Formative mechanism of inhomogeneous distribution of fractures, an example of the Toki Granite, Central Japan

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Abstract

Understanding of the fracture network is important for safety assessment for disposal of high-level radioactive waste (HLW). The number of fractures in Japanese granites is much more than those in Sweden and Finland. Such differences are generally believed to be caused by geological setting of which Japan locates in tectonically active plate boundary while Sweden and Finland locate in the stable East European craton.

Japan Atomic Energy Agency pursues the geoscientific study in the Toki Granite, distributed in Central Japan, to establish scientific basis for HLW disposal in Japan. In this paper, we present our hypothesis on the formative mechanism of inhomogeneous distribution of fracture in the Toki Granite.

In the Toki Granite, fractures are abundant at the shallower part where both low- and high-angle fractures are dominant, while less at the deeper part where high-angle fracture is dominant. Low-angle fracture was formed by unloading during the exhumation of granite prior to deposition of the overlying sedimentary sequence. Distribution of the high-angle fracture is inhomogeneous.

Thermochronological study revealed that the incipient cooling rate was c.30-70 ^{o}C/million years from monazite chemical Th–U–total Pb isochron method closure to zircon fission-track (FT) closures in the range of c.70 to 60 Ma. This was quite rapid compared with that of c.3-13 ^{o}C/million years from zircon FT to apatite FT closures in the range of c.60 to 20 Ma. Paleomagnetic study of the intact granite indicated that the paleomagnetic directions were dispersed, even though any structural disturbance has not been observed. This suggests granite was plastically deformed during rapid cooling period.

The rapid cooling might cause inhomogeneous distribution of cooling strain. When the granite reached to brittle deformation field, inhomogeneous fracture distribution was formed by the inhomogeneous strain. If so, recognition of the cooling history of the granitic body is essential to understand the distribution of the fracture network.

Keywords: fracture, cooling rate, thermochronology, paleomagnetism, Toki Granite, Mizunami Underground Research Laboratory

1. Introduction

Fracture in rock can act as groundwater pathways. Therefore, understanding of the fracture network is important for construction of underground facility and also for safety assessment for disposal of high-level radioactive waste (HLW). The number of fractures in Japanese granites is much more than those in northern Europe such as Sweden and Finland. Such differences are generally believed to be caused by geological setting of which Japan locates in tectonically active plate boundary while Sweden and Finland locate in the stable East European craton.

Japan Atomic Energy Agency pursues the geoscientific research and development project namely by the Mizunami Underground Research Laboratory (MIU) Project in the Toki Granite, distributed in Central Japan, to establish scientific basis for HLW disposal in Japan. In this paper, we present our hypothesis on the formative mechanism of inhomogeneous distribution of fracture in the Toki Granite, on the basis of observation of fractures in the shafts and galleries at the MIU site as well as drill cores, and thermochronological and paleomagnetic studies at and around the MIU site.

2. Geological setting

The MIU is under construction in the Mizunami City, Gifu Prefecture, Central Japan (Fig. 1). Geology around the MIU site consists of Jurassic–Cretaceous accretionary complex (Mino Terrane), Cretaceous–Paleogene volcano–plutonic complex (the Nohi Rhyolite, the Toki Granite and granitic rocks in the Ryoke Belt), Miocene Mizunami Group (c.20–15 Ma; Sasao et al., 2006, 2011) and Mio–Pliocene Tokai Group (c.12–1.5 Ma; Todo Collaborative Research Group, 1999), in ascending order (e.g. Sasao, 2013; Saegusa and Matsuoka, 2011).

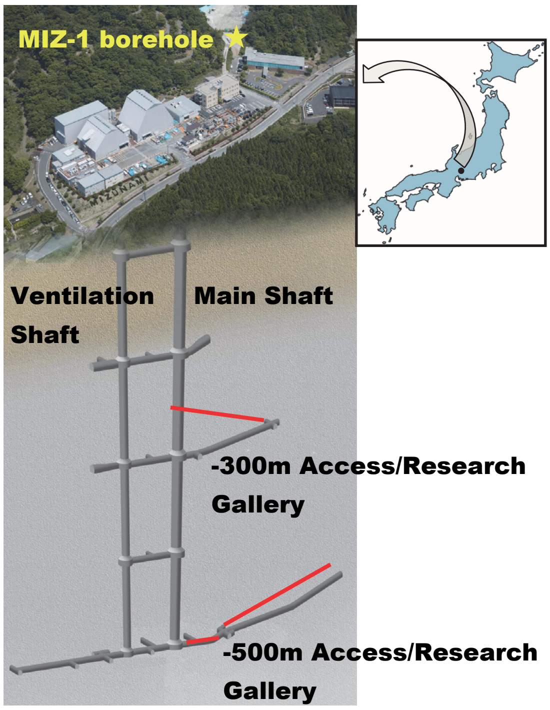

Fig. 1 Location and facility allocation of the Mizunami Underground Research Laboratory (MIU). Red lines indicate the location of boreholes examined, and yellow star indicates the location of MIZ-1 borehole referred in Figure 4.

