In situ visualization of fluid flow image within deformed rock by X-ray CT

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Abstract

We applied an X-ray computed tomography (CT) imaging method to study fluid advection in a laboratory permeameter in order to visualize the advecting fluid image during permeability testing under atmospheric pressure and to elucidate the relationship between fluid flow properties within fault-related rocks and their deformation mechanism. The X-ray CT images show high-resolution, three-dimensional fluid flow distribution in the fault-related rocks. A fault zone without grain cataclasis enables fluid flow, whereas cataclastic fault zones act as barriers. The fluid flow properties of the deformation bands are strongly dependent on the cataclastic fabrics. In sheared rock, including some cracks, only connected cracks can function as fluid conduits. The localized permeabilities along permeable fault zones and fractures, calculated using fluid front rates, are two orders higher than averaged bulk permeability derived from the pressure or volume difference between inflow and outflow in the permeameter.

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1. Introduction

Fluid flow in fractured rock is currently being studied with respect to the sitting of the high-level radioactive waste repository. The concept of geological disposal in Japan is based on a multibarrier system, which combines an isolating geological environment with an engineered barrier system (Japan Nuclear Cycle Development Institute, 1999). Special consideration is given to the long-term stability of the geological environment, taking into account the fact that Japan is located in a tectonically active zone. The characterization of such an active geological environment is important in terms of its barrier function including groundwater flow rates, rock permeability, the geochemical characteristics of groundwater, the thermal and mechanical properties of rock formations and properties relevant for solute transport.

The nature of fluid pathways is complex and strongly depends upon permeability in fault-related rocks which are closely related to the deformation mechanism. Moreover, the mass transfer property of

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the deformed rock is strongly influenced by heterogeneously distributed structures such as faults, cracks and dikes. The impact of fault-related permeability anisotropy on fluid flow has been documented by Randolph and Johnson (1989) and Mozley and Goodwin (1995). Faults profoundly affect patterns and rates of fluid flow and solute transport in the geological environment. They may act as conduits, barriers or combined conduit–barrier systems.

Many laboratory-based permeability measurements have been performed on reconstituted fault material derived from crystalline rocks (Morrow et al., 1981; Morrow and Byerlee, 1988; Chu and Wang, 1988). Evans et al. (1997) presented experimentally determined permeabilities of natural fault-related rocks developed in granitic gneisses. However, these previous experiments treat averaged bulk permeability values derived from the pressure or volume difference between inflow and outflow by any methods (e.g., constant head, flow pump and transient pulse methods). The heterogeneity within samples was not taken into consideration in these studies.

This paper focuses on visualizing the fluid image during permeability testing under atmospheric pressure, and aims to measure the localized permeabilities along permeable zone and compare them with averaged bulk permeabilities. We also elucidate the relationship between fluid flow property within fault-related rocks and their deformation mechanism.

2. Sample descriptions

The samples used in this study were collected from two locations within the Shimanto Belt of Japan. One is situated in the Emi Group and another is in the Inui Group (Fig. 1). The Emi Group is composed primarily of fine to coarse acidic tuffaceous clastic sedimentary rocks intercalated with tuff layers (Hirono and Ogawa, 1998). The age of the rocks ranges from late Oligo-

Fig. 1. Geological map around sampling points.
cene to middle Miocene (Sawamura and Nakajima, 1980; Suzuki et al., 1996). Two types of fault zones are found in the deformed tuffaceous sandstone in the Emi Group. They stand proud of weathered surfaces. They occasionally display a few centimeters of displacement, as inferred from crosscutting relationship with laminations, and resemble deformation bands (Aydin and Johnson, 1983; Antonellini et al., 1994). One type of fault zone commonly exhibits approximately 1–10 cm of displacement. This microfabric is characterized by undeformed grains, preferred orientations of sand grains parallel to veins and collapse of cemented material within the pores (Fig. 2a). These microscopic features are characteristic of Knipe’s (1986) independent particulate flow deformation. The fault zone grades to the intact parts. One core sample including this fault zone (IPF-P) was collected for the experiments (Fig. 3a). This core size was 5.0 cm in diameter and 2.5 cm in height. Two small fault zones are obliquely included in this core sample. Another type of the fault zones exhibits 0.5–1 cm of displacement. This microfabric is characterized by cataclasis of sand grains and collapses of cemented materials within their pore (Fig. 2b). The boundaries between the fault zone and the host rock are very sharp. The host rock is relatively undeformed. These features imply the microscopic deformation mechanism is cataclastic flow of Knipe’s (1986) definition. Two core samples were selected with a variety of orientations relative to the fault plane. One sample includes one cataclasis-related fault zone parallel to the direction of core height (CF-P), and is 5.0 cm in diameter and 3.5 cm in height (Fig. 3b). Another sample includes one cataclasis-related fault zone perpendicular to the direction of core height (CF-V), and is 5.0 cm in diameter and 1.5 cm in height (Fig. 3c).

