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

Japan Beyond-Brittle Project: Development of EGS Beyond Brittle-Ductile Transition

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Keywords: HDR/EGS, brittle-ductile transition, fracturing, high enthalpy geothermal

ABSTRACT

New conventional geothermal energy projects have not been actively promoted in Japan for the last decade because of perceptions of high relative cost, limited electricity generating potential and the high degrees of uncertainties and associated risks of subsurface development. More recently however, EGS (Enhanced Geothermal System) geothermal has been identified as a most promising method of geothermal development because of its potential applicability to a much wider range of sites, many of which have previously been considered to be unsuitable for geothermal development. Meanwhile, some critical problems with EGS technologies have been experimentally identified, such as low recovery of injected water, difficulties in establishing universal design/development methodologies, and the occurrence of induced seismicity, suggesting that there may be limitations in realizing EGS in earthquake-prone compression tectonic zones.

We propose a new concept of engineered geothermal development where reservoirs are created in ductile basement. This potentially has a number of advantages including: (a) simpler design and control of the reservoir, (b) nearly full recovery of injected water, (c) sustainable production, (d) lower cost when developed in relatively shallower ductile zones in compression tectonic settings, (e) large potential quantities of energy extraction from widely distributed ductile zones, (f) the establishment of a universal design/development methodology, and (g) suppression of felt earthquakes from/around the reservoirs.

To further assess the potential of EGS reservoir development in ductile zones we have initiated the “Japan Beyond-Brittle Project (JBBP)”. It is intended that the first few years of the JBBP will be spent in basic scientific investigation and necessary technology development, including studies on rock mechanics in the brittle/ductile regime, characterization of ductile rock masses, development of modeling methodologies/technologies, and investigations of induced/triggered earthquakes. We expect to drill a deep experimental borehole that will penetrate the ductile zone in northeast Japan after basic studies are completed. The feasibility of EGS reservoir development in the ductile zone will then be assessed through observations and experimental results in the borehole.

1. INTRODUCTION

No new geothermal power plants have been constructed in Japan in the last decade, although the country hosts an estimated one third of the world potential for development of hydrothermal resources (http://www.iea.org). This lack of development has arisen largely because Japanese government policy has required geothermal power generation to be economically self-supportable in-line with market principles, even though its current generation costs are much higher than generation based on fossil fuels or nuclear fission. Meanwhile, the Japanese government has actively promoted nuclear power generation because of its potential scale of development and lower rates of emission of carbon dioxide. However, the tragedy of the 2011 Great East Japan Earthquake and the Fukushima Nuclear Power Disaster that followed it have drastically changed the energy policy of the Japanese government. The government, industry, and citizens are now much more positive about developing stable, safe, domestically produced, sustainable, and clean energy resources. For this reason, geothermal energy has now been re-prioritized as one of the most promising solutions for the current energy-shortfall crisis in Japan, and some companies have started constructing hydrothermal geothermal power plants in north-eastern part of Japan.

Although the advantages of geothermal energy as one of the green energy resources have been widely accepted for many years, geothermal power generation using natural hydrothermal reservoirs has not been attractive for many investors in Japan. The most significant reasons for this are the generally perceived risks of development and uncertain returns on investment. Further, since the potential economic benefit from a successful geothermal well is generally much lower than that for an equivalent oil or gas well, it is more difficult to spread the costs of unsuccessful drilling across a whole drilling campaign. Such irrecoverables losses, in the order of several million dollars, can be difficult to commercially absorb. For example, typical success rates of geothermal drilling are estimated to be 60-90% (Goldstein et al., 2011), mainly because even the newest exploration technologies do not have the ability to delineate the locations and orientations of highly productive fractures, which heterogeneously distribute within the reservoir.

Geothermal development using EGS technologies has been considered as one of the best solutions to the problems of localized distribution of the geothermal resources and the risks of “dry wells”. However, we have experimentally learned from the previous Japanese HDR (Hot Dry Rock) projects in Hijiori and Ogachi that the reasonable expectation of water recovery from an EGS reservoir in Japan, located as it is on a fracture-rich tectonic belt, is at best 50% (Kaieda et al., 2005, Tenma et al., 2005). This tendency for low water recovery is a serious practical problem, because it requires large quantities of water to be continuously charged into the EGS reservoir which in turn requires a lot of costly preparation on site. Another important issue to be considered concerns the difficulties in designing EGS reservoirs in the tectonic belt setting where local anomalies in tectonic stress and fracture distribution frequently occur. Because of this heterogeneity, the extension of the EGS stimulated zone is typically highly site dependent and sometimes depth dependent (Kaieda et al., 2005), bringing uncertainty to the EGS development. Furthermore, the occurrence of felt earthquakes from/around the EGS reservoirs during the stimulation and circulation phases (Majer et al., 2007, Häring et al., 2009) introduces additional environmental burdens and risks to the EGS development. The physics behind the generation of these felt earthquakes has not been fully understood (Mukuhira et al., 2011) and consequently, technologies to stimulate reservoirs without inducing earthquakes of this magnitude are not yet available.

