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Field Observation of Joint Structures in Various Types of Igneous Rocks

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Abstract. In this study, field observations of natural fracture network systems in some intrusive and extrusive rocks were undertaken, to clarify the fracturing mechanism in the rocks. Shallow intrusives, whose depth of emplacement was less than several hundred metres, include the Momo-iwa Dacite dome on Rebun Island (Hokkaido), and Jodogahama Rhyolite in Iwate prefecture. Extrusive complexes studied include the Tojinbo Andesite and Ojima Rhodacite in Fukushima prefecture. Rocks of ‘granitic’ composition were collected from the Takidani (Japan Alps) and Hijiori (Yamagata prefecture) plutons. The joint structure in Hijiori Granite was evaluated by analysis of core samples extracted from the HDR-3 geothermal production well. Based on detailed field observation, joint structures related to thermal contraction of a rock mass could be classified according to their inferred depth of formation. Joints from a near surface setting, such as shallow intrusive rocks and extrusives, tend to form pentagonal - hexagonal columnar structures (for a variety of rock types), whilst granitic rocks (from a deeper setting) typically exhibit a parallelepiped structure. The apparent differences in joint form are inferred to be dependent on the confining pressure, which acts on joint generation and propagation. In cases of non-confining pressure, such as the near-surface (shallow intrusive/extrusive) setting, joint networks typically form a columnar structure. On the contrary, confining pressure is considerably greater for deeper rock masses, and these form a parallelepiped joint structure.

Keywords: Field observation, Intrusive and extrusive rocks, Columnar joint, Parallelepiped joint, Thermal contraction.

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INTRODUCTION

It is envisaged that fluid flow and heat transfer in deep-seated, enhanced geothermal systems developed for their electric generating potential will predominantly be on fractures. Intrusive rocks of intermediate-felsic composition are the heat source for numerous active geothermal systems (Bando et al., 2003) and a likely reservoir rock in which to establish an artificial, energy extraction (Hot Dry/Wet Rock; HDR/HWR) system - as well as a host rock for many types of magmatic-hydrothermal (e.g. Cu-Au Porphyry-type) ore deposits, and for possible disposal of high-level radioactive waste.

In this paper we discuss the nature and mechanism for fracture generation in intrusive rocks that characterize the tectonic and structural setting in which a Deep-Seated Geothermal Reservoir (DSGR) may be developed, focusing on the Takidani Granodiorite and Kodake Granodiorite (Hijiori HDR test site) (Honshu, Japan; Figure 1). We examine the effect of thermal deformation on the character of fractures in large intrusions, and comment on the importance of these natural fracture networks both for development of conventional geothermal resources, and hydraulically fractured DSGR systems. Thermal stresses are the primary cause of jointing in deeply emplaced plutonic rocks, affecting both the age and geometry of jointing, and locus of later mineralisation (Bergbauer and Martel, 1999), so understanding the mode of formation and their influence on the hydrology of a hydrothermal system is extremely important.

Columnar jointing, caused by cooling and thermal...
contraction, is a common feature of shallow intrusive and extrusive rocks (Long and Wood, 1986; DeGraff and Aydin, 1987; Grossenbacher and McDuffie, 1995). We examined the joint structure of the Momo-iwa Dacite (Rebun Island, Hokkaido) and Jôdogahama Rhyolite (Iwate prefecture), whose depth of emplacement is inferred to be a few hundred meters; and Tôjinbô Andesite and Ojima Rhyodacite (both from Fukui prefecture, Figure 1), to facilitate direct comparison with the fracture geometry of deep-seated intrusive complexes.