A different type of samples was collected from outcrops of the Inui Group, Akaishi–Shimanto Belt (Fig. 1). The strata in the group are strongly deformed, and have distinctive internal shear textures such as Riedel, P and Y shears (Fig. 2c). One core sample was collected from sheared interbeds of sandstone and mudstone with precipitated siliceous veins. The core is 5.0 cm in diameter and 5.0 cm in height, and includes some cracks and composite planner fabrics such as P-shear planes, which are parallel to the direction of core height (Fig. 3d). This sample is named as Melange.

The permeabilities of core samples, IPF-P, CF-P, CF-V and Melange, were measured by the steady-state method which entails measurement of volumetric flow-through rate under a constant fluid pressure.
gradient. The permeabilities of IPF-P, CF-P, CF-V and Melange resulted in $5.22 \times 10^{-16}$ m$^2$, $1.43 \times 10^{-16}$ m$^2$, $7.57 \times 10^{-17}$ m$^2$ and $3.07 \times 10^{-12}$ m$^2$, respectively.

3. Experimental detail

3.1. X-ray CT system

In order to achieve the abovementioned aims, it was necessary to develop an apparatus with the capability not only of measuring the permeability but also of visualizing fluid advection. In this study, an X-ray computed tomography (CT) medical scanner was used as a tool to noninvasively image three-dimensional flow patterns during permeability testing. X-ray CT is a radiological imaging technique first developed by Hounsfield (1973). It has been often used for core analysis, for visualization of flow network in soils, for measurement of hydraulic conductivity, bulk density, porosity and for study of sedimentary structures (e.g., Jacobs et al., 1998; Perret et al., 2000). Ohtani et al. (2000) also applied it for crack visualization in rocks. The attenuation of two-dimensional fan beams of X-rays, which penetrate a sample, is measured by an array of detectors. These X-ray projection data from various directions are obtained by the 360° rotation of the X-ray source. A two-dimensional image representing the distribution of linear X-ray attenuation is reconstructed using a projection data Fourier transformation. A three-dimensional data set of the sample is obtained by stacking continuous two-dimensional images. The degree of X-ray attenuation depends on the density and atomic number of the samples. Higher density and higher atomic number yield higher attenuation of X-ray.

Fig. 3. Photo image of fault-related rocks examined. (a) IPF-P; (b) CF-P; (c) CF-V; (d) Melange.
An X-ray CT scanner (W2000, Hitachi Medical, Tokyo, Japan) at the Geological Survey of Japan was used for the present study (Fig. 4). A Mo–W alloy target in an X-ray tube is attacked by electrons accelerated at 120 kV with a 175-mA current. The attenuated X-ray beam after the sample penetration is measured by 768 detectors. The in-plane resolution (voxel size) of the X-ray CT is 0.31 mm. The X-ray CT reports the data in the form of the so-called CT number ($N_{ct}$) defined as:

$$N_{ct} = \frac{l}{l_w} \times 1000$$

where $l$ is the linear X-ray absorption coefficient of the sample and $l_w$ is the linear absorption coefficient of pure water used as a standard reference. The CT number of water is defined to be 0, while that of a nonattenuating material such as air corresponds to a value of $-1000$. The CT number is a function of density, condition and chemical composition of the material in any voxel. The output CT image is digitized as a TIFF-formatted 16-bit image file (512 x 512 pixels).

### 3.2. Experimental apparatus

The experiments used a permeameter cell made from acrylic plastic. The system consists of rigid-wall permeameters under atmospheric pressure. It is impossible to produce a more confining pressure on the cell because its strength is not large enough. The schematic diagram and photo image of the permeameter cell are represented in Fig. 5a and b, respectively. It consists of acrylic vessels, four pillars, Teflon tubes and joints. The CT numbers of the constituting parts are fairly constant and range from 82 to 112. Because it has a low density (1.0128–1.0621 g/cm$^3$), acrylic plastic shows a low CT number. The container is set at the center of the X-ray CT with a highly positioned tank of KI solution (see Fig. 4).

