

Microscopic structure of joint terminations in granitic rock

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Abstract: We characterize the microscopic features of natural joint tips observed in the Toki Granite of Central Japan and compare them to cracks generated experimentally in a similar granite. Two types of joint tip are observed out of the 12 natural examples. Type-I tips exhibit a rough surface that often branches out along grain-scale discontinuities (e.g. grain boundaries, cleavages, twins, etc.), and are filled with iron oxides and microbreccias. Type-II tips terminate along the main joint plane and are filled with muscovite and calcite. We propose that the difference between these tip types derives from the depths at which they formed. Iron oxides generally precipitate from percolating meteoric water, while muscovite and calcite are commonly derived from deeper fluid sources. Thus we suggest that Type-I tips are associated with shallow jointing at low confining pressure, allowing joint tips to disperse out of plane along grain-scale discontinuities. Conversely, Type-II tips form at greater depths and pressures, presumably where grain-scale discontinuities no longer provide favorable propagation pathways. Cracks generated experimentally in granite under unconfined uniaxial compression at room temperature strongly resemble the natural Type-I joint tips, exhibiting rough surfaces that often branch out along grain-scale discontinuities. These similarities support our interpretation that Type-I joint tips occur naturally at shallow depth conditions.

Key words: joint tips, joint fillings, grain-scale discontinuities, confining pressure

Introduction

Experimental data from engineering materials (Kanninen and Popelar, 1985) and rocks (Friedman and others, 1972; Hoagland and others, 1973; Peck and others, 1985a, 1985b; Swanson, 1987) indicate the existence of a plastic zone or a microcracking zone at fracture terminations (Pollard & Aydin, 1988). However, direct observation of natural joint tips has been very limited, and the form of joint terminations and the associated deformation in the rock mass are not well known. In this study, the microscopic features of natural joint tips in the Toki Granite are characterized to clarify how joints terminate in granitic rocks. We then compare these field data to observations of cracks generated experimentally in a similar granite.

Geological Setting and Specimens

The Toki Granite was intruded into Mesozoic sedimentary rocks in the Tono district of Central Japan (Figure 1). The CHIME age is 68.3 ± 1.8 Ma (Suzuki and Adachi, 1998).

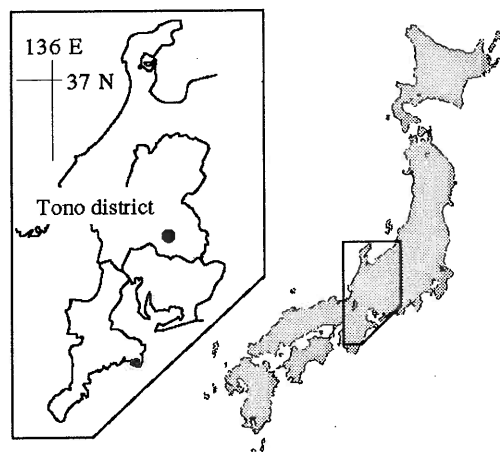


Figure 1. Location of Tono district, Japan.

We obtained 12 natural examples of joint tips from outcrops and a borehole. For the outcrop specimens, we put epoxy on the rock surface and used a hand drill with a diamond core barrel to prevent the destruction. The specimens were encased and penetrated with epoxy. The borehole specimens were provided by Japan Nuclear Cycle Development Institute. All specimens are biotite granite of fine to medium grain size. Joints were the only structure present in specimens.

Natural Joint tips

We identified two types of joint tips. Type-I tips exhibit a rough surface that often branches out along grain-scale discontinuities (e.g. grain boundaries, cleavages, twins, microcracks) and are filled with iron oxides and micro-breccias. Type-II tips terminate simply along the main joint plain and are filled with muscovite and calcite. Below we present photographs and descriptions for both types of joint tip.

Type-I joint tips

Figure 2 shows a joint that branched while propagating right to left (Figure 2b; red arrows). Both branch joints propagated along grain boundaries, cleavages, twins, and microcracks (figure 2c, d, e). The lower branch joint itself branches. Some of these second-order branches terminate at the primary joint, while the others are terminated with attenuated widths. The dark brown-red opaque minerals that fill these joints are iron oxide. Some host minerals are brecciated by both primary and branch joints (figure 2e).

