Anisotropy of Cooling Joint Systems in Granite

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Keywords

Fracture characterization, columnar joint, parallelepiped cooling joint, quenching experiment, thermal cracking, thermal conduction model

ABSTRACT

Field observation and laboratory studies reveal that extrusive lava and intrusive rocks emplaced in the near-surface setting have natural joint networks typically characterized by pentagonal-hexagonal columnar structures, whilst fracture networks in deeper emplaced granitic complexes exhibit a parallelepiped joint structure.

Thermal cracking experiments, using pseudo-magmatic material (i.e. paraffin) have clarified the relationship between the anisotropy of (natural) crack networks and external pressure. The observed difference in joint network patterns and structure in shallow intrusive/extrusive complexes, compared to deep plutonic rocks, is most strongly influenced by (inferred) depth of formation, and effect of confining pressure.

A numerical thermal conduction model was used to evaluate the anisotropy of joint formation in granite. Joints parallel to the surface of granite rock body are explained by '*Eggshell*' and '*Uplift*' models, corresponding to cooling effects along the brittle-ductile transition boundary and/or the removal of superincumbent load, during uplift.

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.*, 2002) 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 (DGSR) may be developed, focusing on the Takidani Granodiorite and Kodake Granodiorite (Hijiori HDR test site) (Honshu, Japan; see 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;

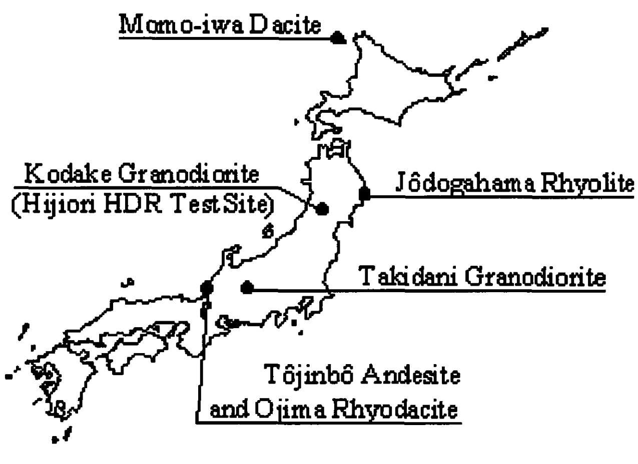


Figure 1. Location map.

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; see Figure 1), to facilitate direct comparison with the fracture geometry of deep-seated intrusive complexes. Our field-based programmes were complemented by laboratory examination of thermally-induced cracking in pseudo-magmatic material (paraffin), at a variety of external compression conditions. We also used a numerical thermal conduction model for a cooling rock mass, to infer mechanisms for the generation and propagation of (natural) fracture networks in granitoid-hosted DSGR.

Field Characterization of Joint Structures in Igneous Rocks

Background

Rock mechanics studies have shown that compressive stresses (or "overburden", in the context of our discussion) act as the main factor inducing fracturing - that is; shear fractures, with displacement parallel to the plane of the break. Secor (1965) analyzed joint propagation and demonstrated that fractures with little or no tangential displacement are more pronounced as the ratio of fluid pressure to overburden weight in the Earth's crust approaches one. Joints form extensional fractures where tensile stresses are large, even at great depth, since compressive lithostatic pressures are counterbalanced by large pore pressures.

Joint Structure in Shallow Intrusive and Extrusive Igneous Rocks

The **Momo-iwa Dacite** (Rebun Island (Hokkaido); 63 wt% SiO_2; 13.0±1.6 Ma; Goto *et al.*, 1995) intruded Late Miocene sedimentary rocks (Goto and McPhie, 1998). The Momo-iwa dome is characterized by columnar jointing, which radiate from the core to the margin of the intrusive (particularly in exposed western parts). Most columns are hexagonal in cross-section (in places tetragonal or pentagonal), with a mean cross-sectional area of 2.5 m^2 at the center and 0.1 m^2 at the margin of the intrusion.

