Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

FIELD OBSERVATIONS OF A COOLING JOINT SYSTEM IN THE QUATERNARY TAKIDANI PLUTON, JAPAN

Shingo Kano, Kenichi Kishi, Kazuya Saito, Chie Shiro, Noriyoshi Tsuchiya, and Katsuto Nakatsuka
Department of Geoscience & Technology, Graduate School of Engineering,
Tohoku University, Sendai 980-8579, Japan

Key Words: Takidani granitoid rocks, natural fracture network, joint spacing, joint block size, cooling joint system

ABSTRACT

Due to rapid uplift in the Quaternary, the natural fracture network in the Takidani Pluton can now be observed in outcrops. Distinctive features characterising fracture networks in the neo-granitoid body were recognised during field observations; preferred orientations were identified but no displacement on fractures were observed. These fractures have the general characteristics of joints and cut across each other to form blocks of parallelepiped shape.

Strike and dip of fracture surfaces were measured and show that fracture orientation changes progressively from the margin of the body towards the centre of the pluton. Joint spacing, measured as a dimension of respective joint blocks, also increases closer to the centre of the pluton. The characteristics of the fracture network, particularly the preferred orientations and joint spacing (with no displacement), indicate that the formation mechanism of fractures in the pluton was due to thermal contraction, rather than shearing, in a regional stress field. Reconstruction of the plutonic body is possible by plotting the perpendicular direction of joint surfaces for each outcrop.

1. INTRODUCTION

Large granitoid bodies are expected to provide the most suitable reservoir rocks for future deep Hot Dry Rock (HDR) and Hot Wet Rock (HWR) geothermal developments (Gianelli *et al.*, 1988, Soma and Niitsuma, 1997). In particular, neo-granitoids occurring in active geothermal areas have been considered to be interesting targets for HDR (HWR) developments. The main channels for heat and fluid transfer are fractures in the reservoir rocks, and an assessment of the fracture network system is indispensable for evaluating potential reservoir performance.

A geometrical approach has been used to model the fracture networks, using fractal concepts (Merceron and Velde, 1991, Velde *et al.*, 1991, Ledésert *et al.*, 1993, Kano *et al.*, 1999, Tsuchiya and Nakatsuka, 1999). These studies, however, did not consider the mechanism of fracture development (i.e. the viscosity of a magma, the rate of cooling, the mechanism of fracture generation). Further investigations based on actual field observations are therefore required which consider the mechanisms of fracture generation and fracture mechanical characteristics of natural fracture networks.These are important for a fundamental study of fracture modeling.

This paper describes field observations in the Takidani Granitoid rocks (TG) and discusses the structure of the fracture networks.

2. GEOLOGICAL OUTLINE

The TG occurs along the major axis of the Japan Alps, one of the active volcanic belts in Japan. It is the youngest exposed granitoid pluton, and intruded into late Pliocene (2.4Ma) Hotaka Andesites according to Harayama (1994). The TG is exposed within a 13 km long and up to 4 km wide (21 km^2) rugged mountain range at elevations between 1,450m to 2,630m above sea level. The TG intruded Mesozoic basement, Tertiary granitic rocks, Hotaka Andesites, and Quaternary Yakedake volcanic rocks (Fig. 1). According to Bando and Tsuchiya (2000), the TG may be divided into six lithofacies on the basis of modal analysis and rock textures. It comprises porphyritic granodiorite, porphyritic granite, biotite-hornblende granodiorite, hornblende-biotite granodiorite, biotite-hornblende granite, and biotite granite. The pluton has a reversely zoned composition in terms of its whole-rock chemistry. The SiO_2 content decreases inwards from the pluton margin (Harayama, 1992, Bando and Tsuchiya, 2000), from more than 70 wt% in the margin to less than 67 wt% in the core. We can recognise the relative (geological) position of any given outcrop within the TG from its SiO_2 content (see Bando and Tsuchiya, 2000).

Field observations were undertaken in six valleys, as shown in Fig. 2. The surveyed outcrops are located in the Yanagi-dani (Yd 01, 02), Shiradashi-zawa (Sd 01-06), Tengu-zawa (Tg 01-06), Nishiho-zawa (Nz 01-03), Chibi-dani (Cd 01, 02), and Taki-dani (Td 01, 02) valleys. The Tengu-zawa and

Nishiho-zawa valleys are located on the eastern side of the pluton, and the others on the western part. On the eastern side, the upper valleys are more than 2,050 m above sea level. Shiradashi-zawa and Tengu-zawa valleys are connected at about 1,850 m above sea level and cross the TG; both valleys intersect the fracture networks of the TG.