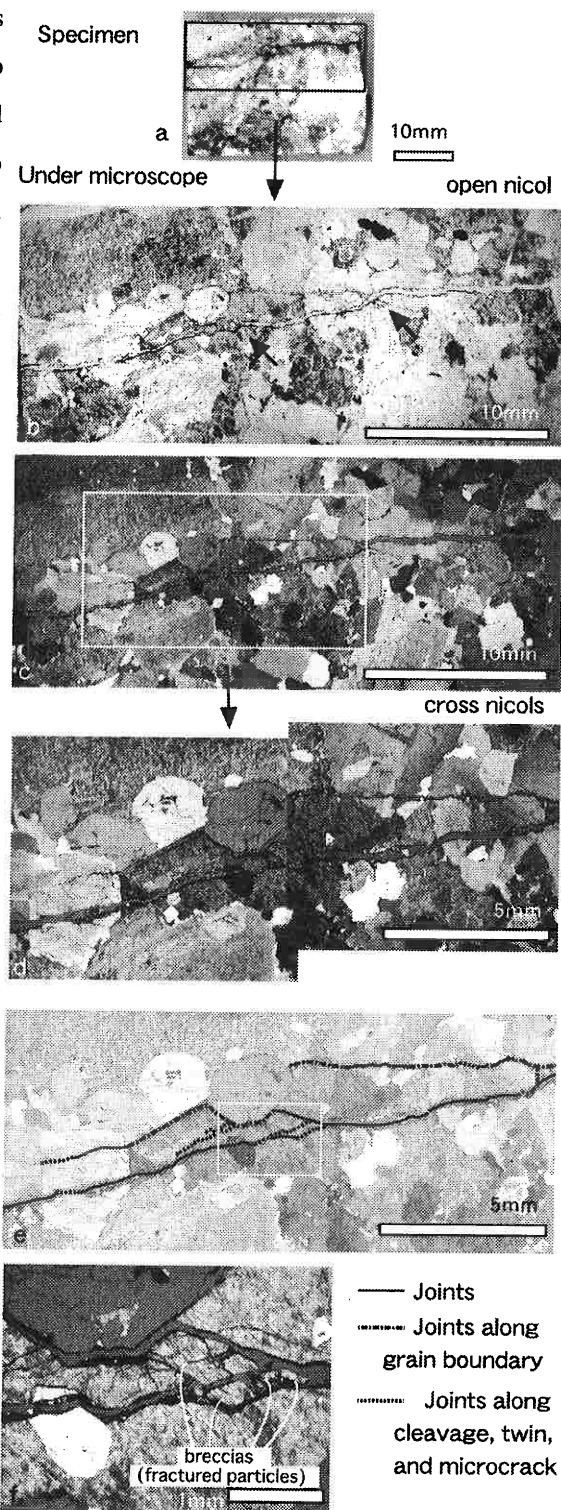


Figure 2. Photographs of Type-I joint tips. (a) Specimen taken from a field outcrop. (b) - (d) Photo-micrographs of joints, plane-polarized light (b) and crossed polarized light (c, d). (e) Trace of joints and joint tips in (d). (f) Photomicrograph of brecciated mineral grains.

Figure 3 shows another example of a Type-I joint tip that propagated from right to left side. The left part of the joint propagated mainly along grain-scale discontinuities.

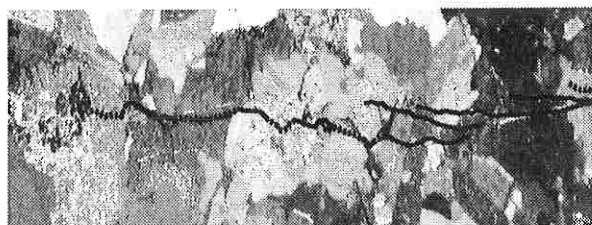


Figure 3. Photomicrograph with trace of Type-I joint tips. This joint was taken from other field outcrop. For explanation of lines, see Figure 2.

In Figure 4, the joint propagated from left to right and split into branches (Figure 4a, b). These branch joints are located along grain-scale discontinuities, and terminate at the right side (figure 4c, d). The main joint is filled with micro-breccias (figure 4e, f).