Jôdogahama Rhyolite (Iwate prefecture; 74 wt% SiO_2, Furukawa and Tsuchiya, 1997) intruded Harachiyama Formation about 50 Ma (Shibata *et al.*, 1977). In outcrop, joints in the Jôdogahama Rhyolite are typically developed in three directions, to form parallelepiped blocks, although vertical columnar jointing occur near the inferred core of the rhyolite, with pentagonal-hexagonal cross-sections.

The **Tôjinbô Andesite** lava flow (Fukui prefecture; 58 wt% SiO_2, Kuroda, 1966) has been dated at 12.7 Ma by K-Ar methods (Higashino and Shimizu, 1987). In outcrop, the andesite contains large-vertical columnar jointing (Figure 2a), with mainly hexagonal, and lesser tetragonal or pentagonal cross-sections. The columns are separated horizontally and form a 'Dutch-cheese structure', after James (1920).

The **Ojima Rhyodacite** (Fukui prefecture; ~71 wt% SiO_2) is about the same age as Tôjinbô Andesite (12.5 Ma by K-Ar dating; Higashino and Shimizu, 1987), and contains columnar and platy jointing with tetragonal-hexagonal cross sections.

Joint Structure in Intermediate-felsic Composition Intrusives

The **Takidani Granodiorite** (Japan Alps; 21 km^2) is chemically zoned, with a SiO_2 content of ~70 wt% at the margin to < 67 wt% in the core (Bando *et al.*, 2002). Field studies reveal three preferred joint orientations, which in outcrop form parallelepiped joint blocks (Figure 2b) (Kano *et al.*, 2000), which are arranged either concentrically or perpendicularly to the surface of the pluton. The distance between adjoining joint surfaces (i.e. joint spacing) increases towards the center of the in-

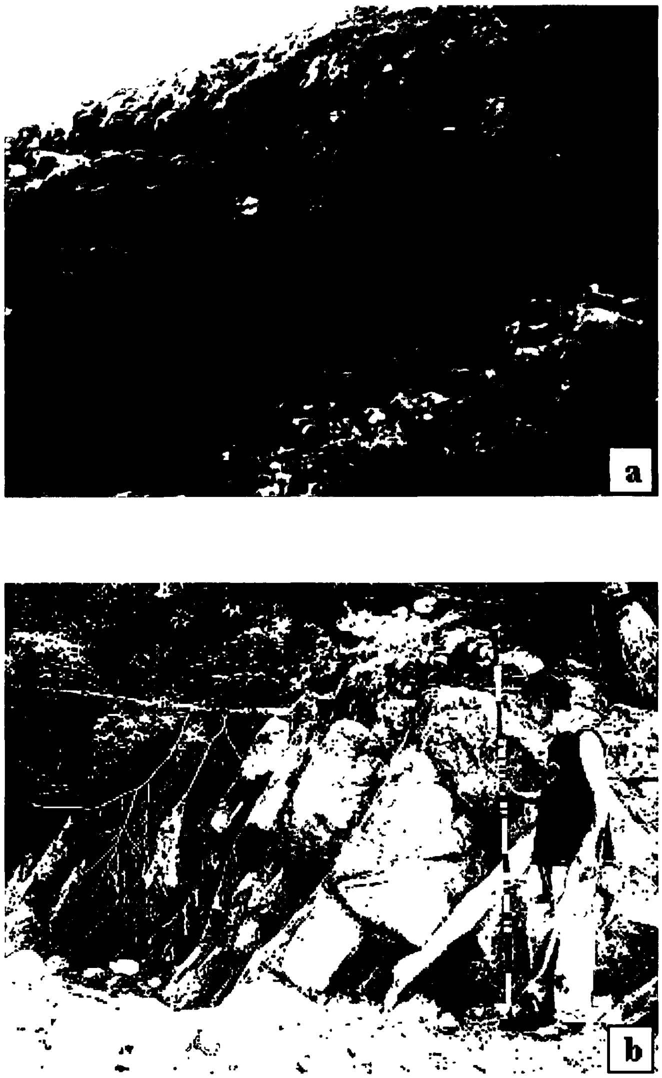


Figure 2. (a) The fracture network in Tôjinbô Andesite is characterized by columnar jointing; in contrast, (b) shows that cooling fractures in Takidani Granodiorite have three preferred orientations, and form parallelepiped blocks.

trusion. The anisotropy of the joint network in the Takidani pluton has been evaluated by measurement of P-wave velocity (Kano and Tsuchiya, 2002).

