Thermal imaging of sparse permeable fractures embedded in intact granite

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Introduction

Characterizing the geometry of permeable faults or fractures is critical to many subsurface applications. It is a key step, for example, in the planning of deep geothermal energy projects and nuclear waste storage facilities, and requires advanced geophysical imaging methods. Here, we present a new approach to extract information on fracture orientation from borehole thermal anomalies. This method assumes the occurrence of a single fracture surrounded by impermeable rock, intersected by a borehole (equipped with temperature sensors) at a known distance to a heat source.

Model of heat conduction from a planar fracture

We assume a planar fracture heated from a point source, intersecting a borehole at a discrete location (Fig. 1). Conduction parallel to the fracture is neglected so that the matrix temperature can be expressed as:

$$T_m(x, y, t) = \int_0^t dt' g(y, t - t') T_f(x, t'), \tag{1}$$

where $g(y, t)$ is the Green function of the heat equation for a Dirac boundary. It is assumed that the initial temperature of the matrix is the same as the temperature of the fracture $T_f(x, t')$.

The temperature profile in a borehole which intersects a heat carrying fracture is given by:

$$T_m(y, t) = \int_0^t dt' g(y, t - t') T_f[a(y + b], t'). \tag{2}$$

Synthetic temperature profiles are illustrated on Fig. 2, showing the effect of varying fracture orientation from 0-80° and time. A finite-element model was setup using the software package COMSOL v5.3 to confirm that lateral heat conduction is negligible (see Fig. 2, right panel).

Field application

Site & Experimental procedure

To test our approach, we performed a 40-day cross-hole heat injection experiment at the Grimsel Rock Laboratory, Switzerland, targeting shallow (0.5 km depth) crustal faults dissecting the Central Aar Massif (Fig. 3). Hot water injection was carried out with an electrical flow-through heater , heating water up to 45 °C at a flow rate of 2.0-2.5 L/min. Distributed temperature measurements were acquired in six boreholes through single-ended measurements using a 4-channel XT-DTS™ Silixa system, with a 0.25 m spatial resolution.

