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Single and cross-borehole temperature profiles for estimating fracture zone hydraulic properties

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The development of high resolution borehole flowmeters have enabled significant progresses in the characterization of heterogeneous porous and fractured aquifers by allowing for the direct measurement of the flow heterogeneity [e.g., Le Borgne et al., 2007, Hess, 1986, Paillet, 1998]. However, the precise estimation of flow velocities generally requires the repeated measurements at a fixed depth. This constrain implies that obtaining a detailed spatial distribution of flow velocities in a borehole is very time consuming.

Alternative indirect estimations of flow velocities based on the inversion of temperature anomalies have been proposed [Anderson, 2005]. The advantage of temperature measurements is that temperature can be measured easily and very accurately, continuously in space and time. Several studies have intended to use temperature anomalies to quantify vertical or horizontal groundwater flow velocities [Bredehoeft, 1965, Cartwright, 1979]. In fractured rocks, well temperature profile often shows temperature changes which are caused by water of warmer or colder origins flowing in permeable fractures [Ge, 1998]. Most of these studies assume that the temperature profile in the well is representative of temperature in the aquifer. However, in open or screened boreholes, differences in hydraulic head between large-scale flow paths that connect to a borehole generally create ambient vertical flow within the borehole (e.g. Paillet, 1998). These differences in hydraulic head may be due to regional flow conditions: downward flow in recharge areas and upward flow in discharge areas. The resulting vertical flow within the borehole significantly disturbs the temperature profile.

Based on a numerical model of flow and heat transfer at the borehole scale, we propose a method to invert temperature measurements to derive borehole flow velocities. This method is applied to an experimental site in crystalline rocks, located in Ploemeur, in south of Brittany (France). Vertical flow velocities deduced from the inversion of temperature measurements are compared with direct heat-pulse flowmeter measurements showing a good agreement over two orders of magnitudes. Applying this methodology under ambient, single and cross borehole pumping conditions allows us to estimate fracture hydraulic head and local transimissivity as well as inter-borehole fracture connectivity. Thus, these results provide new insights on how to include temperature profiles in inverse problem for imaging heterogeneous fracture properties.

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