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Craig B. Forster  
*University of Utah*

James P. Evans  
*Utah State University*

Hidemi Tanaka  
*University of Tokyo*

Ronald Jeffreys  
*Utah State University*

Tsuyoshi Nohara

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## Hydrologic properties and structure of the Mozumi Fault, central Japan

Craig B. Forster,<sup>1</sup> James P. Evans,<sup>2</sup> Hidemi Tanaka,<sup>3</sup> Ronald Jeffreys,<sup>2</sup> and Tsuyoshi Nohara<sup>4</sup>

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[1] Analyses of rocks from the Active Fault Survey Tunnel (AFST) provides insight into the structure and hydrogeology of the northeast-trending Mozumi-Sukenobu fault, an active strike-slip fault with 125 to 500 m of right-lateral slip in central Japan. Interlayered regions of sub-vertical permeability zones formed by cataclasis and slip on clay-rich foliated zones. Core samples range from  $10^{-19}$  m<sup>2</sup> to almost  $10^{-13}$  m<sup>2</sup>. CFC analyses of waters from the fault zone show that water entering the tunnel is 27–36 years old, yielding a bulk fault permeability of  $10^{-14}$  to  $10^{-15}$  m<sup>2</sup>. The data support a fault zone model of a fluid-saturated, low-velocity zone with a sharp velocity contrasting with the protolith. Pore-fluid pressures could build and dissipate in isolated high permeability pods 10's–100's m in dimension. **INDEX TERMS:** 8010 Structural Geology: Fractures and faults; 8045 Structural Geology: Role of fluids; 8025 Structural Geology: Mesoscopic fabrics; 8030 Structural Geology: Microstructures; 8020 Structural Geology: Mechanics. **Citation:** Forster, C. B., J. P. Evans, H. Tanaka, R. Jeffreys, and T. Nohara, Hydrologic properties and structure of the Mozumi Fault, central Japan, *Geophys. Res. Lett.*, 30(5), 8010, doi:10.1029/2002GL014904, 2003.

### 1. Introduction

[2] Numerous geophysical, geologic, and hydrologic investigations indicate that fault zones impact the flow of fluids in the subsurface. The hydraulic structure of faults is important in examining precursor phenomena in earthquakes [Tsunogai and Wakita, 1995; King et al., 1995]; and the relationship between fluids and faulting [Blanpied et al., 1992; Chester et al., 1993]. Deep boreholes or tunnels provide insights into fault zone structures [Ohtani et al., 2000] which allows us to determine the composition, internal structure, and deformation processes of fault zones.

[3] The Active Fault Survey Tunnel (AFST) central Japan [JNC, 1998] provides an opportunity to examine an active fault in an underground gallery. We present the results of laboratory permeability and porosity measurements, and chlorofluorocarbon analyses to document the permeability of the fault-related rocks in an active fault zone.

[4] The AFST is a horizontal drift 480-m-long, N 24°W trending cut through the Mozumi-Sukenobu fault, Gifu

prefecture, Japan. The Mozumi-Sukenobu fault system trends ~N 40°E, with 125 to 500 m of right lateral slip [Ando, 1998]. A low level of seismicity [Mikumo et al., 1988; Mikumo, 1990; Wada et al., 1990]. The tunnel cuts rocks of the Jurassic Tetori Group [Kano and Shimizu, 1992; Figure 1] which consists of immature pebble conglomerates, siltstones, thin organic-rich intervals, and sandstones.

[5] Detailed mapping of the drift walls before they were lined was conducted by Mitsui Mining and Smelting Co. geologists. The tunnel encountered 1–12-m-thick shale beds and 10–20-m-thick sandstone beds cut by two zones of intense deformation (crush zones, Figure 1). Sub-vertical zones consist of clay gouge and breccia, low rock quality (Figure 2a), and reduced seismic velocities. Crush Zone A is ~20 m wide within the tunnel and is interpreted to be the trace of the active Mozumi-Sukenobu fault. Crush Zone B is ~65 m wide. Numerous small faults and clay-rich shear zones separate Crush Zones A and B (Figure 1).