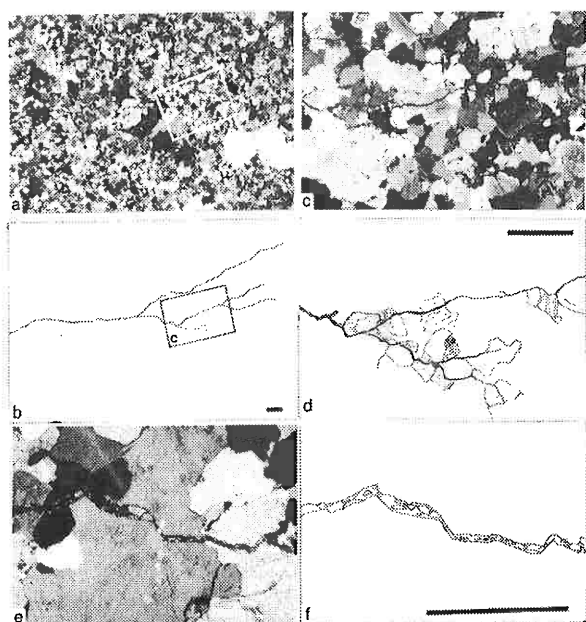


Figure 4. Photomicrographs of joint tips (a, c), joint fillings (e), and sketches of them (b, d, f). These joints were taken from the borehole and show Type-I joint tips. Scale bars are 1mm. (Fujii, 2001)

Joints (1) and (2) in figure 5 formed in echelon style. The tip of joint (1) (figure 5d, e) propagated mainly along grain-scale discontinuities.

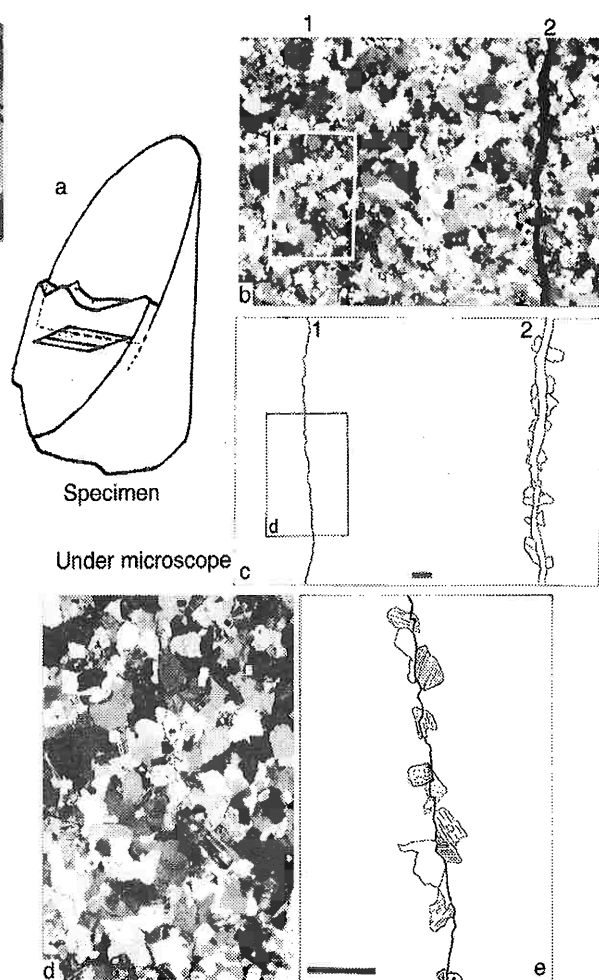


Figure 5. (a) Drawing of a borehole specimen including echelon joints (1 and 2). The thin section is parallel to echelon joint tips and joint 1 is very close to the joint termination. (b), (c) Photomicrograph and sketch of the joints. (d), (e) Photomicrograph and sketch of joint tip (1). Scale bars are 1mm. (Fujii, 2001)

Type-II joint tips

Closely spaced echelon joints interacted and arrested at the center of Figure 6a. Both joints propagated smoothly without tracing grain-scale discontinuities, terminated with tapered widths, and are filled with calcite and muscovite.