The Hijiori area (Yamagata prefecture) is the focus of several HDR geothermal energy programs. **Kodake Granodiorite** is one of the basements of the Hijiori area, and joint structures in the granodiorite were evaluated by analysis of core samples recovered from the HDR-3 well, which intersected the Kodake pluton between 1486 m - 2303 m drilled depth (which is reported by NEDO in 1996). The strike and dip of fractures in HDR-3 core samples were measured by Inoue *et al.* (2002), in order to characterize the structure of the Kodake pluton. According to Inoue *et al.* (2002), three preferred fracture orientations were identified, which are inferred to define a parallelepiped-shaped joint network.

Variation in Joint Structure, Within Extrusive and Intrusives Complexes

Our field work 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. The joint structures do not exhibit significant variation according to rock type (Figure 3), but they are 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, and this presumption was considered further by experimental studies, described below.

Thermal Cracking in Paraffin: Pseudo-Magmatic Material

Background

Shallow intrusive and extrusive rocks typically exhibit a columnar joint structure, which is developed by thermal contraction of the rock mass during cooling. In contrast, deeper emplaced intermediate-felsic composition (granitoid) complexes tend to produce a parallelepiped joint structure. The reason for the observed disparity in rock mechanical behavior has, until now, remained unclear. For this reason, we conducted a series of laboratory experiments, using a pseudo-magmatic material (paraffin), to evaluate the geometry of thermal cracking at various external compression conditions.

Experiment

Paraffin "blocks" (95 mm x 95 mm x 82 mm) were prepared from molten paraffin (melting temperature, 70°C). For each experiment, a 95 mm x 95 mm block surface was quenched using liquid nitrogen (for 3 minutes), with uniaxial compression perpendicularly applied to the quenched surface (Figure 4). A large number of cracks were generated on the cooling surfaces, which had propagated perpendicularly into the block (to several centimeters 'depth'). To observe internal crack patterns, paraffin blocks were sliced parallel to the quenched surface, at intervals of 3-4 mm.

Observation/Results

Cracks formed columnar structures in non-pressured paraffin blocks, with hexagonal cross sections (Figure 5a and Figure 6a, overleaf). In total, 213 columns are evident at 3 mm depth (with a mean column size of 30 mm^2), whilst 55 columns occur 7.5 mm below the surface (mean column size of 100 mm^2). Crack intersection angles, for three cracks at 10