The Toki granite is one of the Late Cretaceous plutonic bodies in the Sanyo Belt (Ishihara and Chappell, 2007), and has been dated at 68.3±1.8 Ma (monazite chemical Th–U–total Pb isochron method; CHIME, Suzuki and Adachi, 1998) and 72.3±3.9 Ma (whole-rock Rb–Sr, Shibata and Ishihara, 1979). The Toki granite is a stock, 14×12 km^2 in areal extent (Ishihara and Suzuki, 1969), with a vertical thickness of a least 1.5 km based on borehole investigations. The Toki granite intruded Jurassic sedimentary rocks of the Mino Terrane and the Nohi Rhyolite (85±5 Ma, allanite CHIME dating; Suzuki et al., 1998). The granite is overlain unconformably by the Mizunami and Tokai Groups (Itoigawa, 1974, 1980). The Toki granite is characterized by systematic spatial changes in rock facies (mode and mineral assemblage) and a corresponding change in bulk chemical composition, and thus is recognized as a zoned pluton (Yuguchi et al., 2010).

3. Investigation of distribution of fractures at the MIU site

Macroscopic fractures are well developed in the Toki Granite (e.g. Fujii, 2000). The previous surface-based investigation such as Saegusa and Matsuoka (2011) revealed that two structural domains, an upper highly fractured domain (UHFD) and a lower sparsely fractured domain (LSFD), have been distinguished in Toki granite based on the fracture frequency with low dip angle (<30 ^{o}). The low angle fractures are considered to be formed by unloading during exhumation of the granite prior to deposition of the overlying Mizunami Group.

We have investigated the distribution and mode of occurrence of fractures at the MIU site (e.g. Ishibashi et al., 2014). The investigation has been performed at the main and ventilation shafts which were excavated to the depth of c.500 meters below ground surface, and horizontal galleries excavated at the GL-300 and -500 meters levels (Fig. 1). Fracture data was also acquired by the borehole investigation. Data on strike and dip of fracture were mainly obtained by numerical analysis of borehole television (BTV) image. At present, more than 50 boreholes has been drilled in the MIU site both from surface and underground galleries. In this study, data obtained by two boreholes drilled at the GL-300 and -500 meters galleries were used for discussion (Fig. 1).

In the ventilation shaft, the boundary between UHFD and LSFD is located at the -460 meters below ground level (GL-460m) (Fig. 2). In the UHFD, high dip angle fractures are densely developed with low dip angle (>30 ^{o}) fractures in the upper part (above GL-300m). Below the boundary, fracture density is apparently decreased.

Based on the horizontal borehole data drilled from the GL-300m and GL-500m galleries, dense and sparse fracture densities are repeatedly appeared (Fig. 3). This tendency is observed in both of UHFD at the GL-300m and LSFD at the GL-500m.

