idea that pumping modifies hydraulic heads in flow paths intersecting a pumping borehole, which in turn produce changes in vertical borehole flow in observation boreholes. In a recent study, a new inversion method was developed to invert such borehole flow data. This approach, referred as flow tomography (Klepikova et al., 2013), was successful in estimating inter borehole fracture hydraulic properties as well as fracture connectivity on synthetic examples. Here, we propose to investigate how both approaches may be coupled to invert borehole temperature data in different flow conditions to estimate fracture connectivity and hydraulic properties between pairs of boreholes.

In this contribution, we propose a multi-stage inversion framework to interpret temperature measurements obtained during sequential cross-borehole pumping tests. We propose to call such experiments as passive temperature tomography experiments. The term “passive” means that temperature is used as a passive tracer without any heat injection, in contrast to the approach taken in other recent works (Leaf et al., 2012; Read et al., 2013; Wagner et al., 2013). Although this study makes use of the methodologies presented in Klepikova et al. (2011, 2013)), it presents three novelties with respect to these previous works. First, in the present study we propose a new method for automatic inversion of borehole temperature profiles that significantly facilitate data interpretation. The tomography approach based of borehole temperature measurements presented here is analogous to the flow tomography approach (Klepikova et al., 2013). However, an important advantage of this new method over direct flow measurements is that temperature can be measured more easily and continuously. Finally, this study presents the first application of this method using a tomographic approach in a fractured rock site.

In the first part we briefly review the source of temperature variations in the subsurface and examine under which conditions and assumptions our inverse approach may be applied. We then present the methods used in the inversion procedure. In the third part, we describe the experimental site and the temperature tomography experiment conducted. Finally, we present and discuss the results of the application of the inverse approach to three boreholes from the experimental field site.

2. Background and methodology proposed

In the near surface, temperature-depth profiles are influenced by seasonal temperature variations of the land surface. Typically, this zone includes the first 10 m below the ground, although this depends on the local thermal properties. Below this depth, the temperature gradient is influenced by the heat flux, the thermal conductivity of rocks (Freifeld et al., 2008), radioactive heat sources (Perry et al., 2006) and longer term climate variations (e.g., Ferguson, 2006). Moreover, depending on hydrogeological parameters, groundwater flow may have a significant effect on the subsurface temperature regime (e.g., Anderson, 2005; Ferguson, 2006). To characterize the factors that control heat transfer in the subsurface, precise measurements of temperature as a function of depth should be considered.

In this study we focus on permeable fractured rocks in the upper crust (typically above 200 m deep), where advection can have a significant effect on the subsurface temperature. We assume that the temperature gradient in the regional rock mass increases monotonically (i.e. constant geothermal gradient) (Klepikova et al., 2011). Given typically small temperature ranges for this depth, the dependence of viscosity on temperature is neglected. In such media induced or natural localized fracture flow generally creates local temperature anomalies. An example of flow and temperature pattern for two boreholes connected by one main flow path under ambient, single and cross-borehole pumping conditions is shown in Fig. 1. In such a system, heat is carried by vertical borehole flow and dissipates to the surrounding rocks. Hence, borehole flow under ambient (Fig. 1A) and pumping conditions (Fig. 1B) significantly disturb the equilibrium borehole temperature profiles.

Ambient vertical borehole flow is induced by differences in hydraulic head between the different flow paths that intersect observation boreholes (e.g., Pehme et al., 2010; Klepikova et al., 2011). These differences in hydraulic heads are in general due to regional flow conditions (e.g., Elci et al., 2001) and the resulting vertical borehole flow may significantly disturb the temperature profile (e.g., Chatelier et al., 2011) (well 1, Fig. 1A). When pumping in one of the wells, hydraulic head changes occur in the flow path connected to the pumping well. The flow paths connecting a borehole pair transmit hydraulic head variations to the neighbor borehole. This difference in hydraulic heads, in turn, depends on the transmissivities of the connecting fractures. For instance, in Fig. 1B the upflow in the observation well 1 is maximum since only the upper fracture is connected and transmits the drawdown induced by pumping, implying a temperature increase in the well 1 in response to pumping from the well 2. In the well 2 (Fig. 1B), an increase of the flow velocity above flowing fractures in the pumping borehole implies that the water flowing in the borehole has less time to exchange heat with surrounding rocks hence it also implies temperature profile perturbations.

Here we propose a multi-stage tomography approach based on an inverse framework for the interpretation of temperature profiles under combinations of pumping conditions to infer the full connectivity pattern as well as fracture hydraulic properties. The inversion framework proposed in this study has three main steps:

1. Automatic detection of fracture zones intersecting each borehole by applying changepoint modeling to temperature profiles under ambient flow conditions and steady pumping flow conditions.