Potassium iodide solution (KI solution) is used as a contrast medium for the advection imaging because it has a high X-ray attenuation while not being harmful to humans. Calibrations of CT numbers of KI concentration under different conditions have been conducted. The CT number increases linearly with the...
molar concentration of KI. A good linearity is found for a KI concentration ranging from 0.2 to 0.8 mol/l. An artefact called beam hardening occurs in CT images obtained with polychromatic X-rays. This artefact results from the higher absorption of X-rays with long photon wavelengths. These are generally absorbed at the outer part of specimen with an apparently higher CT number as a result, because the X-ray detector counts only the total amount of photons without distinction of wavelengths. However, this artefact can be reduced by the use of a T.B.C. compensation program produced by Hitachi Medical. Based on the results of some calibration tests, the best scanning condition could be determined as follows: The T.B.C. compensation program is used for the beam hardening reduction; conditions of electron acceleration are 100 mA X-ray tube current and 120 kV voltage; KI concentration of solution is 0.5 mol/l; 1.0 mm slice thickness (thickness of the X-ray fan beam); $0.313 \times 0.313 \times 1.0$ mm$^3$ voxel size; 4.0 s scan time; 160 mm imaging diameter; a matrix size of $512 \times 512$ pixels.

### 3.3. Image processing

The output CT images are digitized as TIFF-formatted, 16-bit, grey-scale image files. It is however necessary to convert the 16-bit images into 8-bit ones with the image processing software, UltimagePro, because the operation systems of the popular personal

![Fig. 6. A sequence of converted 8-bit X-ray CT image of IPF-P sample.](image-url)
computers such as Macintosh and Windows cannot treat 16-bit binary data. The 256 grey scales are linearly applied for a value range from 32,768 to 36,768 in original images, which corresponds to the CT numbers from 0 to 4000. One grey-scale level has consequently a 15.625 CT number range.

The image subtraction is necessary to identify clearly fluid flow. The conversions are carried out using UltimagePro, NIH-Image and Microsoft Excel based on the following method: (1) export the TIFF-formatted 8-bit CT images as TEXT files using UltimagePro, which have matrix data of the grey scales for all the pixels; (2) subtract the matrix data of the later image from the initial image using Microsoft Excel; (3) import the TEXT-formatted subtracted data into TIFF-formatted image files using NIH-Image.

4. In situ visualization of fluid flow

The experimental arrangement for the in situ visualization of fluid flow images is indicated in Fig. 4. The permeameter cell was set at the center of the gantry of the X-ray CT. The hydraulic head was applied by the higher-positioned tank of the KI solution with a stepladder at 135 cm. The samples were enclosed in acrylic vessels, and sealed by sili-

![Fig. 7. A sequence of converted 8-bit X-ray CT image of CF-P sample. (a) CT image at the initial state. (b) Differential CT image between 120 min and initial state. (c) Differential CT image between 400 min and initial state. (d) Converted 8-bit X-ray CT image of CF-V at the initial state. (e) Differential CT image between 180 min and initial state. (f) Differential CT image between 540 min and initial state.](image-url)
con-based sealing compounds to prevent lateral flow along the vessel wall. The imaging conditions were commonly as mentioned above.

The X-ray CT images of fluid flow within the IPF-P sample with internally two fault zones without cataclasis are shown in Fig. 6a. KI-permeated voxels show brighter CT images in Fig. 6b–d. With time, the KI solution gradually flows upward, in particular, along the fault zone. The trend can be recognized distinctly on the differential images (Fig. 6e–g) that are constructed by image subtraction for all the grey-scale differences at each pixel between the initial and the later images. These image conversions are carried out using abovementioned method. These CT images clearly show that the fluid flow occurs primarily in the fault zone without cataclasis, which plays the role of a selected fluid conduit.

The CT images of fluid flow within the CF-P sample with internally some fault zones with cataclasis parallel to the direction of core height are shown in Fig. 7a. The KI solution appears to flow restrictedly within relatively intact parts on the differential images (Fig. 7b and c). The left part is not relatively deformed and acts as a fluid pathway. The upper-left crack, which is not an original texture but a secondary crack by core-sample drilling, has a concentrated fluid flow. The CT images of the fluid flow within the CF-V sample with internally some fault zones with cataclasis perpendicular to the direction of core height are shown in Fig. 7d. The KI solution flows pervasively upward without restricted flow (Fig. 7e and f). The permeability is lower than that for CF-P sample (CF-P, $1.43 \times 10^{-16}$ m$^2$; CF-V, $7.57 \times 10^{-17}$ m$^2$). The cataclastic fault zones appear to seal the perpendicular fluid transport. These results suggest that cataclastic fault zones act as barriers to fluid flow.

CT images of fluid flow within the Melange sample, which has some cracks and composite planar fabrics parallel to the direction of core height, are shown in Fig. 8a–c. In this experiment, the hydraulic head is set to be 5 cm due to its highly permeable character, by keeping other conditions to be similar to previous experiments. As time goes on, the KI solution appears to flow within only the penetrated crack at the center of the sample. No flow exists within the right larger crack, which is not connected between the end surfaces. In relatively intact parts, the KI solution does not show any flow.