2. OUTLINE OF THE DATASET USED IN THIS STUDY

The above-mentioned problems in the development of hydrothermal and EGS reservoirs can not be readily solved in Japan, because they are intrinsically related to the nature of the brittle rock mass and its tectonic setting. We see this as an impediment to large-scale commercial power generation from EGS reservoirs in tectonic belts in general. We therefore propose to investigate a new concept for engineered geothermal development where reservoirs are created in ductile basement. We expect that power generation using such EGS reservoirs in ductile zones may have the following advantages:

(a) More homogeneous rock properties and stress states are expected inside the ductile zone make it conceptually simpler to design and control the reservoir,
(b) Nearly full (100%) recovery of injected water from the hydraulically closed reservoir can be expected,
(c) Sustainable energy production would be realized by controlling flow rate and chemical contents of the liquid for circulation,
(d)Large-scale EGS systems could be engineered consisting of a number of EGS reservoirs created inside widely distributed ductile zones at relatively shallow depth in the tectonic belt,
(f) Possible site-independent characteristics of the ductile zones may lead to the establishment of universal design/development/control methodologies for ductile EGS reservoirs,
(g) Induced/triggered earthquakes with damaging magnitudes would not occur in the reservoirs.

It is clear that current scientific understandings in related disciplines, including geology, rock mechanics, reservoir engineering, and seismology, will need to be progressed to better understand and characterize the nature of ductile rock masses. Existing engineering technologies may also be insufficient to realize the creation of reservoirs in the ductile zone and power generation from them. The authors consider that many of these issues can be addressed through appropriate R&D by Japanese scientists and engineers, and to further this, a project has been initiated which is referred to as JBBP (Japan Beyond-Brittle Project). The details of the project are summarized in the following.

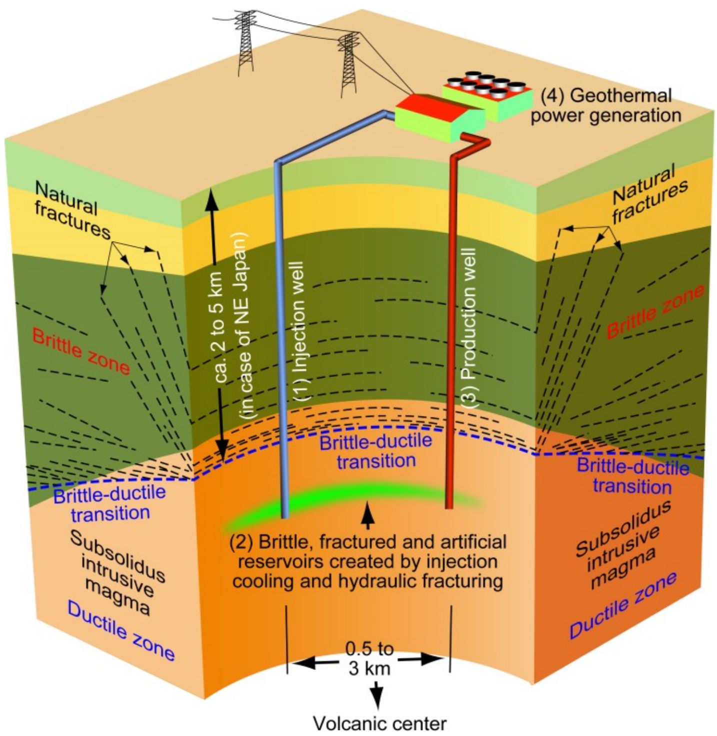

Figure 1: Concept of JBBP.

2.1 Scientific and technological challenges

This project should cover multidisciplinary scientific fields such as geology, geochemistry, geophysics, water-rock interactions, rock mechanics, seismology, drilling technology, well logging technologies, reservoir engineering, and environmental science. The most critical areas of research and technology development in the JBBP are summarized here.

-Characterization of ductile rock masses

Data collected from an exploration borehole (WD-1a) drilled at Kakkonda, Japan, demonstrated the presence of the brittle-ductile transition zone at a depth around 3,100m,.Below this depth, the rock mass showed a thermally conductive depth-temperature relation (Muraoka et al., 1998) consistent with a less fractured state. This observation is a basis for two of our expectations in the JBBP: that the ductile zone can be found at relatively shallow depth and, that significant existing fractures or permeable zones will be absent.