[6] Rock sampling of the fault zone comes from three boreholes (Figure 1). Our samples come from Borehole 1, Borehole A, and Borehole 2. Core recovery was remarkably good.

### 2. Characterization of Faulted Rocks

[7] Protolith is comprised of thin-bedded, fine-grained siltstones, angular breccias, random fabric cataclases, well-foliated clay-rich shear zones, and black, organic-rich shear zones (Figure 2a). Deformation in the fault zone occurred by shearing in clay/calcite-rich regions, plastic deformation of calcite, brittle fracture and faulting, flow of calcite-clay mixtures, and reaction-enhanced dissolution of calcite. Samples tested for permeability represent dark siltstone protolith (sample BH1-50.1), random fabric breccia/clay-rich cataclases (samples BHA-128.3, 133 and 143.2), and highly altered clay-rich gouge (samples BHA-122.4 and 127.8).

### 3. Drillcore Tested as a Function of Confining Pressure

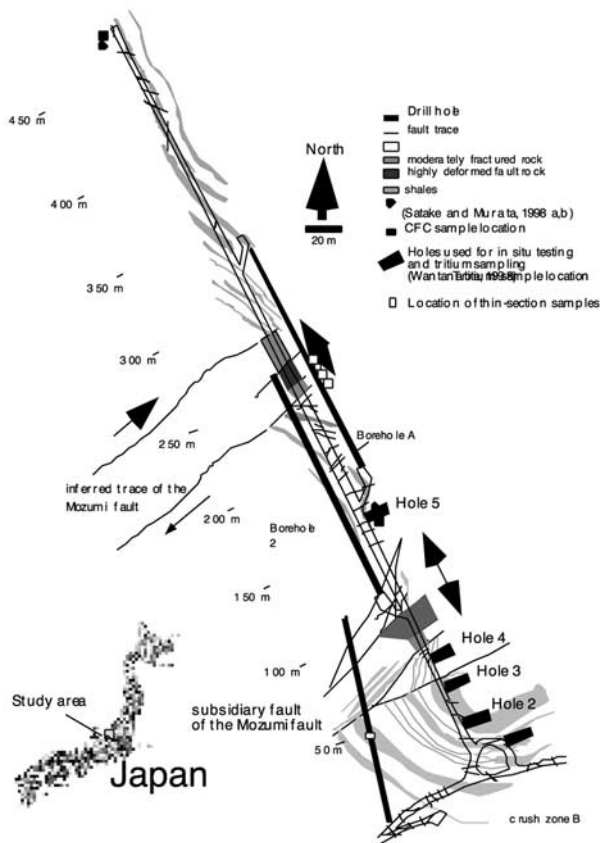
[8] Six drillcore samples (Boreholes 1 and A) (Figure 1) were tested by Terra Tek, Inc. to obtain values of permeability ( $k$ ) and porosity ( $n$ ) over a ranges of confining pressures of 2.8 to 62 MPa. Tests were performed using nitrogen gas and API Recommended Practice # 40 for steady state (higher permeability samples) and transient (lower permeability samples) tests. The samples were dried at 120°C prior to testing. Pore pressures were atmospheric during the tests. Porosity is computed from measurements of both pore volume and grain volume. The nominal confining pressure ( $P_c$ ) at the tunnel depth of 300 m is 7.6 MPa (the reference lines in Figure 3).

<sup>1</sup>Department of Geology and Geophysics, University of Utah, Salt Lake City, UT, USA.

<sup>2</sup>Department of Geology, Utah State University, Logan, UT, USA.

<sup>3</sup>Department of Earth & Planet. Science, Graduate school of Science, University of Tokyo, Tokyo, Japan.

<sup>4</sup>Tono Geoscience Center, Japan Nuclear Cycle Development Institute, Jorinji, Izumi, Tokishi Gifu, Japan.