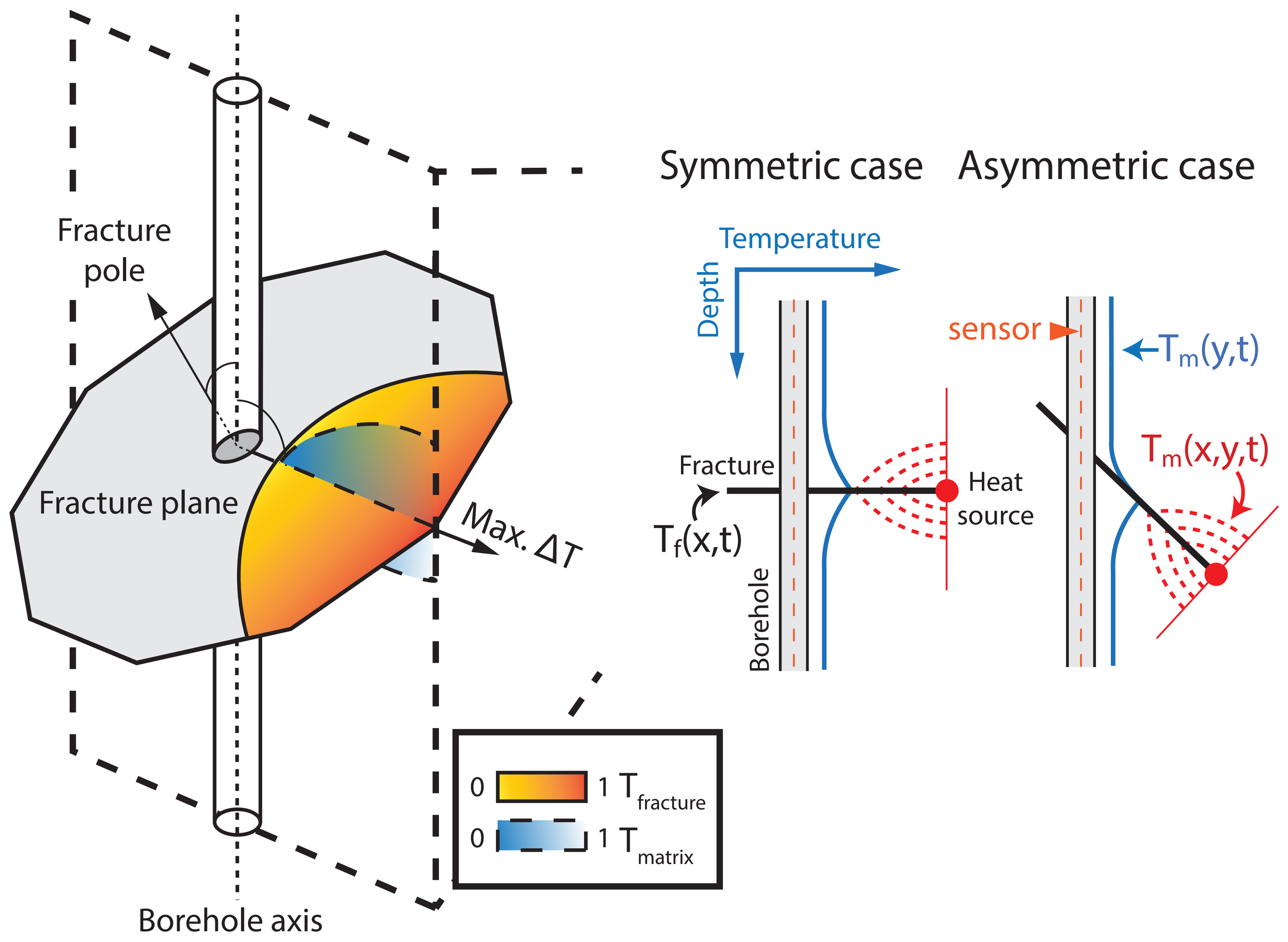

Figure 1: Sketch illustrating the impact of fracture orientation on conduction-dominated heat flow anomalies in borehole temperature profiles.