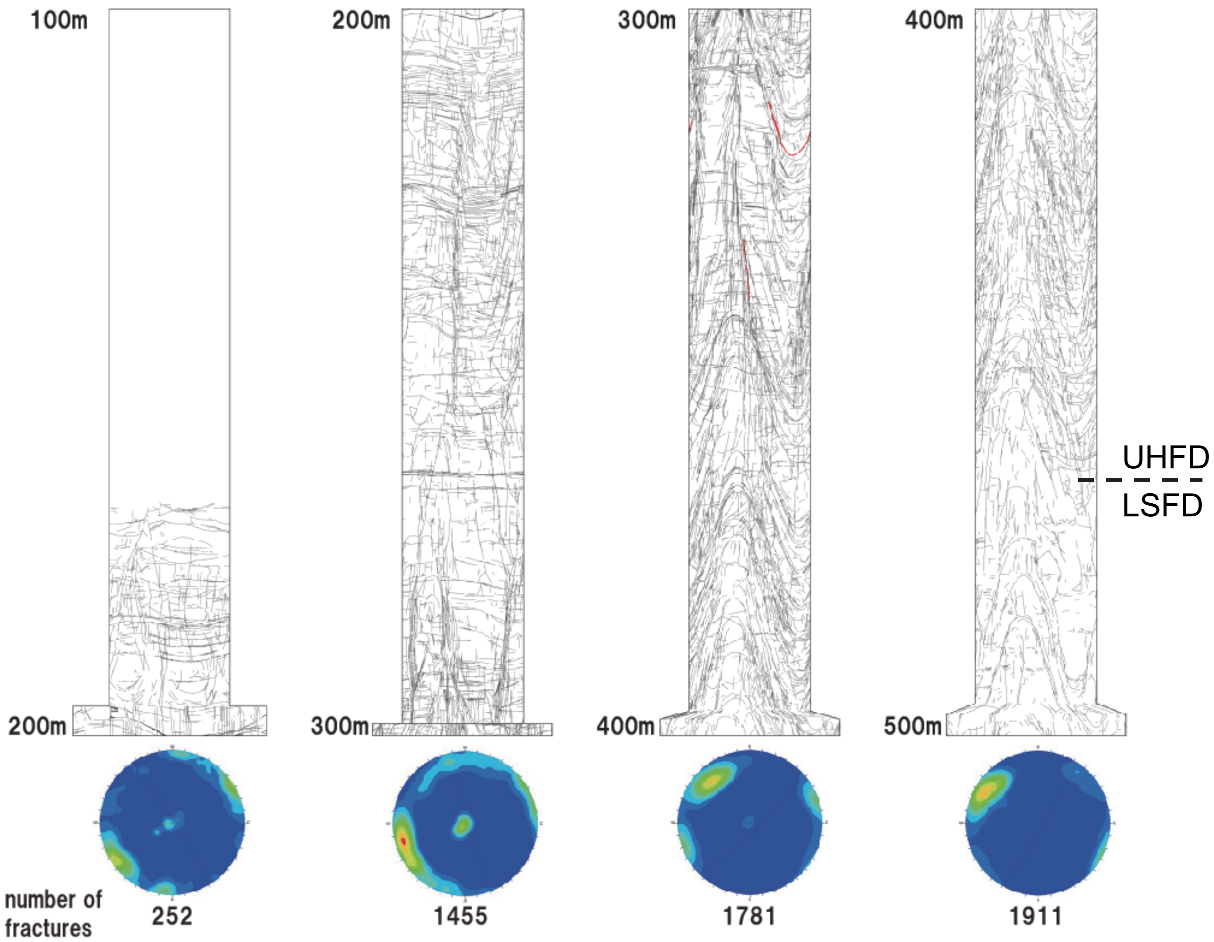

Fig. 2 Sketch map of fracture distribution with in the ventilation shaft (development view of shaft wall), and Schmidt stereonet diagrams showing fracture orientations (lower hemisphere projections of poles to fracture).
The low dip angle (>30 ^{o}) fractures are mainly developed above GL-300m.

4. Cooling rate of the Toki Granite inferred from geochronological data

In the Toki Granite, many chronological data have been obtained such as monazite CHIME age (Suzuki and Adachi, 1998), whole rock Rb–Sr age (Shibata and Ishihara, 1979), and hornblende K–Ar, biotite K–Ar and zircon fission-track (FT) ages (Yuguchi et al., 2011) with some newly obtained apatite FT ages (Table 1).

Apatite fission-track dating was carried out at Kyoto Fission-Track Co. Ltd. Apatite samples were analyzed by the external detector method (ED1, internal mineral surface) using the geometry factor of 0.5 (Gleadow, 1981).

We adopted chronological data obtained from the single borehole to avoid local differences of cooling history as shown in Fig. 4. The result indicates that the incipient cooling rate was c.30–70 ^{o}C/million years from monazite Pb to zircon FT closures in the

Table 1 Compilation of age dating at the Toki Granite.

Method	Age (Ma)	Closure temperature (^{o}C)	Reference
monazite CHIME	68.3±1.8	c.700 ?	Suzuki and Adachi (1998)
whole rock Rb–Sr	72.3±3.9	c.700 ?	Shibata and Ishihara (1979)
hornblende K-Ar	74.3±2.6	510±25	Yuguchi et al. (2011)
biotite K-Ar	78.5±3.9 to 59.7±1.5	300±50	Yuguchi et al. (2011)
zircon fission-track	75.6±3.3 to 52.8±2.6	240±50	Yuguchi et al. (2011)
apatite fission-track	c.32-49	120±20	This study

range of c.70 to 60 Ma. This was quite rapid compared with that of c.3–13 °C/million years from zircon FT to apatite FT closures in the range of c.60 to 40 Ma.

