Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Fundamental Study for Beyond Brittle Geothermal Reservoirs

Noriyoshi Tsuchiya, Hiroshi Asanuma, Atsushi Okamoto, Kiyotoshi Sakaguchi, Nobuo Hirano, Akihisa Kizaki and Noriaki Watanabe

Aramaki-aza-Aoba 6-6-20, Aoba-ku, Sendai, 980-8579, JAPAN

tsuchiya@mail.kankyo.tohoku.ac.jp

Keywords: Deep-seated geothermal reservoir, beyond brittle, fracture cloud, supercritical geothermal reservoir, ductile rock mass

ABSTRACT

Our research group is conducting a new scientific program on Science and Technology for Frontier of Geothermal Energy. Deep-seated and high temperature geothermal reservoirs are a dream-inspiring target as an advanced EGS, and future geothermal reservoirs are under supercritical and superheated conditions in and around ductile rock bodies. The ductile regime which is estimated to exist beyond the brittle zone is the target region for future geothermal development due to high enthalpy fluids and relatively weak water-rock interaction. It is very difficult to determine the strict depth of the Brittle-Ductile boundary due to strong dependence of temperature (geotherm) and strain rate, however, the ductile zone is considered to be developed above 400ºC and below 3 km around active volcanic fronts in Tohoku District, Japan. Additionally, caldera structures which formed in Plio-Pleistocene are also candidates for deep-seated geothermal reservoirs. In this case, the depth of the reservoir will be greater than 3 km, and geofluids whose origin is considered to be slab melting fluids will be reserved.

Hydrothermal experiments associated with additional advanced technology are being conducting to understand the 'Beyond Brittle World' and to develop deeper and hotter geothermal reservoirs.

We are expecting the following advantages: (a) simpler design and control of the reservoir, (b) full heat mining and/or injected water, (c) sustainable production, (d) cost reduction by development of the relatively shallower ductile zone in compression tectonic zones, (e) large quantity of energy extraction from widely distributed ductile zones, (f) establishment of universal and conceptual design/development methodology, and (g) suppression of felt earthquakes from/around the reservoirs.

In the ductile regime, a mesh-like fracture cloud has great potential for heat extraction between injection and production wells in comparison with a single and simple mega-fracture. Based on field observation and high performance hydrothermal experiments, our research goals are: 1) Analysis and understanding of geothermal structure and geofluids in ductile condition of the Japanese Island arc, 2) Fundamental technologies of drilling under ductile region for geothermal reservoir, 3) Development of geothermal reservoir simulator for two-phase and multiphase flow including supercritical state through rock fracture, 4) Lab scale support for ICDP-JBBP (International Continental Drilling Project, Japan Beyond Brittle Project), 5) Application of new EGS technologies to conventional geothermal fields as recovery from the 2011 Great East Japan Earthquake and energy crisis in Japan.

1. INTRODUCTION

Geothermal energy is one of the most promising solutions for global warming, shortage of energy resources, and energy security especially in volcanic zones. Utilization of geothermal energy had not been promoted during 10 years or more in Japan until the 2011 Great East Japan Earthquake because of cost consideration, amount of generated power per power plant, various uncertainties and risks in development of geothermal resources, even though Japan has the world's third largest potential of hydrothermal energy. However, the tragedy of the 2011 Great East Japan Earthquake and Fukushima Nuclear Power Disaster has drastically changed the energy policy of the Japanese government. The government, industry, and citizens are much more positive to develop stable, safe, indigenous and clean energy resources. Geothermal has been considered as one of the most promising solutions for the energy-related crisis occurring currently in Japan. Tohoku University is one of the leading universities in the world on engineered geothermal systems (EGS), and our research team had been studying particularly on water–rock interaction under supercritical conditions (Tsuchiya and Hirano, 2007) and microseismicity in geothermal fields since the 1990s (e.g. Asanuma et al., 2005).

The northeast part of Japan (Tohoku District) has about 45% of the geothermal potential of Japan, and we have several active volcanos along a volcanic front related to subduction of the Pacific Plate. Tohoku has great geotherm, and the highest temperature geothermal driling above 500ºC was performed in the Kakkonda geothermal field in Tohoku District (1995-96) (Muraoka et al., 1998). Tohoku district is one of the most suitable geothermal areas for touching the geothermal frontier of the ductile zone.