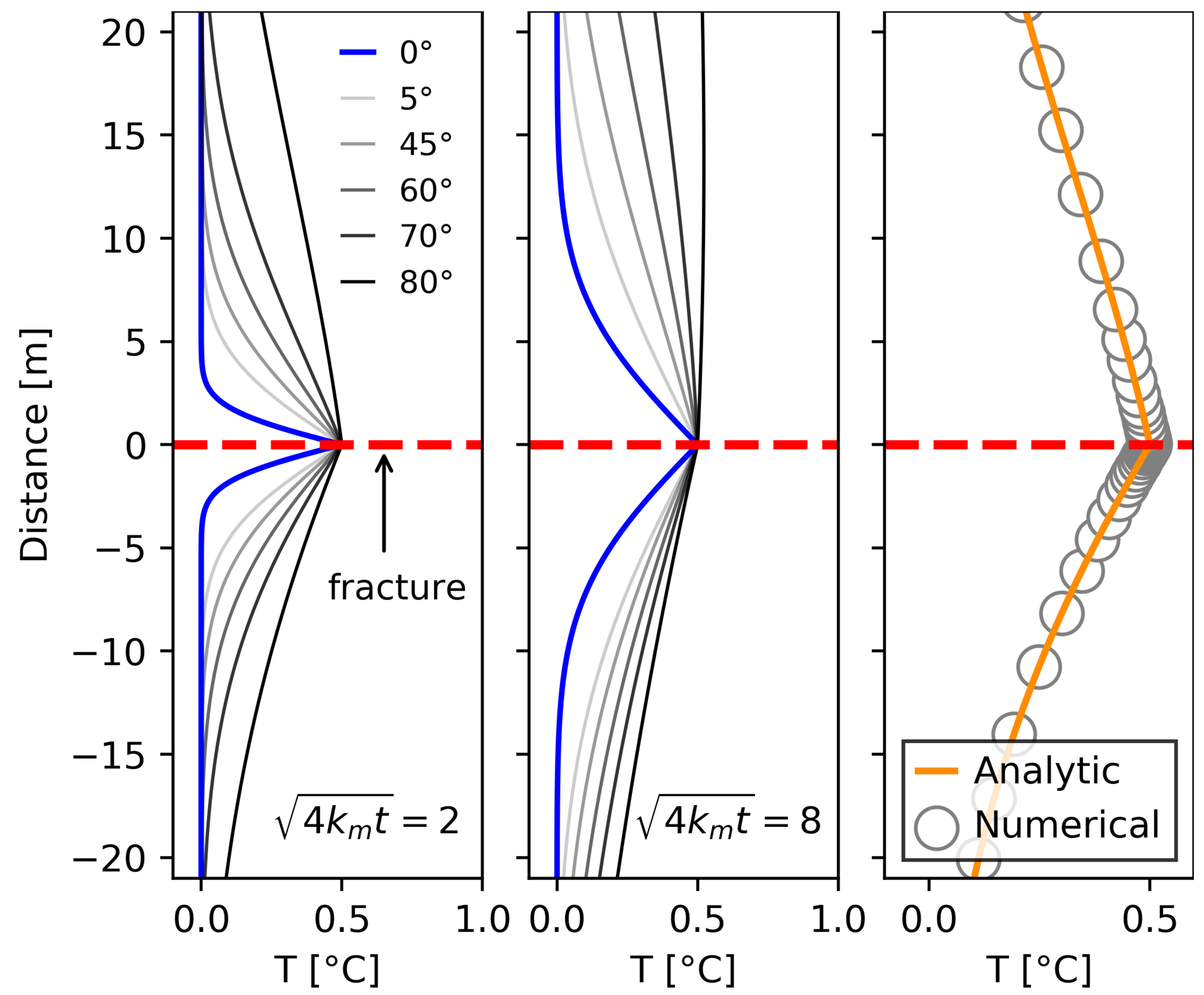

Figure 2: Synthetic borehole temperatures for various fracture orientations (left and center panels). Analytic and numerical solutions for a 80° fracture (right panel).

Initial results

Discrete thermal breakthroughs were observed in all six boreholes. Temperature profiles for FBS2 after 20, 30 and 40 days are plotted on Fig. 4, including also fracture density (p_{10}) and initial fits (indicating a good match between 50-60°, i.e. within the range of orientations observed).

Outlook

Results suggest that temperature signals carry structural information which may help to constrain flow paths geometry in sparse fractured media. Numerical inversion of the field data are currently undertaken.

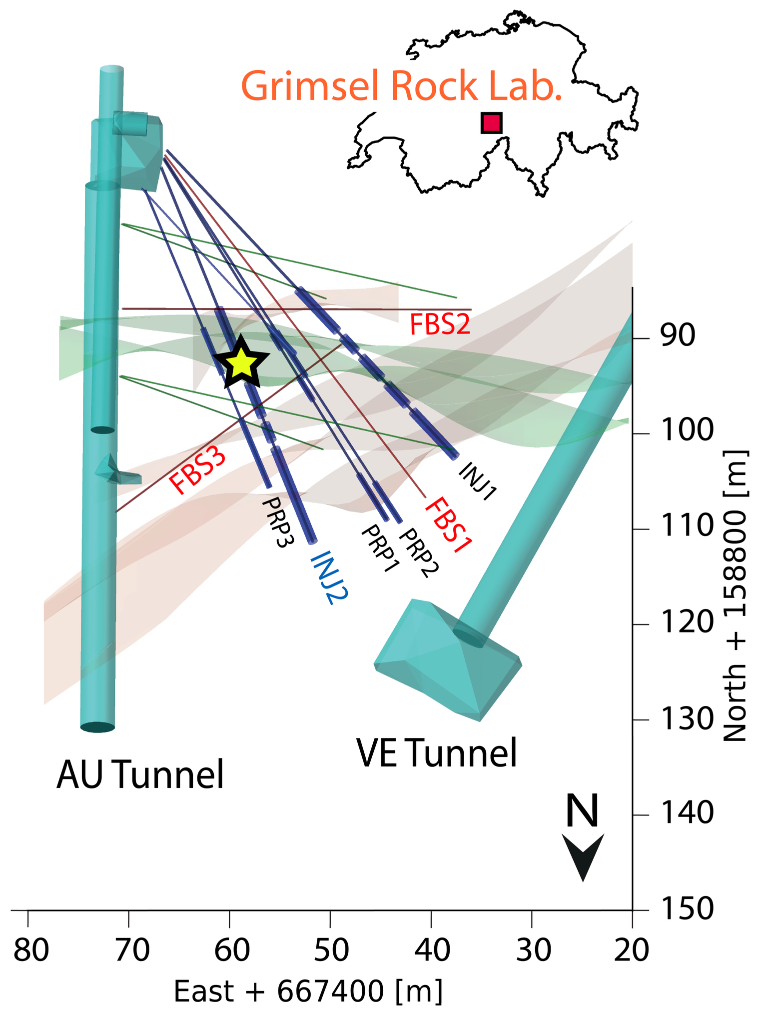

Figure 3: Distributed temperature sensing was carried out using 6 boreholes: 3 packed-off (PRP) and 3 grouted boreholes (FBS). The star denotes the injection point.