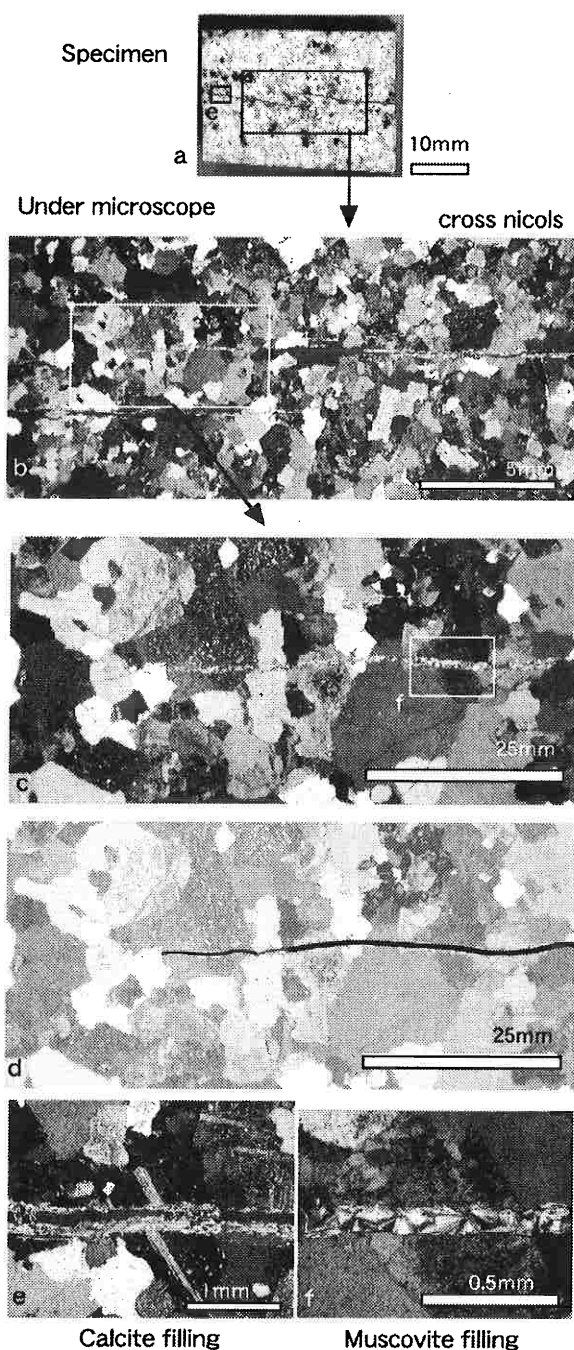


Figure 6. Photographs of Type-II joint tips. (a) Specimen taken from the borehole. (b), (c) Photomicrographs of joint tips, crossed polarized light. (d) Trace of the joint tip in (c). (e), (f) Photo-micrographs of joint fillings, calcite (e) and muscovite (f).

Figure 7 shows another example of Type II joint tips. The lower joint propagated smoothly from the right side and terminated in the middle of the

specimen. In the final part, joints propagate smoothly without tracing microcracks, which intersect at the acute angles. Both joints are filled with muscovite.

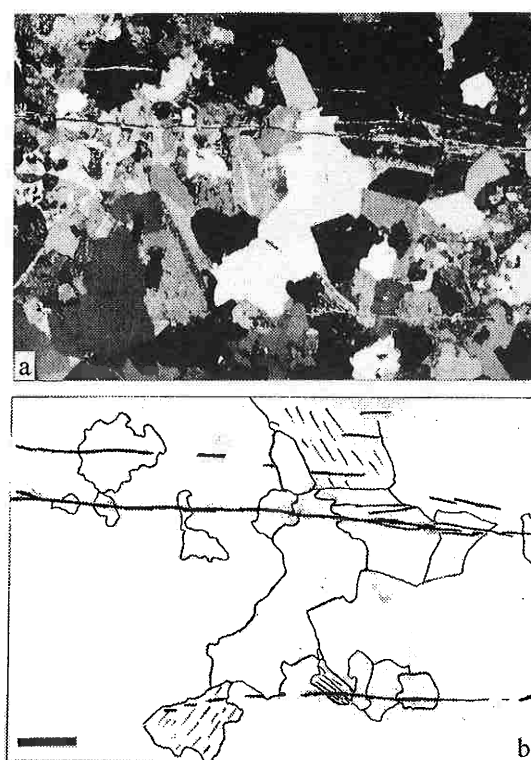


Figure 7. Photomicrograph (a) and sketch (b) of an echelon Type-II joint tips. This specimen was taken from the borehole. Scale bar is 1mm. (Fujii, 2001)

Discussion about natural joint tips

We have identified two types of joint tips, and propose that the difference between these derives from the depths at which they formed. Iron-oxide fills joints which are shallower than the depth of 130 m in the AN-1 bore hole (Yoshida, 1989, Iwatsuki and Yoshida, 1997). Thus it could be reasonable that iron-oxide fillings precipitate from percolating meteoric water (Fujii, 2000). Therefore we suggest that Type-I tips form at shallow depth. The low confining pressures involved in the shallow depth might explain why the joint plane is able to disperse along pre-

existing grain-scale discontinuities at its tip. Furthermore low differential stress state might be needed to form rough surface tips along grainscale discontinuities, because high differential stress could make them straight (Olson and Pollard, 1992, Renshaw and Pollard 1993).