5. Paleomagnetic Study

Six intact granite samples were collected from the horizontal borehole at the GL-300m (Figs. 1 and 3). Geographical coordinates of potentially rotated core samples were carefully determined by comparison of azimuths of more than one fractures between core and borehole surface observed by BTV image. Some examples of magnetic measurement are shown in Fig. 5 on the equal-area projections of site-mean magnetic

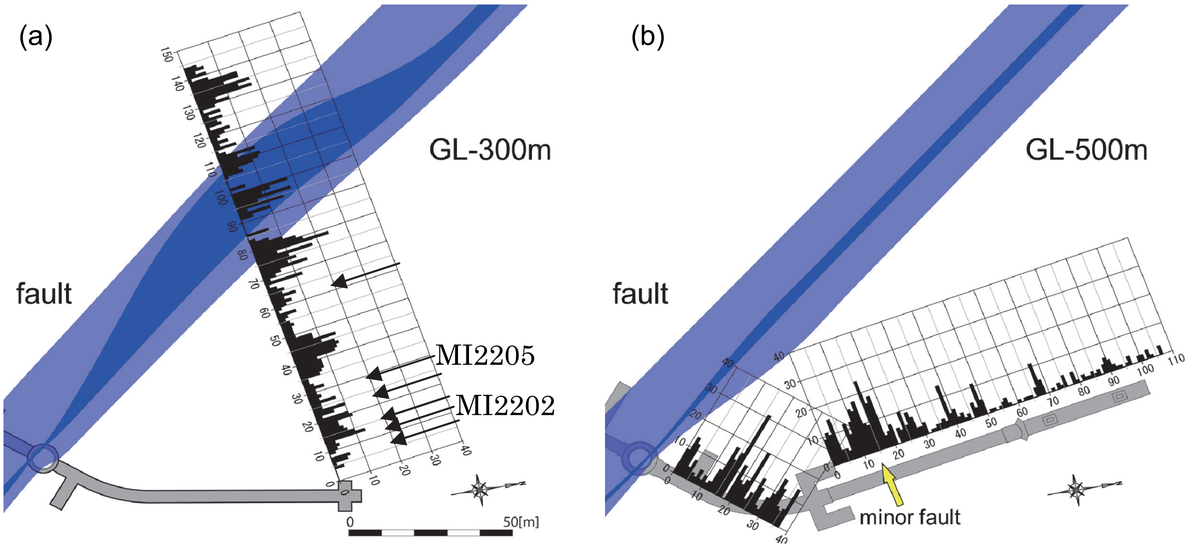

Fig. 3 Density of fractures confirmed by borehole investigation at two different level. (a) at the GL-300m, and (b) at the GL-500m.
Dark blue and pale blue indicate horizontal distribution of fault core and surrounding damaged zone, respectively. Arrows indicate sampling points for paleomagnetic study.

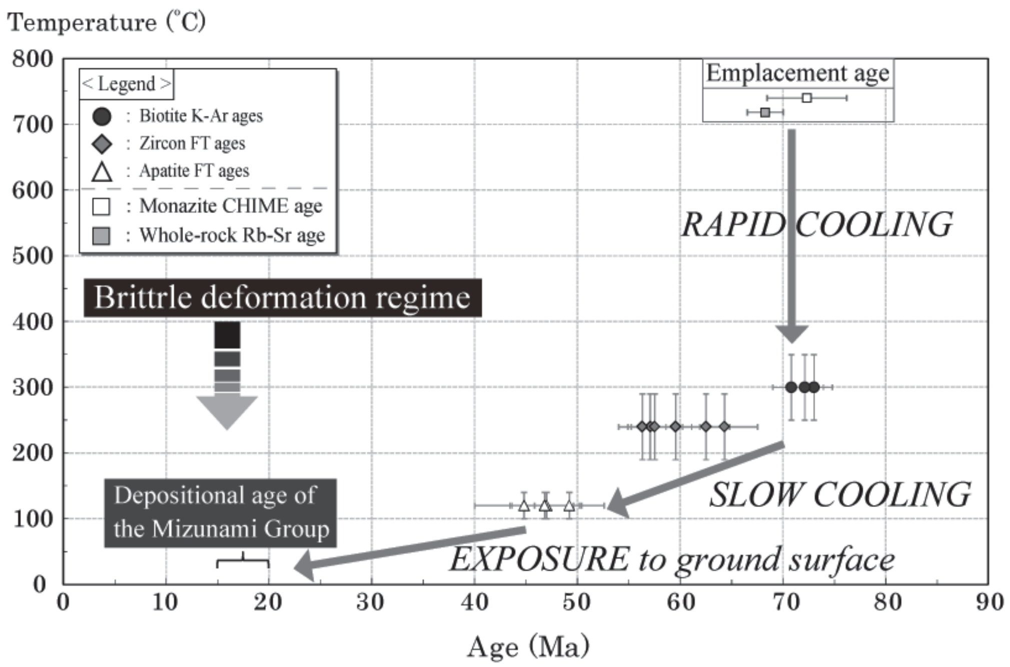

Fig. 4 Relationship between age dating and closed temperature (cooling history) of the Toki Granite. K-Ar and fission-track ages are obtained from the MIZ-1 borehole drilled in the MIU site, as shown in Figure 1. CHIME and Rb-Sr ages are quoted from Suzuki and Adachi (1998) and Shibata and Ishihara (1979), respectively.