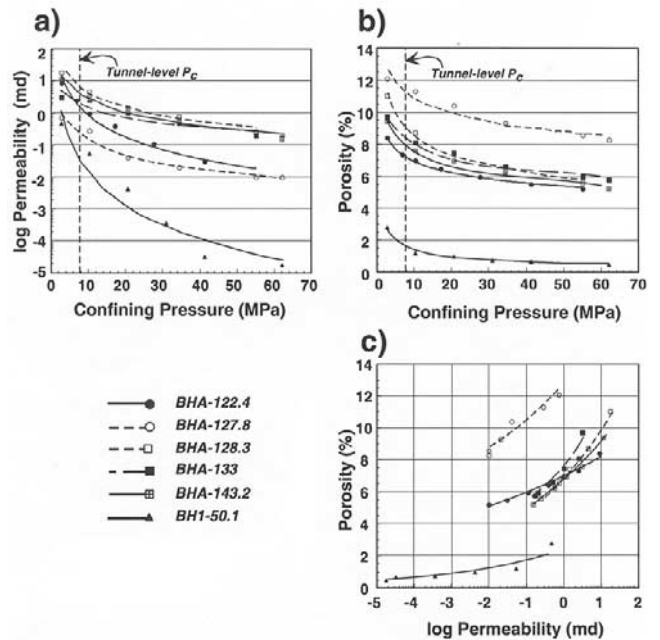
**Figure 1.** Simplified map of the Active Fault Survey Tunnel across the Mozumi Fault. Mapping conducted by JNC geologists indicates that the fault zone consists of subparallel slices of clay-rich gouge, breccia, and fractured rocks.

[9] With the exception of the shale breccia sample (BHA-133). Log permeability *vs* confining pressure  $P_c$  (Figure 3a) are well-fitted with a relationship of  $k = mP_c^a$  (Table 1). Although sample BHA-133 is best fit with an exponential

A



**Figure 2.** View of the fault zone within the Active Fault Survey Tunnel through the Mozumi fault. Field book is approximately 20 cm high. Narrow slip surface at left side of window consists of narrow clay-gouge surface; bedding is subhorizontal above the field book.



**Figure 3.** Results of permeability and porosity tests on drillcore samples obtained from the active fault survey tunnel cutting Mozumi-Sukenobu fault zone: (a) log permeability *kvs* confining pressure  $P_c$ , (b) porosity *n vs* confining pressure  $P_c$ , and (c) porosity *nvs* log permeability *k*. The nominal confining pressure at the tunnel level (~350 m below ground surface) is 7.6 MPa.

relationship, we show a reasonable power law fit for comparison. All fault rock samples experience about a 1.5 order of magnitude decline in permeability as confining pressure is increased. The protolith shale sample (sample BH1-50.1) exhibits about 4.5 orders of magnitude decline in permeability (Figure 3a). This amplified response to changes in confining pressure results from its clay content and grain size similar to *Evans et al.* [1997] and *Seront et al.* [1998].

[10] Two breccia categories provide *k* values of  $10^{-17} \text{ m}^2$  and  $2 \times 10^{-16} \text{ m}^2$  at elevated confining pressure. This suggests that fault zone anisotropy is caused by distinct contrasts in the permeability of fault breccia. Porosity (*n*) for all breccia samples, except sample BHA-122.4, approaches a limiting value of 5 to 6% (Figure 3b). Sample BHA-122.4 approaches a limiting porosity of about 8%.