EXPLANATION OF IGNEOUS ROCKS AND RESULT OF FIELD OBSERVATION

Takidani Granodiorite (TG)

Geology

The TG is a pluton situated along a major axis of the Japan Alps, one of the active volcanic belts in Japan. It is reportedly the youngest exposed pluton on the Earth (Harayama, 1994). The TG, distributed over a rugged mountain range, is 13 km long and up to 4 km wide (21 km²), and has a vertical exposure from 1,450 m to 2,630 m above sea level. The TG intruded Mesozoic sandstone and mudstone basement rocks, Tertiary granitic rocks and Hotaka Andesites, and was covered by the Quaternary Yakedake volcanics (Figure 2). The pluton has, on the whole, a reversely zoned composition in terms of whole-rock chemistry. SiO₂ content decreases inward, from the pluton margin (Harayama, 1992; Bando et al., 2003), from more than 70 wt% at the margin to less than 67 wt% in the core. Thus we can infer the relative (geological) position within the TG, by determining the SiO₂ content of collected outcrop samples.

Result of Field Observation

Field observation was undertaken in six valleys. The following features were measured; (1) strike and dip of joint surfaces at 507 locations, (2) joint spacing, constituting the distance between adjoining joint surfaces, was measured using digital photographs of outcrops.

Three preferred joint orientations were identified at any outcrop. The three individual joint planes were classified as Face 1, Face 2, and Face 3. Face 1 is parallel to valley direction in vertical, Face 2 dips west...

FIGURE 2. Generalized geological map and SiO₂ contours for the TG, Japan Alps (after Hareyama (1992), Kano and Tsuchiya (2001) and Bando et al., 2003))

FIGURE 3. An outcrop in the TG. Joints show three preferred orientations

FIGURE 4. Schematic illustration of parallelepiped joint block with face name provisionally labeled 'Face1', 'Face2' and 'Face3'. (a) is joint spacing of 'Face2' and (b) is joint spacing of 'Face3'.
to northwest, and Face 3 dips east to southeast (Figure 3). The joints cross each other with no joint displacement and form parallelepiped joint blocks. For a traverse from the western margin to the center of the pluton, the dip of Face 2 changes from high-angle to low-angle, whilst that of Face 3 changes from low-angle to high-angle. The joint directions are inferred to conform to the overall (domed) shape of the intrusive.

The distance of adjoining joint surfaces (i.e. joint spacing, Figure 4) was measured for Face 2 and Face 3. The average joint spacing increases as the center of the pluton is approached. Joint block size ($m^2$) was calculated, by multiplying the average spacing of Face 2 and Face 3, as shown in Table 1. The block size also increases with towards the center of the pluton (Kano et al. 2000).

### Kodake Granodiorite (KG)

**Geology**

The Hijiori area (Yamagata prefecture) is the focus of several HDR geothermal energy programs. The KG is one of the basements of the Hijiori area. The New Energy and Industrial Technology Development Organization (NEDO) drilled three geothermal production wells (HDR-1, HDR-2 and HDR-3) during six years from 1987 for the purpose of developing technologies of Hot Dry/Wet Rock (HDR/HWR) geothermal energy programs in the Hijiori region. These wells reached the KG at the depth of 1450 m - 2205 m, 1480 m - 2303 m and 1486 m - 2303 m.

Inoue (2000) measured the azimuth of fractures on oriented core samples extracted from HDR-3 well. In this study the joint structure in the KG was characterized based on the result of Inoue (2000).

**Measurement of Core Samples**

Figure 5 shows an example of joint directions on core samples at the deeper depth extracted from HDR-3 well (Inoue, 2000). Joint orientations were predominant in three directions as a whole. This result corresponds with the NEDO’s measurement of fracture orientations (NEDO, 1991).

**Momo-iwa Dacite (MD)**

**Geology**

The MD is located in the south end of Rebun Island, Hokkaido. It intruded Late Miocene sedimentary rocks (Goto and McPhie, 1998; Figure 6), and the range of exposure is about 300 m long in north-south, 200 m long in east-west, and 190 m in height. An Overview of the MD is shown in Figure 7. SiO$_2$ content was

![Geological map of Rebun Island (after Nagano et al., 1963).](image)
about 63 wt%, and the radiometric age of the rock by K-Al method showed 13.0±1.6 Ma (Goto et al., 1995). The rock body shape did not deform after emplacement, and kept the original shape from intrusion.

We can see the internal joint structure at the western side of the rock body because of tidal scour. Field observation was undertaken at there in 1998. Two-dimensional joint networks on outcrops were traced on a polyvinylchloride film sheet and digital photographs of outcrops were taken.

