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Use of heat as a groundwater tracer in fractured rock hydrology

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Crystalline rocks aquifers are often difficult to characterize since flows are mainly localized in few fractures. In particular, the geometry and the connections of the main flow paths are often only partly constrained with classical hydraulic tests. Here, we show through few examples how heat can be used to characterize groundwater flows in fractured rocks at the borehole, inter-borehole and watershed scale. Estimating flows from temperature measurements requires heat advection to be the dominant process of heat transport, but this condition is generally met in fractured rock at least within the few structures where flow is highly channelized. At the borehole scale, groundwater temperature variations with depth can be used to locate permeable fractures and to estimates borehole flows. Measurements can be done with classical multi-parameters probes, but also with recent technologies such as Fiber Optic Distributed Temperature Sensing (FO-DTS) which allows to measure temperature over long distances with an excellent spatial and temporal resolution. In addition, we show how a distributed borehole flowmeter can be achieved using an armored fiber-optic cable and measuring the difference in temperature between a heated and unheated cable that is a function of the fluid velocity. At the inter-borehole scale, temperature changes during cross-borehole hydraulic tests allow to identify the connections and the hydraulic properties of the main flow paths between boreholes. At the aquifer scale, groundwater temperature may be monitored to record temperature changes and estimate groundwater origin. In the example chosen, the main water supply comes from a depth of at least 300 meters through relatively deep groundwater circulation within a major permeable fault zone. The influence of groundwater extraction is clearly identified through groundwater temperature monitoring. These examples illustrate the advantages and limitations of using heat and groundwater temperature measurements for fractured rock hydrology.