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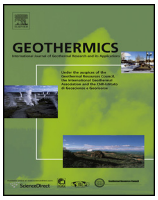

Supercritical geothermal reservoir revealed by a granite–porphyry system

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ABSTRACT

To understand the geological properties of a supercritical geothermal reservoir, we investigated a granite–porphyry system as a natural analog. Quartz veins, hydrothermal breccia veins, and glassy veins are present in Neogene granitoids in NE Japan. The glassy veins formed at 500–550 °C under lithostatic pressures, and then pressures dropped drastically. The solubility of silica also dropped, resulting in formation of quartz veins under a hydrostatic pressure regime. Connections between the lithostatic and hydrostatic pressure regimes were key to the formation of the hydrothermal breccia veins, and the granite–porphyry system provides useful information for creation of fracture clouds in supercritical geothermal reservoirs.

1. Introduction

Following the Great East Japan Earthquake and the accident at the Fukushima Daiichi Nuclear power station on 3.11 (11th March) 2011, geothermal energy came to be considered one of the most promising sources of renewable energy for the future in Japan. However, there are several geological and geophysical issues to consider. First is that ~80% of the potential geothermal energy in Japan lies inside National Parks, second is Onsen (hot springs) problem which is conflict between geothermal developers and Onsen owners due to some misunderstandings of geothermal and hot spring resources, and another is induced seismicity related to the development of geothermal energy. The temperatures of geothermal fields operating in Japan range from 200 to 300 °C (average ~250 °C), and the depths range from 1000 to 2000 m (average ~1500 m). In conventional geothermal reservoirs, the mechanical behavior of the rocks is presumed to be brittle, and convection of the hydrothermal fluid through existing network is the main method of circulation in the reservoir. In order to minimize induced seismicity, a rock mass that is "beyond brittle" is one possible candidate, because the rock mechanics of "beyond brittle" material is one of plastic deformation rather than brittle failure (Asanuma et al., 2012; Muraoka et al., 2014).

At Kakkonda in NE Japan, the exploration well WD-1a encountered the partly solidified Kakkonda Granite and inferred reservoir temperatures in excess of 500 °C (Doi et al., 1998; Ikeuchi et al., 1998; Kasai et al., 1998; Kato et al., 1998; Matsushima et al., 2003; Muraoka et al., 1998; Sasaki et al., 2003; Tosha et al., 1998). The project called DSGR (Deep-Seated Geothermal Reservoir) was conducted by NEDO (New Energy Development Organization, Japan); nevertheless, there were no strong emissions of steam from the bottom of the well. In an attempt to understand the findings of DSGR, we have studied an exposed Quaternary granitoid (the Takidani Granodiorite), since it is analogous to the type of granitoid rock mass that might host a deep-seated (artificial) geothermal reservoir (Bando et al., 2003; Kano and Tsuchiya, 2002). From an engineering point of view, the Takidani Granodiorite is a suitable candidate as a natural analog for a HDR/HWR (Hot Dry Rock/Hot Wet Rock) geothermal reservoir, particularly under supercritical geofluid conditions. The Takidani Granodiorite is located at the boundary of the Eurasian and North American Plates (Harayama, 1992), and extensive silicic magmatic activity (both volcanic and plutonic) occurred through the Pliocene and Pleistocene. In addition, we have investigated hydrothermal activity in order to understand the evolution of supercritical geothermal fluids in certain geological settings. Temperatures over 350 °C are in the "beyond brittle" condition (a temperature of ~350 °C coincides with the brittle–ductile transition), and the ways in which fractures develop under these conditions are unclear.