[11] Porosity *vs* confining pressure relationships are well fitted by  $n = mP_c^a$  (Figure 3; Table 1). The groupings are similar to those found in Figure 3a. Responses of *k* and *n* to changes in confining pressure are reflected Figure 3c. The results are well fitted with  $k = mk^a$  (Table 1). The protolith shale sample (sample BH1-50.1) has the lowest *k* and *n* of all samples tested, and suffers the greatest decline in permeability as a function of increasing confining pressure. Most samples of shale and siltstone breccia yield tunnel-level permeability values that vary between  $10^{-14}$  and  $10^{-15} \text{ m}^2$  (Figure 3a). The shale breccia with fine matrix yields values of porosity about 1.5 times greater, and permeability about one order of magnitude lower than the those of other breccia samples for each value of applied  $P_c$ . This shows that high porosities do not equate to high

**Table 1.** Curve Fitting Results and Computed Values of Tunnel-Level  $k$  and  $n$ 

| Sample    | $k = mP_c^a$ |       |      | $n = mP_c^a$ |        |      | $n = mk^a$ |       |      | Tunnel-Level Values   |         |
|-----------|--------------|-------|------|--------------|--------|------|------------|-------|------|-----------------------|---------|
|           | $m$          | $a$   | R    | $m$          | $a$    | R    | $m$        | $a$   | R    | $k$ (m <sup>2</sup> ) | $n$ (%) |
| BHA-122.4 | 148.6        | -2.25 | 0.98 | 9.97         | -0.159 | 1.00 | 7.00       | 0.070 | 0.99 | $1.6 \times 10^{-15}$ | 7.2     |
| BHA-127.8 | 4.46         | -1.49 | 0.96 | 14.41        | -0.125 | 0.95 | 12.67      | 0.083 | 0.97 | $2.2 \times 10^{-16}$ | 11.1    |
| BHA-128.3 | 88.22        | -1.39 | 0.99 | 14.14        | -0.221 | 0.99 | 6.903      | 0.159 | 1.00 | $5.3 \times 10^{-15}$ | 9.0     |
| BHA-133   | 13.59        | -0.98 | 0.85 | 11.73        | -0.165 | 0.99 | 7.52       | 0.154 | 0.96 | $1.9 \times 10^{-15}$ | 8.4     |
| BHA-143.2 | 57.27        | -1.35 | 0.99 | 11.49        | -0.181 | 0.99 | 6.68       | 0.133 | 1.00 | $3.7 \times 10^{-15}$ | 8.0     |
| BH1-50.1  | 47.09        | -3.48 | 0.99 | 4.81         | -0.549 | 1.00 | 2.42       | 0.145 | 0.94 | $4 \times 10^{-17}$   | 1.6     |

R = "Goodness of Fit";  $m$ ,  $a$  = fitting parameters in Power Law relationships (e.g.,  $k = m P_c^a$ ).

permeabilities, due to the connectivity of the pore space in fine-grained rocks [Evans et al., 1997]. Clay-rich fault pods may be able to store fluid, but not allow flow.

#### 4. Chlorofluorocarbon (CFC) Estimates of Groundwater Age

[12] Two sample sets of groundwater for CFC-age determinations were collected in clean 3/8-inch O.D. copper tubing sealed by cold welding the ends [Wilkowske, 1998]. Sample set MZ-164 was collected from the flowing Hole 5, and sample set MZ-480 was collected at the tunnel terminus (Figure 1). Sample analyses were performed with an analytical system similar to Wisegarver and Cline [1985]. Apparent recharge years were determined by computing the atmospheric concentration of CFCs that would be in equilibrium with the measured values at 5°C and a nominal groundwater recharge elevation of 1000 msl above sea level. These atmospheric concentrations were compared with observed atmospheric values to assign a recharge year.

[13] Sample set MZ-164 shows a groundwater age of about 36 years. Sample set MZ-480 shows an age of about 27 years. These ages are consistent with the intermediate values of tritium concentration determined at the same locations by Satake et al. [this issue].

[14] Approximate bulk  $k$  values parallel to the fault zone can be estimated at the 100 m scale using apparent CFC ages. Using transit time of 31 years, and an intermediate porosity of 9%, bulk  $k$  at the 100-m scale is  $3 \times 10^{-15}$  m<sup>2</sup>. This is remarkably similar to the *in situ* permeability test results ( $2 - 20 \times 10^{-15}$  m<sup>2</sup>) of Nohara et al. [this issue] where we collected Sample set MZ-164.