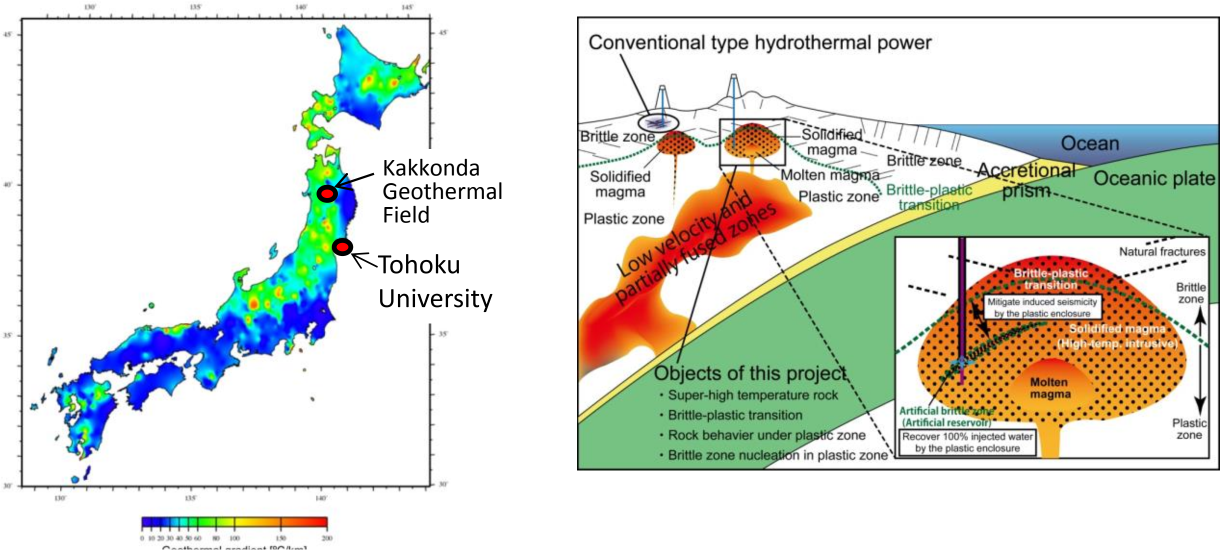

Figure 1: Potential map for ductile geothermal reservoir in Japan from the geothermal gradient (left) and ductile regime related to subduction of the Pacific Plate (right) (Muraoka et al., 2014).

2. SCHEME OF FUNDAMENTAL STUDY

EGS has been highlightened as a promising method of geothermal development recently because of its applicability to sites that have been considered to be unsuitable for conventional geothermal development. Meanwhile, some critical problems have been identified experimentally, such as low recovery of injected water, difficulties to establish universal design/development methodology, and occurrence of large induced seismicity. A future geothermal target is supercritical and superheated geothermal fluids in and around ductile rock bodies under high temperatures.

The ductile regime that is estimated to occur beyond brittle zone is a target region for future geothermal development due to high enthalpy fluids and relatively weak water-rock interaction. It is very difficult to determine the exact depth of the Brittle-Ductile boundary due to strong dependence of temperature (geotherm) and strain rate, however, the ductile zone is considered to be developed above 400ºC and below 3 km in geothermal fields in the Tohoku District.