Muscovite (fine grain muscovite is called as sericite) are originated from hydrothermal activity (Iwao, 1953). The K-Ar age of sericite veins are almost same as the host granite in Chugoku district (Kitagawa et al., 1988). In the Tono district, there was no more volcanic or hydrothermal activity after late Cretaceous and early Paleogene when the Toki Granite was intruded (Yamashita et al., 1988). Therefore muscovite fillings are guessed from hydrothermal fluid related to magma water in the depth of granite intrusion (Fujii, 2000). Thus Type-II tips likely result at greater depths and pressures, presumably where grain-scale discontinuities no longer provide energetically favorable propagation pathways (Table 1).

Table 1 Relationship between joint tip types and their formation

	Type-I	Type-II
Formation	Rough termination trace along the discontinuities	Straight termination
Fillings	Iron-oxide, Micro-breccia	Muscovite, Calcite
Generatred	Low Confining and Low Differential Pressure and Low Temperature	High Confining Pressure and High Temperature
Circumstance & Depth	Shallow	Deep

Figure 8 shows a specimen containing both types of joint tips. A joint filled with muscovite propagated from left to right and terminated as a Type-II tip in the center of the specimen (white lines in Figure 8b). Subsequently, a new joint initiated from the tip of original joint and continued propagating to the right mainly along grain-scale discontinuities. This joint is filled with iron oxide (Type-I joint, black bold

lines in Figure 8b). We estimate that the Type-II joint tip formed at depth. Following a period of uplift, the joint reinitiated from the pre-existing Type-II tip and terminated as the Type-I joint tip.

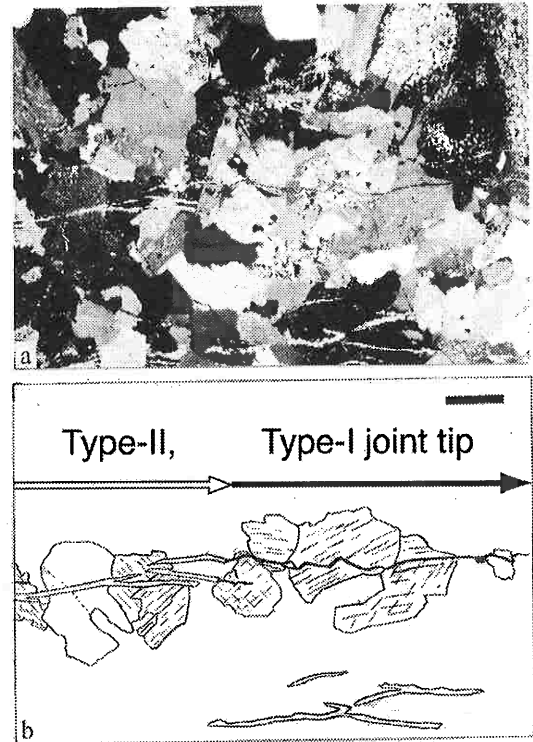


Figure 8. Photomicrograph (a) and sketch (b) of joint tips. The specimen was taken from a field outcrop and contains both Type-I and II joint tips. Scale bar is 1mm. (Fujii, 2001)

Experimental Crack tips

Cracks were generated experimentally in Inada Granite (a biotite granite of moderate grain size substantially similar to the Toki Granite) under uniaxial compression to 80 - 90 percent of critical strength at room temperature.

The cracks, which are almost parallel to the compression axis (axial-cracks), produced exhibited rough surfaces that often branched out along grain-scale discontinuities (Figure 9b, c, d, e). Thus, the