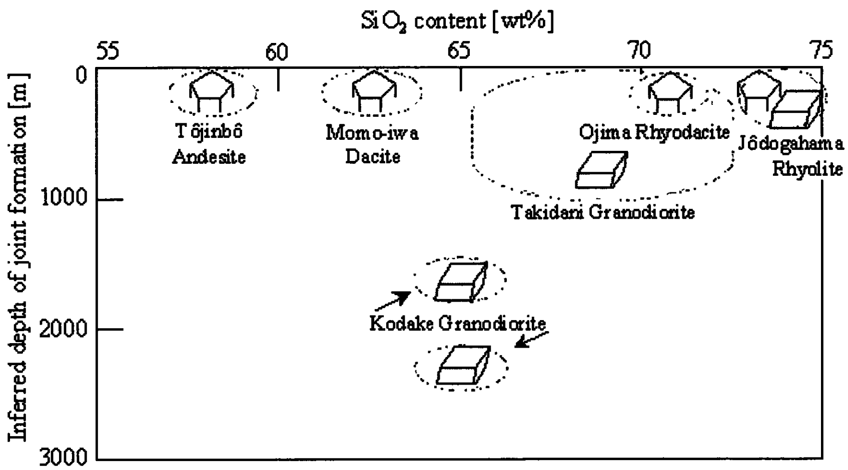


Figure 3. Joint structure in intrusive and extrusive igneous rocks, characterized by SiO_2 content and inferred depth of joint formation: (i) Momo-iwa Dacite, Jôdogahama Rhyolite, Tôjinbô Andesite and Ojima Rhyodacite are near-surface (<500 m) intrusive/extrusive rocks; (ii) Kodake Granodiorite emplacement is inferred from drilling data; (iii) Takidani Granodiorite emplacement is inferred from mineral geobarometry and fluid inclusion data (Bando *et al.*, 2002).

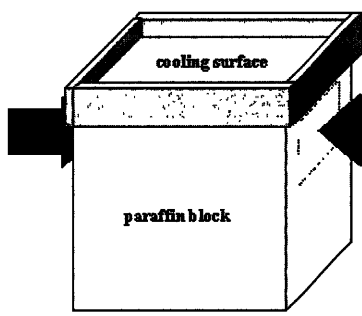
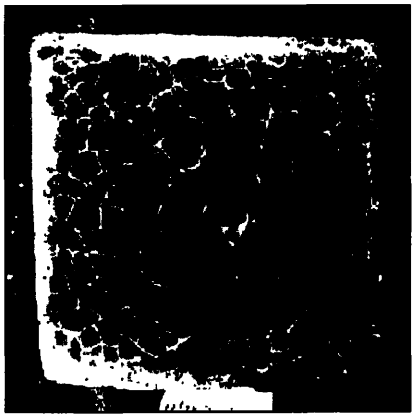
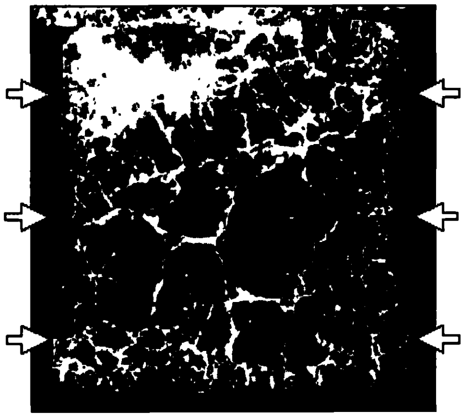


Figure 4. Schematic illustration of paraffin cooling experiment in uniaxial compression condition. Paraffin block size is 95 mmx95 mmx82 mm.



(a) non-pressured condition



(b) uniaxial compression condition

Figure 5. Cross section parallel to cooling surface: (a) 3.0 mm below the surface in non-pressured condition, and (b) 1.3 mm below the surface in uniaxial (direction of arrows) compression condition.

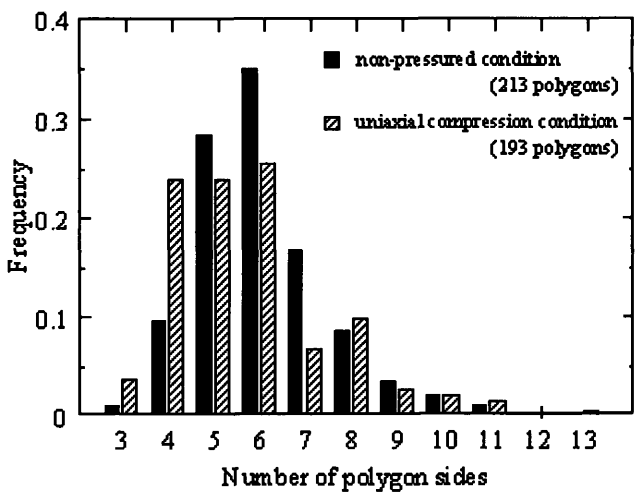


Figure 6. Histogram of the number of polygon sides, for non-pressured and uniaxial compression experiments, shown in Figure 4 (a), (b).