3. MEASUREMENT OF FRACTURE NETWORKS

The following fracture features were measured: (1) strike and dip of fracture surfaces at 507 locations, (2) joint spacing given by the distance between adjoining fracture surfaces. Joint spacing was measured using digital photographs of outcrops in the Shiradashi-zawa and Tengu-zawa valleys.

4. RESULTS OF FIELD OBSERVATIONS

4.1 General Fracture Features within the TG

Fracture surfaces are reasonably flat and smooth, and fractures cross each other without any primary displacements. This means that fractures in the TG represent the general characteristics of “joints”. Three preferred joint orientations were identified at any outcrop. The three individual joint planes were classified as Faces 1, 2, and 3. Face 1 is vertical and parallel to the valley direction, Face 2 dips west to northwest, and Face 3 dips east to southeast. The joints cross each other and form joint blocks of parallelepiped shape.

4.2 Distribution of Joint Orientations

The orientations of Faces 1, 2, and 3 can be further defined. The strike of Face 1, which is a vertical plane, strongly depends on the direction of the stream in the valley. The direction of Face 1 shows no correlation with the position of the outcrop within the TG. On the other hand, the strike of Face 2 and Face 3 is almost perpendicular to Face 1, and the dips of Face 2 and Face 3 vary according to the position of the outcrop. Table 1 shows representative dips of Face 2 and Face 3. For a traverse from the western margin (1,550 m above sea level) to the center of the pluton (1,835 m above sea level), the dip of Face 2 changes from high-angle to low-angle, whilst that of Face 3 changes from low-angle to high-angle. On the other hand, a transition was not so evident on the eastern side of the pluton compared with results from the western side. In the Tengu-zawa valley, the dips of Face 2 and Face 3 are constant to up to 2,000 m elevation; both show discontinuous variations at greater elevations.

4.3 Joint Spacing

The distance between adjoining joint surfaces (i.e. joint spacings a and b in Fig.3) was measured for Face 2 and Face 3 in the Shiradashi-zawa (Sd 01-05) and Tengu-zawa (Tg 01) valley. As shown in Table 2 (a) and 2 (b), the average joint spacing increases closer to the centre of the pluton. A joint block size [in m^2] was calculated and is shown in Table 2 (c). Fig. 4 shows that the block size also increases towards the centre of the pluton.

5. DISCUSSION

Generally, joints are classified as shear joints or extensional joints on the basis of dynamical conditions during their formation. In the former case, a joint system is mainly controlled by the regional stress field with slight displacements along the joint surfaces. In the latter case, the driving force for joint formation is thermal contraction, without displacement along joint surfaces. Shear joints are formed in an anisotropic stress field and show preferred orientations (Hirano, 1969). Joint dips in the TG change successively inward from the margins of the body, as shown in Table 1. Three different orientations were obtained, with no unique orientation occurring throughout the pluton.

The block size was smaller at the margin of the pluton and larger towards its centre. Fig. 5 shows the distribution of calculated block size from the margin to the core. Sd 04 is assumed to be the nearest outcrop to the core, based on the SiO_2 content of samples collected at this locality. It appears that block size is not constant throughout the pluton, but increases from its margin to the center of the body. Fig. 6 shows an illustration of observed block shapes along the Shiradashi-zawa valley traverse which complements joint dip and block size data presented in Table 1 and Table 2. Such variations in joint orientation and block size are typically attributed to the cooling of an intrusion and is a characteristic of joints caused by thermal stresses (Goto and McPhie, 1998). Joints initiated by thermal stresses propagate perpendicularly to the isotherms during the cooling of a pluton (Yokota, 1974). Grossenbacher and McDuffe (1995) suggest that the thermal gradient is linked to column diameter, with steeper gradients leading to narrower columns. According to their explanation, the direction of joint propagation depends on the distribution of block size and thermal gradients in the pluton. Thus it is reasonable to infer that the process of jointing in the TG occurred under thermal stresses produced during cooling of the magma, rather than as an effect of a regional tectonic stress field. One of the TG joint systems was therefore perpendicular to the isotherms in the pluton, i.e., the direction of Face 3. Isotherms in magmatic bodies are deduced to have a concentric configuration, similar to the shape of a dome (Spry, 1962). As for the TG, the original shape of the plutonic body is no longer evident, due to strong erosion related to rapid uplift, but the shape of the plutonic rock can still be reconstructed, by plotting in a map the direction perpendicular to Face 3 at each outcrop. The two-dimensional shape of the rock body along the Shiradashi-zawa and Tengu-zawa valley section is shown in Fig. 7. It is assumed that some faults are present and are cut by the Shiradashi-zawa and Tengu-zawa section, since field observations show a displacement in the joint system at 1,850 m to 1,900 m above sea level (where the Shiradashi-zawa and Tengu-zawa valleys are connected).