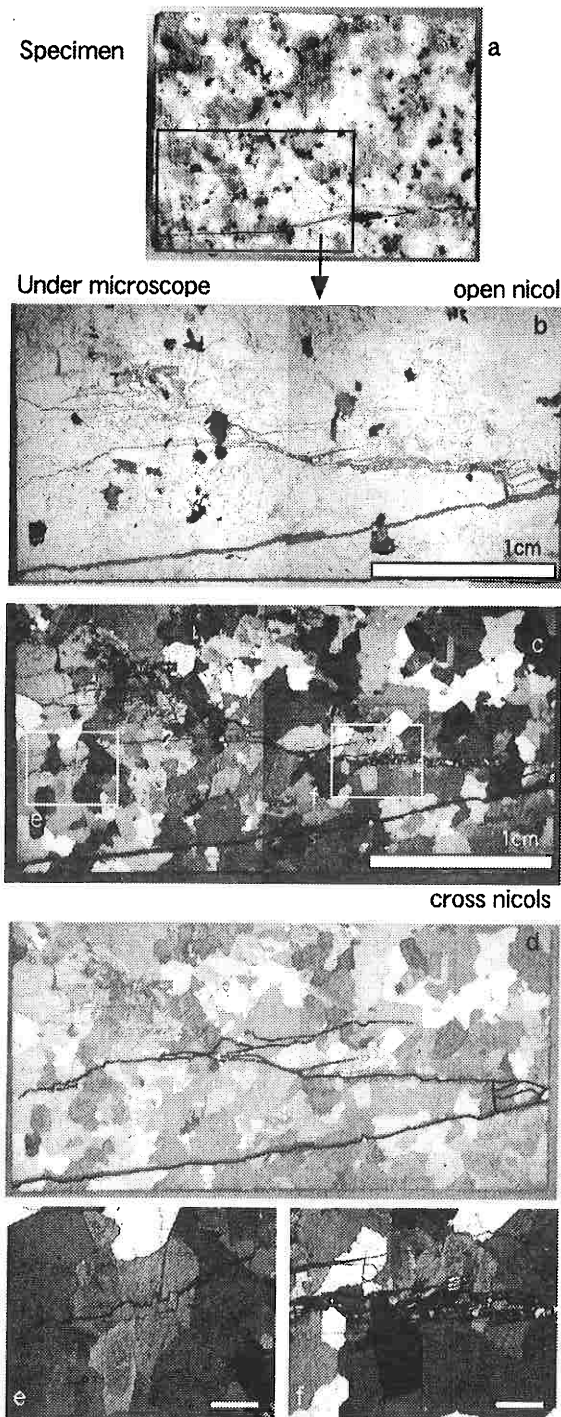


Figure 9. Photographs of experimental crack tips. (a) Specimen including experimental axial cracks. (b), (c) Photomicrographs of cracks, plane-polarized light (b) and crossed polarized light (c). (d) Trace of the cracks and crack tips in (c). (e), (f) Photomicrograph of a crack tip (e), and filling of micro-breccias. Note these breccias from shear fracture. (f). For explanation of lines see Figure 2.

experimentally generated crack tips resemble the natural Type-I joint tips. To further examine this similarity, we calculated the length ratio of grain-scale discontinuities to the total joint tip trace for both the natural Type-I joint tips and the experimental crack tips. The total joint tip trace starts at the first dispersion to grain-scale discontinuities from host joint (Figure 10 arrow). Thus, the ratio in figure 10 is calculated by (broken lines) / (broken lines + solid lines), in the left part from the arrow. The mean ratio of natural Type-I joint tips is 0.72, while the experimental ratio is 0.69. This similarity supports our interpretation that Type-I joint tips occur naturally at shallow depths, low temperatures and confining pressures.

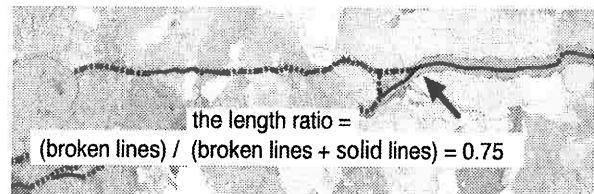


Figure 10. The length ratio of grain-scale discontinuities to the total joint tip trace. This is a part from Figure 2b, c.

Experimental cracks are filled with micro-breccias (Figure 9f). However these micro-breccias might be from shear fracture which is formed by the coalescence of axial-cracks (Peng and Johnson, 1972, Wong, 1982).

Conclusion and Summary

Natural joint terminations in the Toki Granite show two types of joint tips. Type-I tips exhibit a rough surface along grain-scale discontinuities (e.g. grain boundaries, cleavages, twins, etc.), and are filled with iron oxides and micro-breccias. Type-II tips terminate simply along the main joint plain and are

filled with muscovite and calcite. Cracks generated experimentally under unconfined uniaxial compression at room temperature strongly resemble the natural Type-I joint tips. We suggest Type-I tips form at shallow depth, where the confining pressure is low and iron oxide is precipitated from percolating meteoric waters. Type-II tips form at greater depth, where grain-scale discontinuities cannot provide favorable propagation pathways, and muscovite and calcite precipitate from fluid sources at depth.

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