mm depth, were 108°, 138° and 114°, respectively. For experiments having uniaxial compression, a tetragonal network is noted, with cracks oriented parallel to the compression direction (Figure 5b and Figure 6b). The internal geometry of the crack network is 193 columns (31 mm^2 mean column size) at 1.3 mm depth, and 91columns (60 mm^2 mean column size) at 4.5 mm below the surface. In contrast to non-pressured samples, cracks formed in the uniaxial compression regime (e.g. 14 mm below the surface) cross at near right angles. In our experiments, column width (cross sectional area) is larger towards the interior of the block, which match field observations in the Momoiwa Dacite dome (which is also characterized by variations in column (block) width) and Takidani Granodiorite (Kano *et al.*, 2000). Variations in crack intersection angle indicate that the propagation of thermal cracking (i.e. direction of cracking) is strongly dependent on the direction of external pressure.

Numerical Analysis of Fracture Characteristics in a Cooling Igneous Body

The origin of jointing in a cooling intrusive (granitoid) complex can be constrained using a numerical approach. We used a thermal conduction model to assess the thermal stress field in an elastic cylinder, with an initial temperature condition of 1000°C. In our approach, the side surface of the cylinder was instantaneously quenched to 0°C, with a radially distributed thermal gradient. The corresponding equations of thermal stress are:

$$\sigma_{rr} = \frac{\alpha E}{1-\nu}\left(-\frac{1}{r^2}\int_0^r \tau r dr + \frac{1}{b^2}\int_0^b \tau r dr\right)$$

$$\sigma_{\theta\theta} = \frac{\alpha E}{1-\nu}\left(\frac{1}{r^2}\int_0^r \tau r dr + \frac{1}{b^2}\int_0^b \tau r dr - \tau\right)$$

$$\sigma_{zz} = \frac{\alpha E}{1-\nu}\left(\frac{2}{b^2}\int_0^b \tau r dr - \tau\right)$$

where σ_{rr} is radial stress, $\sigma_{\theta\theta}$ is tangential stress, σ_{zz} is the stress along z-axis, α is coefficient of thermal linear expansion, E is Young's modulus, ν is Poisson's ratio, τ is dimensionless time, and b is radius of the cylinder.

Tangential stress on the cooling surface of an intrusive body is likely to be extensional (Figure 7a), and facilitates generation of the joint network. At Takidani, such jointing is orientated perpendicular to surface of the pluton (Figure 8). In shallow intrusive and extrusive lavas, columnar jointing is also derived from cooling of the rock mass (Kano *et al.*, 2000).

Radial stress in our cylindrical model is compressive (Figure 7b), which means that no extensional jointing can occur parallel to the rock shape. Indeed, at Takidani, jointing is orientated perpendicular to surface of the pluton, such as at Shiradashi-zawa (Kano and Tsuchiya, 2001). This model is appropriate for elastic matter, but not for a rock body that has two phases (i.e. corresponding to a region coincident with brittle-ductile transition behavior). Therefore, the model cannot explain jointing observed in Takidani Granodiorite, that developed parallel to the surface of the rock body.