6. CONCLUSIONS

In this study the structure of the fracture network in the TG has been evaluated on the basis of field observations. This fracture network shows characteristics of being a thermally derived joint system, with three preferred orientations (Faces 1 - 3). The measurement of strike and dip show that the directions progressively changes from the western contact to the centre of the pluton. The average joint spacing also increases towards the centre of the pluton. A joint block size was calculated by multiplying joint spacings of Face 2 and Face 3; this showed that block size also increases from the contact towards the centre of the pluton.

These field observations indicate that the joint structure in the TG was formed by thermal contraction rather than by tectonic stress.

On the basis of field observation and analysis of the fracture network, an evaluation of joint structure in the pluton and reconstruction of the plutonic rock body shape is clearly possible. Our results are of importance for the evaluation of fracture networks in deep-seated geothermal reservoir which may be developed as HDR and HWR systems.

ACKNOWLEDGEMENTS

We would like to express our gratitude to Dr. T. Sawada of Hodaka Sedimentation Observatory, Disaster Prevention Research Institute, Kyoto University for his kind help during the field program. This work was financially supported by JSPS (RFTF97P00901).

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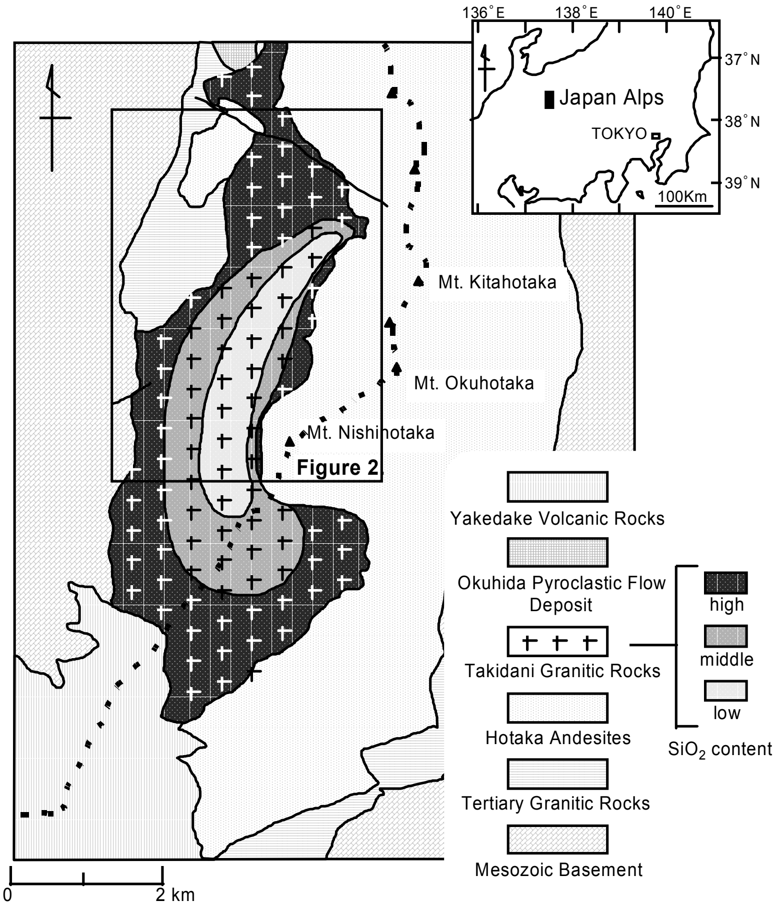

Figure 1. Generalized geological map and SiO_2 contours for the TG, Japan Alps (simplified and modified after Harayama (1992) and Bando

