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Testing of Drill Core Permeability and Porosity in Fault Zones: Implications for Groundwater Flow Under Basins and Geothermal Resource Mapping

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1. Introduction

In Japan, it is recognized that much of the geothermal water resources are channeled through fracture zones that occur along tectonic lines or faults. Many wells that produce thermal water (e.g. onsen or hot spring bath water, heating water, and high-temperature water and steam for power production), either source the thermal water from permeable sedimentary or volcanic strata that cover the fracture zones in the crystalline basement, or directly from faulted crystalline rocks. There is always a significant interest in the hydro-physical properties of such fault zones, because it can help with modelling and calculations of water flow and heat transfer.

2. Data Sources and Methods

Permeability to gas or water is recognized as the main physical property of rocks for controlling the rate of fluid flow through low-porosity rocks. Porosity of rocks is directly related to the poro-elastic or storative properties of any aquifers in rocks, and also correlated with permeability. However, the sampling and results of these properties depend on the scale of investigation and various methods exist (Fig. 1).

One of the major sources of information is the drill core from exploration boreholes and wells. At Kyoto University, we have been testing the drill core from active fault zones and from granitic rocks, using practical N2 gas probe permeameter directly on spots on drill core (Scibek, 2019; Scibek and Annesley, 2021).

One fault is the Tsukiyoshi normal fault at Mizunami, Gifu (granite), part of a pull-apart zone in a small basin. That research site has been studied by JAEA and Kyoto University for two decades, as an analog site for radioactive waste repository in granitic rocks.

The second research site is the drill hole and drill core from the Nojima fault zone on Awaji Island, Hyogo. That fault cuts granitic rocks on the edge of Osaka basin, is linked to the active fault system in that region, recently displaced during the 1995 Kobe earthquake. The exploration hole was drilled after that disaster to study the fault structure and properties.

3.Example from Nojima fault

Form our studies on active faults, such as Nojima fault at NIED drill hole from Awaji Island, we study how the rock deformation and alteration appear to relate to rock porosity and permeability. The more detailed results allow us to map the rock permeability continuously along the drill core, correlate it to detailed rock deformation and mineralogical properties, porosity, and in-situ interval

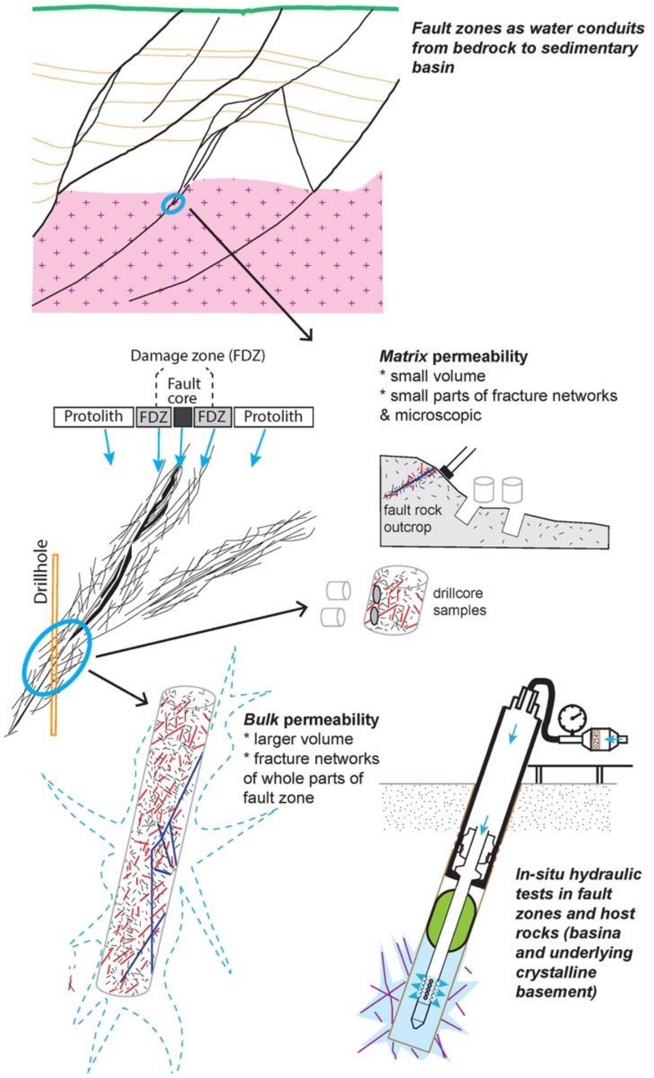

Figure 1. Conceptual diagram of permeability and porosity testing scales on drill core and in-situ in fault zones under sedimentary basins that may host geothermal resources. Modified after Scibek (2019, 2020).