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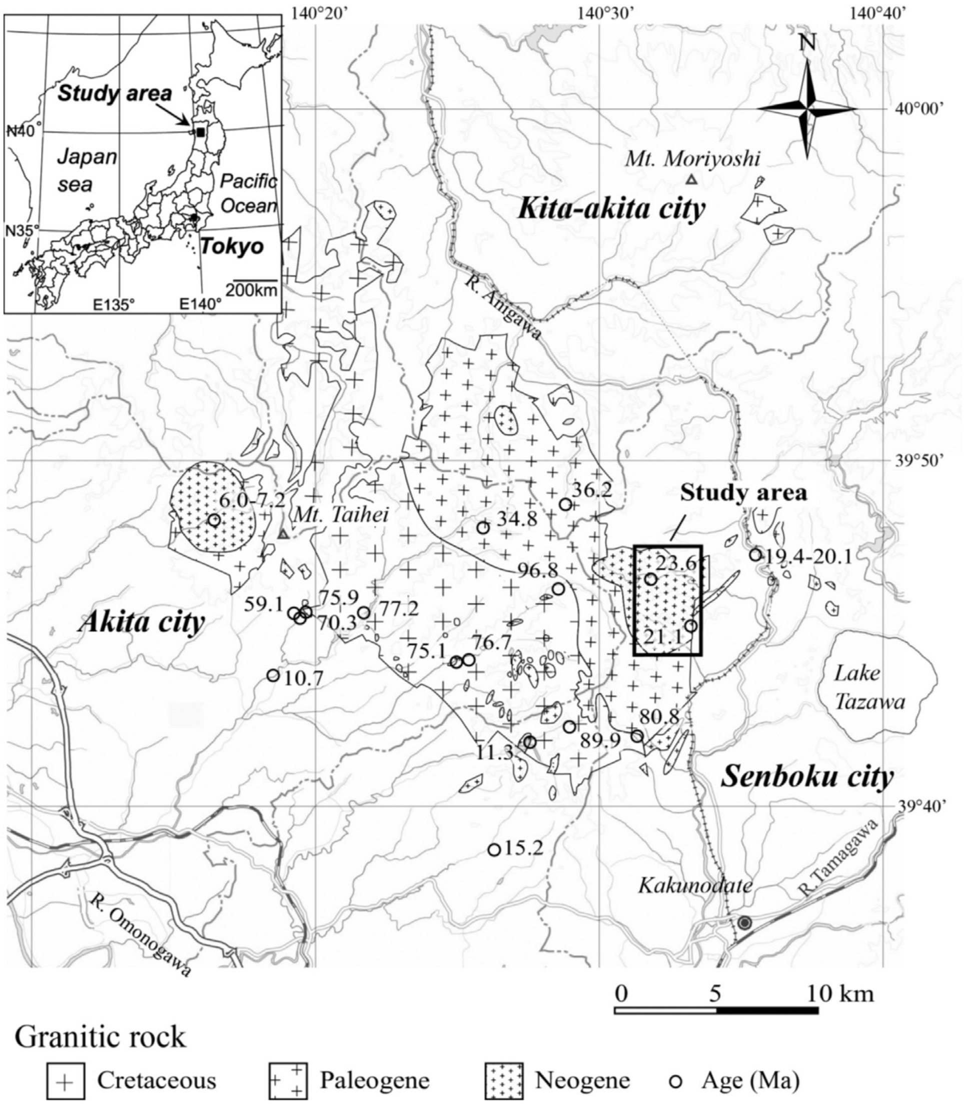

Fig. 1. Map of the study area and the granitoid complex. The regional geology is based mainly on Osawa et al. (1981) and Fujimoto (2006), and was revised by MITI (1986). Numbers in the figures indicate dating results shown in MITI (1986).

Porphyry copper deposits represent natural "beyond brittle" analogs where fluids from molten material (magma) infiltrate a ductile rock mass at ~600 °C, and where lithostatic pressures cause fractures in the rock mass, creating a stockwork fracture system (Batkhishig et al., 2014; Mercer and Reed, 2013; Davies et al., 2008; Ingebritsen, 2012; Rusk and Reed, 2002). The large strain rates during fluid injection released from the host rock render the rock mass brittle, allowing it to fracture in tensile and shear modes. In these porphyry deposits, we are able to observe several kinds of fractures represented by millimeter- to centimeter-scale quartz veins (Bons, 2001; Okamoto et al., 2008, 2010), where quartz filled and plugged the fractures; apparently the quartz was precipitated during adiabatic decompression and cooling as the fluids traversed from lithostatic to hydrostatic pressure regimes.

A granite–porphyry system, associated with hydrothermal activity and mineralization, provides a suitable natural analog for studying a deep-seated geothermal reservoir where stockwork fracture systems are created in the presence of supercritical geothermal fluids. In this paper we describe fracture networks and their formation mechanisms using petrology and fluid inclusion studies in order to understand this "beyond brittle" supercritical geothermal reservoir.

2. Geological setting

The study area is located in central Akita Prefecture, Tohoku District, NE Japan. In the vicinity of the area, volcano-sedimentary rock sequences of Paleogene to Neogene age were deposited around a basement of Cretaceous granitoids. The tectonic setting was one of an intra-rift rise formed during the period of back-arc spreading of the Sea of Japan that started at 28 Ma and continued until 13 Ma. Paleogene sequences since the Eocene are mainly made up of terrestrial andesite lavas with subordinate pyroclastic rocks, and they represent continental margin volcanism prior to back-arc opening. These sequences were followed by volcanoclastics with several basaltic lava flows in the periphery of the study area, as back-arc volcanism continued during the period 20–13 Ma. After 13 Ma, the peripheral area gradually changed to a bathyal environment, but the study area itself remained as a small continental rise, the result of differential uplift and corresponding intrusions of granitoids. Granitic intrusive activity occurred intermittently in the area. In the eastern margins of the area, diorites and dioritic porphyries were intruded during the period 24–19 Ma, and in the western margins of the area similar rocks were emplaced at 7.2–6.0 Ma. Numerous quartz–porphyry or dacite dikes were also emplaced at 11–8 Ma

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