Investigations of the characteristics of the ductile rock mass have been started by members of the JBBP. We have observed hydrothermal brecciation in several geological settings, such as geothermal fields, the accretionary prism, mineralized areas, and metamorphic rocks. The classical view of hydrothermal breccias is that they are formed by explosive failure without any chemical reactions such as dissolution or precipitation. However, our field observations and lab work suggest a more intimate relationship between "hydrothermal conditions" and "brecciation". We have already proposed "HDF: Hydrothermally Derived Fracturing" (Hirano et al., 2003). Meanwhile, fluids also have significant roles in creating fracture networks during large-scale explosive failures. Experimentally we have also investigated hydrothermal brecciation by using a hydrothermal pressure vessel. Starting materials of single quartz crystal and intact granite were subjected to temperature ranges from 300 ºC to 600 ºC, and pressures from 0.1MPa to 30MPa (Tsuchiya et al., 2012).

This preliminary work has revealed some of the behavior of the ductile rock mass, however, fundamental understandings of key parameters such as the stress state, lithological structure, mechanical and compositional homogeneity, and thermal characteristics require much additional work. Beyond this, other phenomena to be investigated include the nature of water rock interactions and the behavior of pre-existing pore water in the ductile zone because both impact on the long term behavior of the reservoir and the chemical contents of the produced geothermal fluid. Laboratory tests would be the most effective means to obtain fundamental knowledge on the ductile rock mass in the initial stages of the project combined with analysis of core samples and pore water collected from an experimental borehole. This combination of laboratory and borehole data will generate, new knowledge on the rock mass and provide constraints on, and validation of the laboratory tests.

-Response of the ductile rock mass to cooling and hydraulic fracturing

Current laboratory test data suggest that a brittle fracture network consisting of very fine fractures at grain boundaries, is created by cooling and pressurization from the borehole (see Figure-2)(Hirano et al., 2003).

If a similar process operates during drilling then cooling of the ductile rock by the drill fluid may be expected to induce a grain-scale fracture network in the near field of the borehole during the drilling phase. If a part of the borehole is subsequently isolated after well completion and cold liquid is injected into the formation, our expectation is that a ductile fracture system will be extended from near the well into far field by the effects of cooling and pressurization. The size of the resulting reservoir and the distribution of permeable zones would be potentially controllable during the production phase by changing the flow rate and pressure and thereby inducing a mechanical mode change between ductile and brittle responses. However, current rock mechanics understanding does not extend to the design and control of such the brittle-ductile systems. We consider that the establishment of a frontier of rock mechanics, "brittle/ductile rock mechanics", is one of the keys to success in the JBBP and that this can be best achieved by combining theoretical and experimental studies in the laboratory with field studies of multi-level fracturing and borehole testing in a brittle-ductile rock mass.

-Numerical modeling of the EGS reservoir in the ductile rock mass

Numerical modeling has been often been adopted for the evaluation of geothermal reservoirs, and a wide range of computer programs ("numerical simulators")are available (e.g. O'Sullivan et al., 2001). Most of the existing numerical simulators are applicable to brittle conditions in the Earth and simulations including the presence of supercritical fluids have already been achieved. However, the JBBP will require a new numerical simulator which has the ability to simulate the behavior of rock masses in both the brittle and ductile regimes as well as in the transition between these regimes by integrating observations on the characteristics of the rock mass and the theory of brittle/ductile rock mechanics. The developed simulator will be used to design the EGS reservoirs and to gain insights into the control of these reservoirs in long term production to maintain sustainability.

-Risk assessment of induced earthquakes

It is to be expected that the seismic energy released during the creation phase of an EGS reservoir in the ductile zone will be much smaller than that from existing geothermal reservoirs in brittle zones, because laboratory tests show that the size of the fractures, which are mainly induced by cooling effects and WRI rather than by an increase in pore pressure, is in the order of millimeters or smaller (Hirano et al., 2003). Large earthquakes are also unlikely to be triggered because neither pervasive high pore pressures nor a drastic reduction in the friction coefficient would likely be produced during EGS operations. Furthermore, what seismic energy is generated in the ductile zone would be attenuated because of the higher coefficient of attenuation for shear waves in the ductile zone (Scholtz, 2002). However, more work is clearly required on this subject and this could include integrated theoretical and numerical studies of ductile/brittle rock mechanics and characterization of ductile rock masses with existing seismology.

The other possible mechanism of the induced seismicity is activation of faults outside the ductile zone by the deformation of the reservoir (Suckale, 2009). Geomechanical modeling of the target area could be effectively used for the risk assessment of such earthquakes.