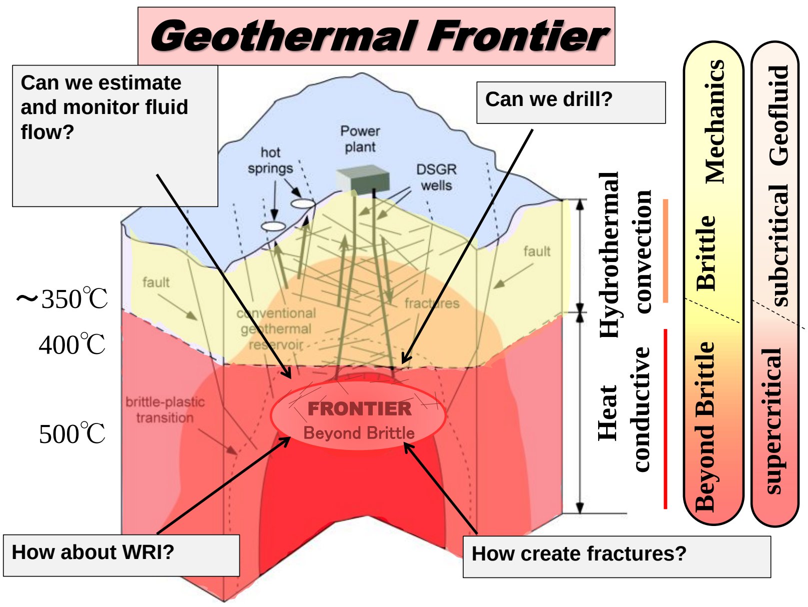

Figure 2: "Geothermal Frontier" and estimated essential issues for the development.

Conventional geothermal reservoirs are located at shallower depths, in which temperature is up to 350ºC. Here, hydrothermal convection is the dominant fluid flow, and the mechanical behavior of reservoir rocks is brittle. Geofluid is under subcritical conditions. "Geothermal Frontier" is expected to exist below the conventional geothermal reservoir, where temperature is over 400ºC and heat conduction is the dominant process to transport thermal energy. Mechanical condition might be Beyond Brittle (Brittle-Ductile transition and then Ductile regime), and geofluid shows supercritical characteristics.

We have four major problems to develop the “Geothermal Frontier” where Beyond Brittle and Supercritical conditions occur. 1) Can we estimate and monitor fluid flow under such conditions? Elastic wave is a tool to monitor this “Geothermal Frontier”. 2) We have to consider Water-Rock Interaction under supercritical conditions (Saishu et al., 2014). Supercritical conditions are subdivided into vapor-like and liquid-like region in terms of dissolution of rock (Tsuchiya and Hirano, 2007). The Supercritical state shows complicated phenomena of Water-Rock Interaction. We carefully examine dissolution and precipitation reactions and entire chemical behaviors of multicomponent geofluids under supercritical conditions. 3) We have to develop new technology to create fractures for fluid paths in the “Geothermal Frontier” under the ductile regime. We can observe many mineral filling veins in metamorphic rocks (Okamoto and Tsuchiya, 2009; Okamoto et al., 2008) . Those were considered to be evidence of brittle failure under the ductile regime. 4) Important engineering is drilling technology, which is a critical technology to develop the “Geothermal Frontier”. Can we drill to the ductile regime? Can we penetrate the brittle-ductile transition? Can we take a supercritical fluid from great depth? These are great issues and we have plans to investigate these essential issues to develop the “Geothermal Frontier”.

3. RESEARCH OBJECTIVES AND TARGETED GOALS

We propose a new concept of the engineered geothermal development where reservoirs are created in the ductile basement, expecting the following advantages: (a) simpler design and control the reservoir, (b) nearly full recovery of injected water, (c) sustainable production, (d) cost reduction by development of relatively shallower ductile zone in compression tectonic zones, (e) large quantity of energy extraction from widely distributed ductile zones, (f) establishment of universal and conceptual design/development methodology, and (g) suppression of felt earthquakes from/around the reservoirs.

In the ductile regime, a Mesh-like fracture cloud has great potential for heat extraction between injection and production wells in contrast to a single and simple mega-fracture. Based on field observation and high performance hydrothermal experiments, our research goals are: 1)Analysis and understanding of geothermal structure and geofluids in ductile conditions of the Japanese Island arc, 2) Fundamental technologies of drilling into the ductile region for a geothermal reservoir, 3) Development of geothermal reservoir simulator for two-phase and multiphase flow including supercritical state through rock fracture, 4) Lab scale support for ICDP-JBBP (International Continental Drilling Program – Japan Beyond Brittle Project), 5) Application of new EGS technologies to conventional geothermal fields as recovery from the 2011 Great East Japan Earthquake and energy crisis in Japan.