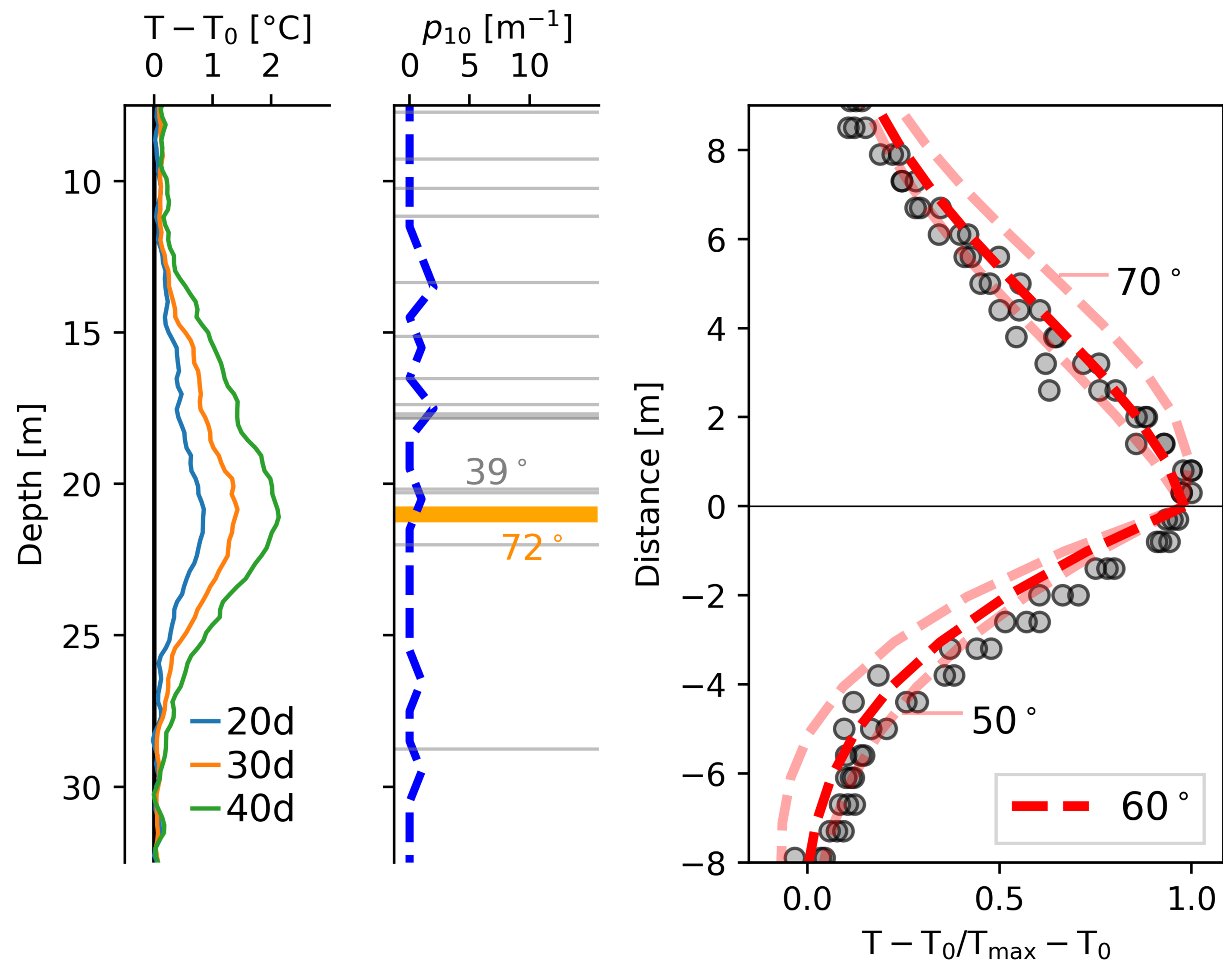

Figure 4: Temperature along FBS2 after 20, 30 and 40 days (left). Fracture density (blue) and intersections (gray lines, the orange line denotes a fault). Manual fits to observed temperatures (right).