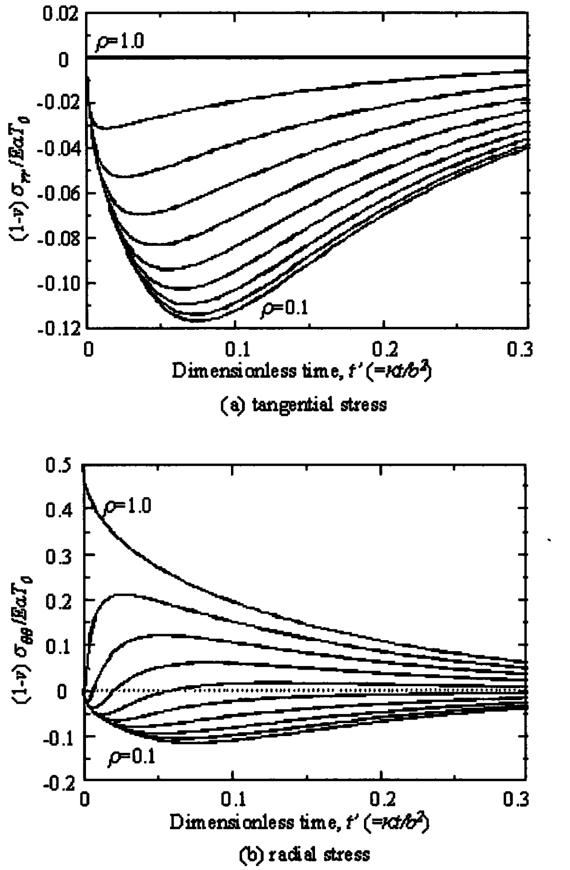


Figure 7. Distribution of σ_{rr} and $\sigma_{\theta\theta}$. t' is dimensionless time (=$\kappa t/b^2$). ρ is a dimensionless radius (=r/b). Tangential stress of ρ=1.0 shows maximum tensile stress at an early time (a), whilst radial stress is always compressive (b).

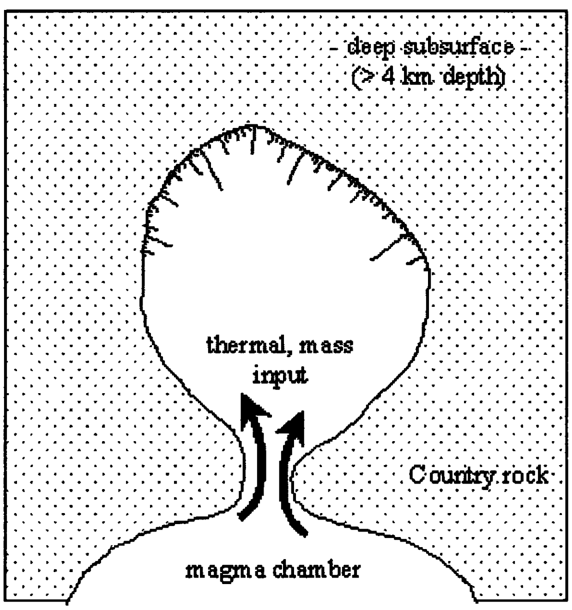


Figure 8. Schematic representation of jointing produced perpendicular to the surface of intrusion, during cooling.

Discussion

Thermal stresses may result in the formation of fractures, which provide flow paths for thermal fluids and can add, in the case for enhanced geothermal systems, new surface area for heat extraction. In "conventionally" developed geothermal resources, intersecting the upper part of a fractured granitoid rock mass by deep drilling may facilitate the tapping of hot >>300°C fluids, useful for electric generation. The majority of these thermally-derived fractures, however, are likely to be sealed and not conducive for hydraulic circulation of thermal fluids.

Understanding the nature of natural fracture networks is vital for development of enhanced geothermal systems. The presence of interconnected fractures can be a beneficial factor, particularly where they complement hydraulic fracturing, by providing access to the geothermal heat source. However, the presence of a large, interconnected network of natural (thermally-derived) fractures may also provide pathways for injected fluid to 'escape' from the artificial geothermal reservoir, or allow injected fluids to quickly reach the production 'zone', thus cooling potential production fluids.

Clearly, understanding the nature of natural fracture systems in a potential DSGR (either hosted by deep granitoids, shallow emplaced intrusive or extrusive rocks) can facilitate hydraulic fracturing programmes undertaken to establish an efficient energy extraction system.