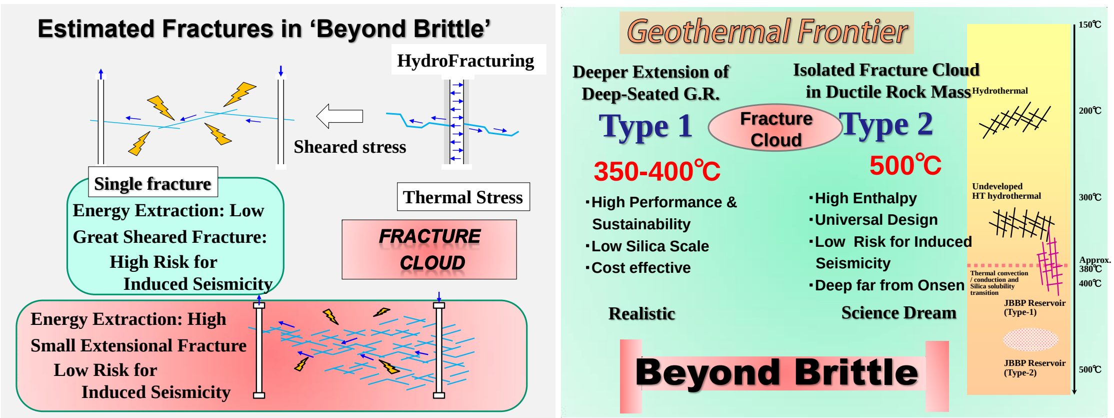

Figure 3: Estimate fracture type in “Beyond Brittle” (left) and research goals of “Geothermal Frontier” (right).

Fig. 3 shows a schematic illustration of estimated fracture types in the beyond-brittle condition. In the conventional HDR (Hor Dry Rock) concept, hydrofracking (fracturing) and a big sheared fracture is the single and dominant fluid path for heat exchange. However, a sheared fracture has great risk of induced seismicity, and the area for heat exchange is relatively small. We have a plan to create extensional fractures caused by thermal stress. Thermal stress will be developed by rapid cooling of the reservoir rocks, which has been examined experimentally (Hirano et al., 2002). We study the creation of fracture networks (fracture cloud) caused by thermal stress with physicochemical phase changes of fluids and minerals.

We consider two types of fracture system for the “Geothermal Frontier”. One is under 350ºC-400ºC. Here is a deeper extension of conventional geothermal reservoir and/or deep-seated geothermal reservoir. We can keep high performance of sustainability and here is a realistic condition to develop as a near future technology. The other type of fracture is over 500ºC. Here, we can expect high enthalpy geothermal energy, and it is possible to design a universal system due to relatively homogenous conditions. The most important point of this region is low risk for induced seismicity due to the ductile characteristics of reservoir rocks.

The research targets are as follows:

1. <u>Analysis and understanding of geothermal structure and geofluids in ductile conditions of the Japanese Island arc</u>

We perform field survey of geothermal fields for assessment of deep and high temperature geothermal reservoir (Bando et al., 2003), and we also carry out field surveys in metamorphic terrane to understand crustal failure under high temperature and pressure conditions, which is the natural analogue of development of fractures in ductile regime.

2. Fundamental technologies of drilling under ductile region for geothermal reservoir

We design several types of hydrothermal experimental apparatus. Targets of each apparatus are the followings; UNIT-I: Creation of fracture cloud in high T (<700ºC), UNIT-II: Water-Rock Interaction in fracture cloud under high T and confining P, UNIT-III: Mechanical mechanisms of fracture cloud under differential stress regime, UNIT-IV: Drilling simulation.

1) Development of geothermal reservoir simulator of two- and multiphase flow through rock fracture

Fluid flow through fractures and fracture clouds are estimated as heterogeneous two-phase (water and steam, and supercritical state) flow. We have to establish a 3D Discrete Fracture Network model coupled with heat extraction and fluid flow including phase change under high T and high confining P conditions. It is an important point of view to realize sustainability of ductile geothermal reservoirs (Watanabe et al., 2008, 2009).

2) ICDP-JBBP

We carry out theoretical and experimental back-up for ICDP-JBBP, and then our new EGS technologies can be applied to conventional geothermal reservoirs.

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