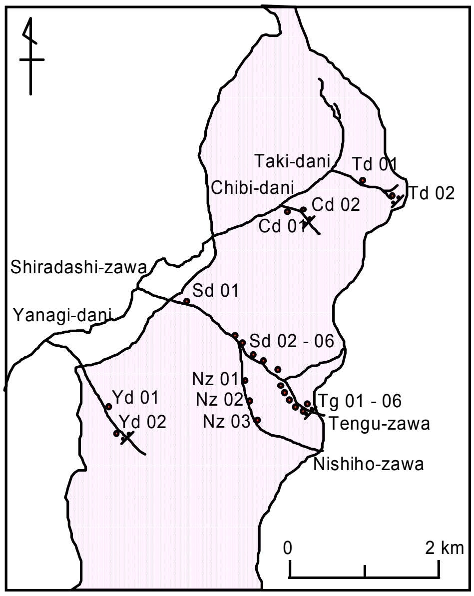

Figure 2. Location of outcrops used for surveying the fracture structure in the TG

Table 1. Representative joint dips of Face 2 and Face 3 at Shiradashi-zawa (Sd 01 - 06), Tengu-zawa (Tg 01 - 06), Yanagi-dani (Yd 01 and 02), Nishiho-zawa (Nz 01 - 03), Chibi-dani (Cd 01 and 02), and Taki-dani (Td 01 and 02) valleys in the TG

	Outcrop	Above sea level [m]	Face 2	Face 3
Margin	Sd 01	1550	60° W	45° E
↑	Sd 02	1810	35° W	35° E
	Sd 03	1820	30° W	53° E
Core	Sd 04	1835	20° W	60° E
↓	Sd 05	1840	17° W	77° E
	Sd 06	1880	85° W	24° E
	Tg 01	1900	40° W	60° E
	Tg 02	1905	40° W	70° E
	Tg 03	1910	30° W	70° E
	Tg 04L	1930	41° W	70° E
	Tg 05	1940	54° W	5° E
	Tg 06L	2010	18° E(?)	89° E(?)
Margin	Tg 06R	2010	40° W	70° E

	Outcrop	Above sea level [m]	Face 2	Face 3
Margin	Yd 01	1650	15° W	55° E
↑	Yd 02	1800	26° W(?)	70° W(?)
	Nz 01	1965	37° W	0° E
↓		1970	78° W	12° E
	Nz 02	2000	13° W	82° E
Margin	Nz 03	2020	10° W(?)	81° W(?)
Margin	Cd 01	1780	50° W	25° E
↑	Cd 02	1805	37° W	41° E
Margin	Td 01	1865	47° W	62° E
↑	Td 02	1930	58° W(?)	7° W(?)

Shiradashi-zawa Sd 01 - 06
Tengu-zawa Tg 01 - 06
Yanagi-dani Yd 01, 02
Nishiho-zawa Nz 01 - 03
Chibi-dani Cd 01, 02
Taki-dani Td 01, 02

Table 2. Measured joint spacings and calculated block sizes; outcrop labels as in Fig.2 and Table 1

(a) Face 2

	Outcrop	Sea level [m]	Number of data	Minimum [cm]	Maximum [cm]	Average [cm]
Margin	Sd 01	1550	33	6	87	33
↑	Sd 02	1810	46	5	143	57
	Sd 03	1820	15	30	235	117
Core	Sd 04	1835	6	123	184	151
↓	Sd 05	1840	15	18	212	101
Margin	Tg 01	1900	14	31	103	55

(b) Face 3

	Outcrop	Sea level [m]	Number of data	Minimum [cm]	Maximum [cm]	Average [cm]
Margin	Sd 01	1550	24	7	56	28
↑	Sd 02	1810	23	22	268	100
	Sd 03	1820	20	10	245	92
Core	Sd 04	1835	3	266	419	330
↓	Sd 05	1840	4	250	390	325
Margin	Tg 01	1900	7	49	131	65

(c) Calculated block size

	Outcrop	Sea level [m]	Block size [m^2]
Margin	Sd 01	1550	0.09
↑	Sd 02	1810	0.57
	Sd 03	1820	1.08
Core	Sd 04	1835	4.98
↓	Sd 05	1840	3.27
Margin	Tg 01	1900	0.36