hydraulic tests. Such data can be used to relate these physical properties and to model the hydrogeologic system there. The local structure, downhole probe porosity estimates, and our recent rock drill core matrix permeability results in the NIED Hirabayashi drill hole can be briefly illustrated (Fig. 2). In 1999, NIED and USGS tested only a few small core plug samples for permeability (Lockner *et al.*, 2009).

The downhole Neutron probe gives an initial estimate of in-situ porosity. Across the Nojima fault zone, the porosity is surprisingly high, compared to the host granite (<1% porosity). We noted that a much more porous and permeable 100 to 200m thick "aquifer" has formed along the steeply-dipping fault zone over a period of tectonic activity (Fig. 3). The drill core samples shown const of weakly pulverized and hydrothermally altered granite of high porosity at present time, compared to low-porosity original host granite rock. The porosity type was examined under digital microscope at 50 to 200 × magnification directly on drill core at many test spots and around the test spots.

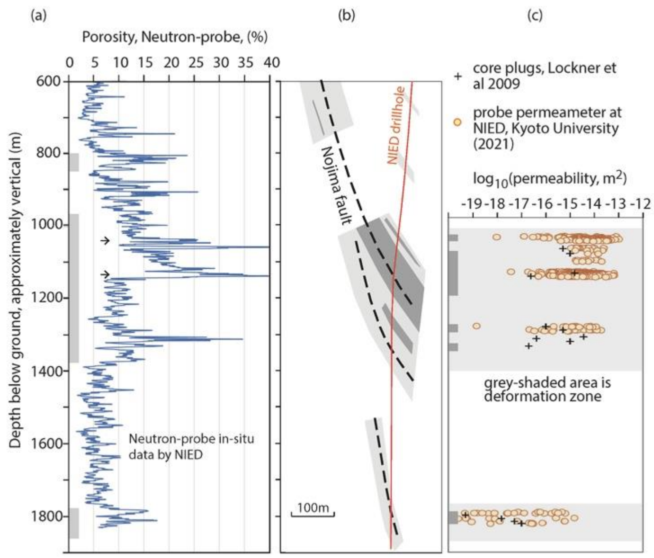

Figure 2. Example of fault zone properties at NIED drill hole, Hirabayashi drill site, Awaji Island. (a) Neutron-probe in-situ porosity, NIED data, and (b) drill core rock matrix permeability tested by Kyoto University.

4. Discussion

In mature tectonic fault zones, the fault activity appears to create highly porous and locally permeable "aquifers" in the crystalline host rocks that the fault cuts. Later hydrothermal alteration may partly seal the pore spaces that were created during deformation in parts of the fault zones. Such "fault aquifers" may exist in geothermal areas, in addition to channels in fractured more fresh rocks. Furthermore, porosity can be sensed by electrical geophysical methods at regional scale, while permeability is difficult to test and requires many in-situ and drill core measurements.

Hot spring flow systems along fault zones, and we are working on integrating historical data with the newest databases of thermal springs in Japan (Sakaguchi and Murata, 2020). Thermal spring flow systems in fracture zones in the brittle crust offer one method of estimating the permeability of these structures in the brittle crust (e.g. Muraoka *et al.*, 2006). The work on hot springs

Figure 3. NIED Hirabayashi drill core at about 1050m depth. Photo by authors in 2021 at NIED facility in Tsukuba, Ibaraki.

requires GIS analysis, analytical calculations of upflow velocity and permeability, and we work toward numerical modelling of sub-regions.

The regional geostatistical modeling efforts of geothermal gradients, rock properties, hot spring occurrence, and structure, will help in the overall understanding. Regional and world-wide data of hydraulic properties of fault zones are also available in various rock types (Scibek, 2020). We use these data to compare our site-specific results.

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