directions. The directions of natural remanent magnetization (NRM) are dispersed (Fig. 5). The radius of the 95 % confidence circle is in the range of 19 to 30.

Magnetite is estimated to be the dominant contributor of the stable remanent magnetization on the basis of the stepwise acquisition experiment of isothermal remanent magnetization.

6. Discussion

Key finding of this study is dispersion of the NRM direction. The measured granite is intact without apparent deformation in the core-scale and was carefully sampled from the narrow range of the core without fracture. Such careful treatment of sample preparation avoids artificial error of the paleomagnetic measurement.

Curie temperature of magnetite is 580 ^{o}C (e.g. Butler, 1992). Fracture network could be formed at the brittle regime, i.e. below 300–400 ^{o}C. This suggests granite was plastically deformed during the temperature regime ranging from c. 570 to 300–400 ^{o}C. At this time, cooling rate was quite high, as suggested by closure temperature and age dating (Table 1, Fig. 4).

The pacific plate began to subduct at 70 million years ago (Maruyama and Seno, 1986). Thus the Japanese islands was placed under compressed field up to now. Such compressed stress field could cause rapid uplift of the granitic body, indicated by rapid cooling rate, and might cause inhomogeneous plastic deformation like “starch syrup”. This mode of deformation could generate inhomogeneous distribution of cooling strain.

When the granite reached to brittle deformation field, fractures were formed by the inhomogeneous strain. At the part of strain concentration, fracture could be densely developed.

If it is the case that the above-mentioned model is true, recognition of the cooling history of the granitic body is essential to understand the distribution of the fracture network.

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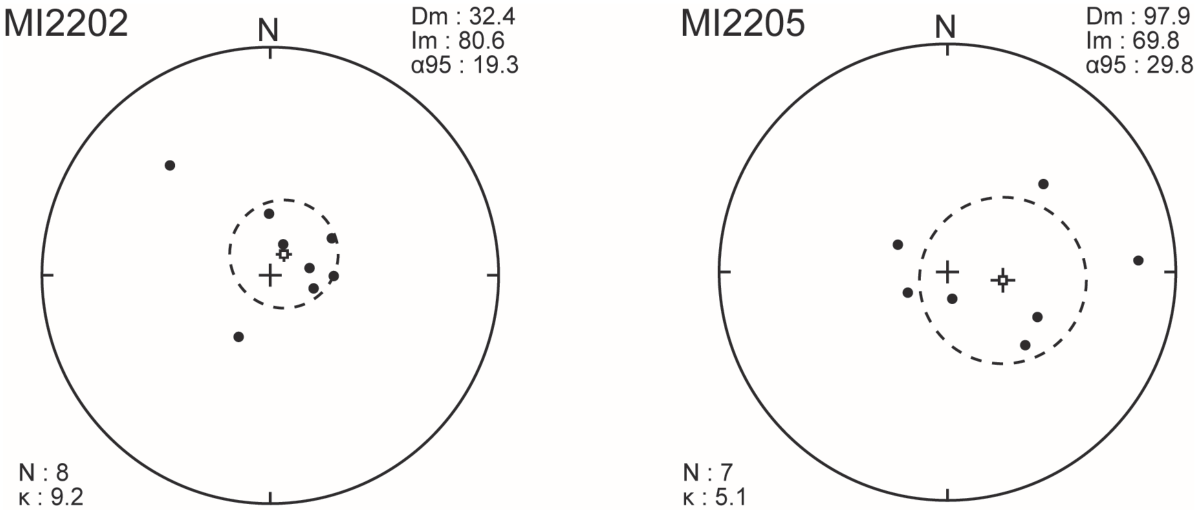

Fig. 5 Equal-area lower hemisphere projections of site-mean magnetic directions obtained from the some intact granite samples from GL-300m.
Dm and Im, mean declination and mean inclination in degrees, respectively; α95, radius of 95% confidence circle in degrees; N, number of specimens; κ, Fisherian precision parameter, respectively.