**Result of Field Observation**

Joint orientation and joint spacing were measured at ten outcrops (Md 01 - Md 10, Figure 8) on the sea cliff at western side of rock body. We could identify a massive core at the center of the MD, and columnar joints propagated from the center to the margin radially. Shapes of cross section seem to be mainly pentagonal or hexagonal. Figure 9 shows an example of histogram about the number of column surfaces. The total number of data was 296. Histogram vertical axis was standardized by the number of data. Shapes of cross section at the core were tetragonal, pentagonal and hexagonal. Other columns showed tetragonal (Md 07 and Md 08), pentagonal (Md 01 and Md 08), hexagonal (Md 04) and octagonal (Md 06). These data much coincide with the result of field observation.

Cross sectional area of column was calculated by counting pixels of the area in a digital photograph. Outcrops of the analysis object was Md 01, Md 04, Md 06, Md 07, Md 08 and the core where column cross section could be well observed. Figure 10 shows the result of the calculation. The average of area decreased toward the margin of the rock body.

**Jôdogahama Rhyolite (JR)**

**Geology**

The JR is a Paleogene intrusive rock exposed at the Jôdogahama Coast in Iwate prefecture. Northern and Southward of it intruded Harachiyama Formation, and Northwest part of it intruded Raga Formation (Figure 11). The rock body is white or an ash gray. The phenocryst chiefly consists of fine-grained plagioclase and grainy quartz, and the groundmass is grassy and has a flow structure. SiO₂ content was about 74 wt% (Furukawa and Tsuchiya, 1997), and the radiometric age of the rock by K-Al method showed 50 Ma (Shibata et al., 1977).

**Result of Field Observation**

The field observation was carried out for three times during 1998 to 2001. We observed outcrops and measured an azimuth of joints and flow surfaces.

The measurement of flow structure at ten outcrops shows that the strike changed continuously, and the dip was almost horizontal at the x-indication in Figure 11.

**FIGURE 7.** Overview of the Momo-iwa dacitic dome.

**FIGURE 8.** NS-N50°E cross section of the westward of the MD.
and high-angle at the margin of the JR. This result should indicate that the flow structure would be dome which x-indication is the center. In another words, the shape of the JR would be dome which x-indication is the center.

Joint orientations were measured at 27 outcrops. At the southward of the JR, vertical dipping and strike EW was predominant. We also could see the other joints that dipped westward and strike NS, and dipped eastward. We could identify three preferred orientations as a whole. At the center of the exposed rock body, we could clearly see three preferred orientations, which were vertical dipping and strike EW, NS, and horizontal (Figure 12). EW-strike joints were the most predominant and they formed columnar joints that have tetragonal cross section. We also could see parallelepiped joint blocks and other columnar joints with pentagonal cross section near the center of the JR. The interval of those joints distributed between few score centimeters and several meters, which was definitely larger than that of at the margin of the JR.

At the northward of the JR, joint orientation and the intervals was different from that observed at the southward of the JR. Two preferred orientations were identified which directions were N70°W 65°W and N60°E 70°E. The interval of those joints distributed between several centimeters and few score centimeters, which was smaller than that of the center of the JR. We observed the hyaloclastite at northeast part of the JR. This would indicate that the JR intruded Harachiyama formations with keeping high temperature and were quenched by seawater after intrusion.
Tōjinbō Andesite (TA)

Geology

The “Tōjinbō” is a place of rare scenic beauty along a coast in Fukui prefecture. We can see well developed columnar joints along the coast in about 1 km (Figure 13). The TA is classified into two-pyroxene andesite, and phenocryst of pyroxene and plagioclase could be observed macroscopically (Miura, 1957). The TA intruded sedimentary formations consisted of conglomerate and tuff and extruded on the ground (Kuroda, 1966; Figure 14). SiO₂ content of the TA lava flow was 58 wt% (Kuroda, 1966), and it has been dated at 12.7 Ma by K-Ar methods (Higashino and Shimizu, 1987).