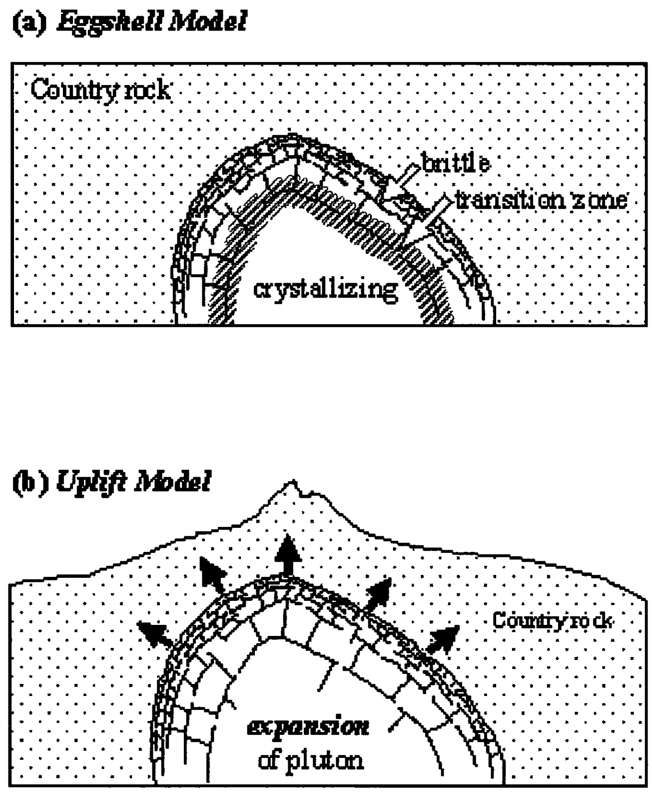


Figure 9. Schematic representation of jointing produced parallel to the surface of intrusion, in the vicinity of the brittle-ductile transition zone (a), and/or during uplift (b).

Two possible mechanisms are considered, to explain the observed jointing network in the intermediate-felsic granitoid rocks we have studied:

(i) 'Eggshell' Model: This model infers early stage solidification of the pluton by rapid cooling, but an inner part that remains ductile. Strain occurs along the brittle-ductile zone, as the inner part of pluton shrinks, with resultant extensional stress perpendicular to the transition boundary (Figure 9a).

(ii) 'Uplift' Model: During uplift, a release of primary confining pressure occurs through removal of the superincumbent load. The unloaded rock 'expands', with jointing occurring where internal stress exceeds the elastic strength, with jointing propagating parallel to the rock body (Figure 9b).

These models show how joints parallel to the surface of the rock body could have formed during (i) early stage solidification of the pluton; or (ii) during uplift of the pluton.

Conclusions

Deciphering the character of the natural (cooling-derived) fracture system is essential for the effective utilization of a deep-seated, granitoid-hosted EGS. We have found that joints networks in shallow intrusives, and extrusive rocks emplaced in the near surface, tend to produce pentagonal-hexagonal columnar structures, whereas deeper emplaced, granitic complexes exhibit a parallelepiped joint structure. Apparent differences in joint structure vary most strongly according to inferred depth of formation, and corresponding effect of confining pressure, which acts on joint generation and propagation.

The relationship between the anisotropy of crack network and external pressure was evaluated by thermal cracking experiments, using pseudo-magmatic material (i.e. paraffin). For non-pressured cooling, cracks form columnar structures, with a large number of hexagonal joint sets. In contrast, in uniaxial compression experiments, a tetragonal shaped joint network is formed. For both experimental conditions, column width (in terms of cross sectional area) is larger towards the core of the 'paraffin block', which matches field observations at Momoiwa, Takidani and elsewhere.

A thermal conduction (numerical) model was used to evaluate the anisotropy of joint formation in granite. Cooling joints are formed by thermal contraction of the rock body, with additional jointing produced either from an extensional effect, due to the removal of superincumbent load, during uplift, and/or cooling effects along the brittle-ductile transition boundary. By understanding the natural fracture network in the intrusive and extrusive complexes, developers of Enhanced Geothermal Systems may better develop their energy extraction and/or hydraulic fracturing programmes, for more effective heat and fluid transfer (flow paths), whilst reducing the risk of injected fluids either rapidly cooling system.

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