#### 5. Discussion and Conclusions

[15] Our permeability values obtained from groundwater tracers and permeability testing of fault rocks range from  $10^{-13}$  m<sup>2</sup> to  $10^{-19}$  m<sup>2</sup> (Table 2). The largest values of permeability are estimated at length scales of 1 to 100 m associated with fractured rock in the fault zone and limited

clay gouge content [Nohara et al., this issue]. Intermediate values of  $k$  ( $10^{-14}$  to  $10^{-16}$  m<sup>2</sup>) are estimated at length scales of 0.01 to 1 m for fault breccia with intermediate, clay gouge content. The smallest  $k$  values ( $10^{-18}$  to  $10^{-19}$  m<sup>2</sup>) are estimated at the cm-scale from samples collected from clay-rich zones [see also Watanabe et al., this issue]. These results suggest faulting creates an interlayered sequence of sub-vertical, high, intermediate, and low  $k$  zones.

[16] Both maximum and minimum values of  $k$  are found within the fault zone. This structure fits the conceptual model of a conduit-barrier system [Caine et al., 1996]. The  $k$  controlling flow in the plane of the fault is enhanced relative to the host rock while  $k$  controlling flow across the fault is reduced relative to the host rock.

[17] Thin slivers of high permeability fault rocks (less than 10 m wide) likely transport the bulk of the subsurface flow. Distinct changes in geochemical regimes on each side of the fault are inferred from Ca/Na values [Satake et al., this issue] and support the inference that water flowing parallel to, but on opposite sides of, the fault likely remains unmixed while moving towards the Takana River because the fault acts as a barrier to flow across the fault.

[18] The near-surface structure of several narrow slip surfaces embedded within breccia and cataclastic zones, some of which exhibit variable degrees of fluid-rock interactions, mimics that documented in studies of faults exhumed from 2–5 km deep [Chester et al., 1993; Gray et al., 1999; Janssen et al., 1998; Schulz and Evans, 2000].

[19] The Mozumi-Sukenobu fault, where cut by the research tunnel, is a conduit-barrier system with bulk anisotropy for the fault zone (width of ~200 m) on the order of  $10^6$ . The fault zone comprises a complex structure with thin, sub-vertical slivers (cms to ms wide) of high- to low-permeability fault rocks. The fact that ongoing deformation is observed within the fault zone suggests that pore fluid pressures could be building and dissipating in high permeability pressure pods distributed within the fault zone.

**Table 2.** Summary of Fault Permeability Estimates

| Sample analysis            | Age              | Permeability                         | Source                                     |
|----------------------------|------------------|--------------------------------------|--|
| CFC analysis               | 27 yrs<br>36 yrs | $10^{-13} - 10^{-14}$ m <sup>2</sup> | This study                                 |
| Core-faulted sandstone     |                  | $10^{-14} - 10^{-16}$ m <sup>2</sup> | This study                                 |
| Core-shale gouge           |                  | $10^{-16} - 10^{-19}$ m <sup>2</sup> | This study;<br>Watanabe et al., this issue |
| In situ falling head tests |                  | $10^{-13} - 10^{-15}$ m <sup>2</sup> | Watanabe et al., this issue                |

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C. B. Forster, Department of Geology and Geophysics, University of Utah, 135 S. 1460 E. Salt Lake City, UT 84112-0111, USA. (cforster@mines.utah.edu)

J. P. Evans, Department of Geology, Utah State University, Logan, UT 84322-4505, USA. (jpevs@cc.usu.edu)

H. Tanaka, Department of Earth & Planet. Science, Graduate school of Science, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan. (tanaka@eps.s.u-tokyo.ac.jp)

R. Jeffreys, Department of Geology, Utah State University, Logan, UT 84322-4505, USA.

T. Nohara, Tono Geoscience Center, Japan Nuclear Cycle Development Institute, Jorinjii, Izumi, Tokishi Gifu, Japan. (nohara@tono.jnc.go.jp)