Ojima Rhyodacite (OR)

Geology

In the Ojima Island, located in the north-northwest of the Tōjinbō, the OR was observed. Since it is about the same age as the TA (12.5 Ma by K-Ar dating; Higashino and Shimizu, 1987), it was extruded on the ground by the sequence of volcanic activity caused in Mikuni region as well as in the case of the TA (Figure 14). SiO₂ content of the OR is unknown, but we estimated it about 71 wt% because Kuroda (1966) reported that the SiO₂ content of rhyodacite exposed on a coast where was few kilometers distant from Ojima Island was 71 wt%.

Result of Field Observation

Field observation was undertaken in 2001. Joints were observed macroscopically and their azimuth was measured.

There are many columnar joints at the Cape Tōjinbō. The shape of cross section would be dominant tetragonal, pentagonal and hexagonal. Columnar joints were divided horizontally by fractures, and formed like ‘Dutch-cheese structure’ (James, 1920).

CHARACTERIZATION OF JOINT STRUCTURES IN IGNEOUS ROCKS

Joint Structure in Shallow Intrusive and Extrusive Complexes

Columnar jointing dominates in shallow intrusive and extrusive complexes, producing a pentagonal - hexagonal cross section. In the MD, columns are developed in a radial pattern from the center of rock mass, with their width increasing toward the center of the rock mass. Columnar jointing in the JR and the TA developed subvertically. These columns are considered...
Joint Structure in Deeper Plutonic Rocks

Joints in the Takidani Granite show preferred orientations in three directions, forming parallelepiped joint blocks, with no fracture displacement. The joint directions change progressively, from the margin toward the center of the pluton, and are inferred to conform to the overall (domed) shape of the intrusive. Joint spacing, measured for respective joint blocks, is larger nearer to the center of the pluton. The physical character of the joint network points to thermal contraction being the formation mechanism for jointing in the pluton. Drill core of Hijiori Granite also have strongly preferred joint orientations, in three directions, which vary with depth.

Relationship Between Joint Structure and Its Inferred Depth of Formation

Our fieldwork found that columnar jointing, with pentagonal - hexagonal cross sections, dominate in shallow intrusive and extrusive complexes. In contrast, jointing in Takidani and Kodake plutonic rocks show three preferred orientations, and form parallelepiped joint blocks. The physical character of the fracture networks point to thermal contraction being the formation mechanism for jointing in both intrusive and extrusive complexes.

Figure 17 shows the relationship between joint structure and its inferred depth of formation. The vertical axis corresponds with the depth of intrusion for the MD, JA, TA and OR. That of the KG indicates the drilling depth. As for the TG, the higher limit of temperature generating fracturing estimated about 390°C which is the higher limit of temperature generating micro-cracking (Sekine and Tsuchiya, 2000). Since Bando et al. (2003) suggested that the depth below 390°C should be approximately 1200 m, we estimated the depth generating fracturing in the TG should be shallower than 1200 m. Figure 17 indicates that the joint structures do not exhibit significant variation according to rock type (i.e. SiO₂ content) but they would be apparently influenced by their depth of joint formation and corresponding effect of confining pressure, which acts on joint generation and propagation. For very low confining pressure, such as the near-surface (shallow intrusive/extrusive) setting, joint networks invariably form a columnar structure, whereas deeper rock masses exhibit a parallelepiped
joint structure corresponding to greater confining pressure.

**CONCLUSION**

In this study, joint structure in various igneous rocks was characterized by field observation. In shallow intrusive rocks and extrusives such as the Momo-iwa Dacite, Jōdogahama Rhyolite, Tōjinbō Andesite and Ojima Rhyodacite, pentagonal-hexagonal columnar structures could be observed. In contrast, joints in plutonic rocks such as the Takidani Granodiorite and the Kodake Granodiorite show preferred orientations in three directions, forming parallelepiped joint blocks. It was considered that the confining pressure relates to the difference in both joint structures. These results will give the fundamental knowledge about the fracture information in a DSGR.

**REFERENCES**

14. S. Nagao, C. Akiba, T. Oomori, Hokkaido Development Agency (1963)