Thus, only connected cracks or fractures function as fluid conduits.

5. Localized permeability along fault zone or fracture

Permeability is generally derived from the pressure or volume difference between inflow and outflow to represent the averaged bulk permeability. This bulk permeability does not taken into consideration the internal heterogeneity of fluid flow distribution within the specimen. The present experimental results, however, show heterogeneous selected pathways in the
IPF-P and Melange samples. In order to evaluate the localized permeabilities along permeable fault zones and fractures, the following calculation is conducted. Permeability (cm/s), \( k \), can also be defined as the following equation:

\[
v = n \times V = k \times i
\]

where \( v \) is average velocity (cm/s), \( n \) is effective porosity (dimensionless), \( V \) is real average velocity (cm/s) and \( i \) is the hydraulic gradient (dimensionless). Fluid front on the differential CT images can be recognized by thresholding at the 140th grey scale corresponding to 2187.5 of CT number (Fig. 9). The error is checked by thresholding at the 130th and 150th grades, but there are very small errors for the recognition of fluid front (less than one pixel).

In the case of the IPF-P sample, because fluid front moves at a distance of \( 2.44 \pm 0.04 \text{ cm} \) during the period of 30 min, the real average velocity is \( 1.34 \times 10^{-3} \text{ cm/s} \). The error of \( \pm 0.04 \text{ cm} \) results from the thresholding of fluid front. The effective porosity within the fault zone is 31.7%. The hydraulic gradient can be considered to be \( 34.0 \pm 0.1 \) by compensating the ratio of hydraulic head to the fracture length. The localized permeability along fault zone can therefore be calculated as \( 4.00 \times 10^{-5} \text{ cm/s} \), which is two orders higher than the bulk permeability, \( 5.80 \times 10^{-7} \text{ cm/s} \) (Table 1).

In the case of the Melange sample, as the fluid front moves a distance of \( 2.32 \pm 0.04 \text{ cm} \) during the period of 20 s, the velocity is \( 1.16 \times 10^{-1} \text{ cm/s} \). The error of \( \pm 0.04 \text{ cm} \) also results from the thresholding of fluid front. The local porosity within the fracture is 100%. The hydraulic gradient can be compensated as \( 1.2 \pm 0.1 \). The localized permeability along permeable fracture can be calculated as \( 0.99 \times 10^{-1} \text{ cm/s} \). This value is again two orders higher than the bulk permeability, \( 3.41 \times 10^{-3} \text{ cm/s} \). These differences between localized and bulk permeabilities suggest the importance of studying real permeabilities along fracture or fault zones in heterogeneous deformed rocks (Table 1).

### Table 1
<table>
<thead>
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<th>Permeability (cm/s)</th>
<th>Localized</th>
<th>Bulk</th>
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<tbody>
<tr>
<td>IPF-P</td>
<td>( 4.00 \times 10^{-5} )</td>
<td>( 5.80 \times 10^{-7} )</td>
</tr>
<tr>
<td>Melange</td>
<td>( 0.99 \times 10^{-1} )</td>
<td>( 3.41 \times 10^{-3} )</td>
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6. Discussion and conclusion

The results of fluid visualization during permeability testing can indicate that the fault zone, whose deformation mechanism is independent particulate flow, plays a role of fluid conduit, whereas cataclastic fault zones act as barriers. Smith (1980), Pittman
(1981) and Seeburger et al. (1991) suggested that the permeability perpendicular to a fault zone in sandstone decreases due to granulation and cataclasis. According to Nelson (1985) and Antonellini and Aydin (1994), faults may enhance or decrease permeability depending on whether the faults are characterized by cataclasis or mineral precipitation. They suggested that the intensity of cataclasis strongly reduces the permeability. Zhu and Wong (1997) observed that the permeability evolution in porous sandstone depends on effective mean stress and deviatoric stress, and concluded that a drastic decrease in permeability is triggered by the onset of cataclasism. Their interpretation on the role acting as a barrier of the cataclastic fault zone is supported by the present experimental results.

The X-ray CT imaging has been successfully applied to the quantitative visualization of heterogeneous fluid flow in deformed rocks. High-resolution, three-dimensional fluid flow distributions were measured for fault-related rocks. The results of fluid visualization during permeability testing can indicate that the fault zone, whose deformation mechanism is independent particulate flow, plays a role of fluid conduit, whereas cataclastic fault zones act as barriers. The localized permeabilities along permeable fault zones and fractures, calculated by fluid front rates, are two orders larger than the averaged bulk permeability derived from the pressure or volume difference between inflow and outflow in the permeameter. These results indicate that fault zones and fractures profoundly affect patterns and rates of fluid flow in deformed rocks.

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