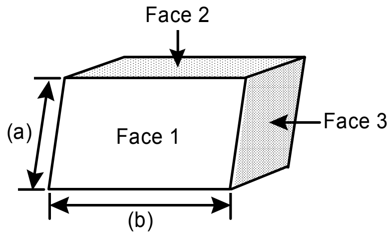

Figure 3. Schematic illustration of parallelepiped joint block with faces named Face 1, Face 2, and Face 3. (a) is joint spacing of Face 2, and (b) is joint spacing of Face 3

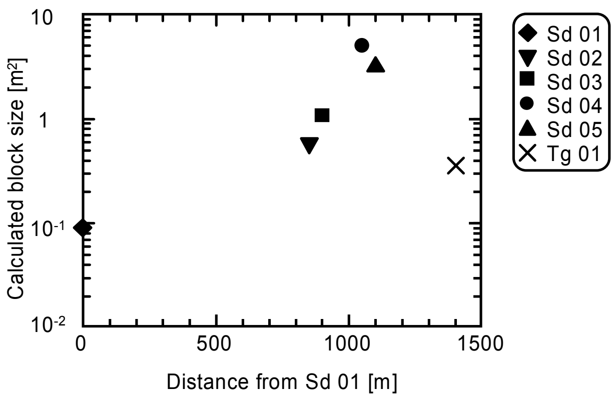

Figure 4. Relationship between calculated block size and distance from Sd 01

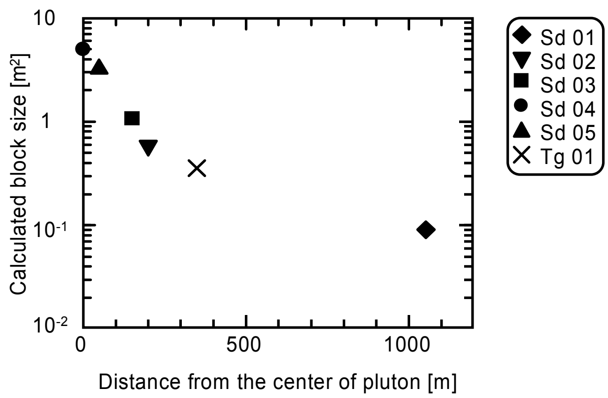

Figure 5. Relationship between calculated block size and distance from margin to core. Sd 04 is assumed to be the nearest outcrop to the core of the TG

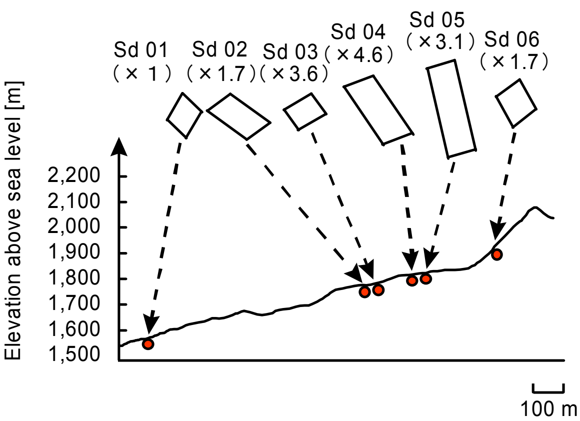

Figure 6. Observed joint block shape at outcrops in Shiradashi-zawa

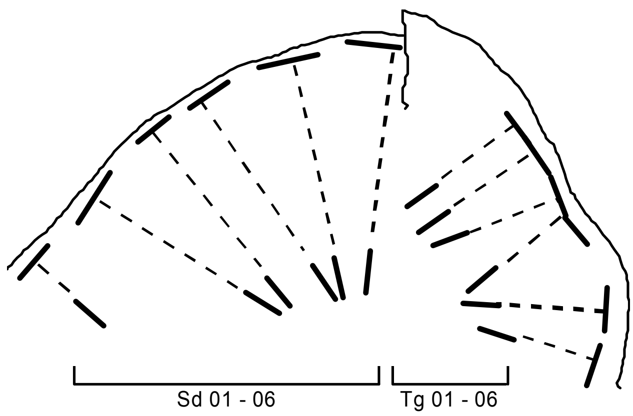

Figure 7. Reconstruction of TG shape, made by connecting the direction perpendicular to Face 3 (dotted line) at each outcrop. Figure shows the traverse from Shiradashi-zawa to Tengu-zawa valley. It is inferred that faults are present near the connection of Shiradashi-zawa and Tengu-zawa valley.