-Monitoring of the EGS reservoir

Seismic monitoring has been used as one of the most practical monitoring methods during the stimulation of EGS reservoirs (Niitsuma et al., 1999, Häring et al., 2009, Asanuma et al., 2004). Deployment of HT/HP seismometers in experimental boreholes near the isolated zone is one of the key monitoring methods for collecting microseismic signals during the reservoir creation process, although HT/HP seismometers and deployment technologies in the experimental borehole should also be developed in the initial stages of this project. We realize that new electromagnetic monitoring techniques are another option to be considered.

-Technology development

Ongoing technology development will be indispensable in the development of EGS reservoirs in ductile zones, because such zones are particularly technologically harsh environments. Experiences from drilling deep geothermal exploration wells in Iceland and Japan (Skinner et al., 2010, Saito et al., 1998) have revealed that efficient cooling of the borehole during the drilling operation reduces borehole temperatures below 200 ºC where critical damage to the bit, drill-strings, and drill mud are not induced. Considering the subsequent temperature recovery after the drill-induced cooling and the possible pressurization of the borehole during the hydraulic fracturing phase, cementing materials must be carefully selected. We have to find or develop cementing material, the cementing operation, and the methods for quality evaluation of the cementing in the casing annulus in the preparation phase of this project to ensure effective hydraulic stimulation and borehole safety.

Currently, there are no available technologies for creating reservoirs by cooling and hydraulic fracturing in a specific depth interval in the ductile zone. We, therefore, must investigate practical reservoir creation techniques in this project as a high priority.

Logging tools for HT/HP borehole exceeding 200 ºC have been recently developed mainly in service companies in the oil industry. Temporary cooling of the borehole below 200 ºC may therefore be an effective strategy to allow borehole logging in this project though this may result in some loss of temperature-dependent physical parameter data for the formation. In situ information including the stress state and hydraulic characteristics, which need to be determined in the borehole, would be much more difficult to obtain because of expected rapid temperature recovery in the borehole. Temperature-tolerant technologies to estimate the stress state around the target depth of the fracturing must be investigated, because we realize that the stress state is of critical importance if reliable estimates of the response of the ductile rock mass to the EGS operation are to be made.

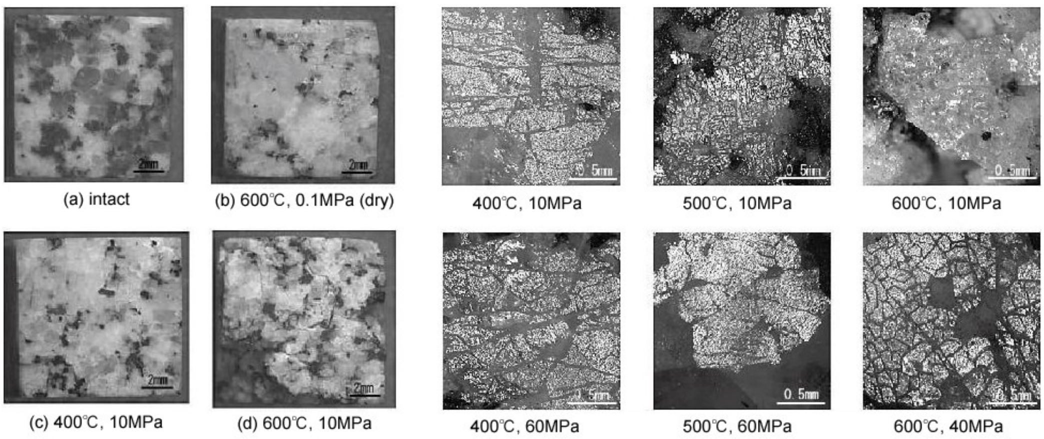

Figure 2: Fracture development in granite after hydrothermal experiment (Tsuchiya et al., 2012).

2.2 Target area

The northeastern part of Japan (Tohoku area) has several geological advantages for EGS R&D in the ductile zone, namely, the relatively higher density of host rocks, the neutral buoyancy depth of magmatic intrusions tends to be shallower in compression tectonic belts (see Figure-3)(Muraoka and Yano, 1998). Previous drilling also points to the Tohoku area where the exploration borehole WD-1 demonstrated that the brittle-ductile transition zone can be reached at a depth of only 3-4km, reducing cost for drilling and risk of troubles in the borehole. Furthermore, the geothermal temperature gradient map of Japan (Figure-4)(Yano et al., 1999) shows that such shallow depths to the brittle ductile transition are widely distributed along the backbone range (Ohu Range) in northeast Japan, suggesting the potential for a large amount of electricity generation at what is expected to be an economically acceptable cost using the universal design/control methodology of ductile EGS. Such areas can also be found in the compression tectonic belts of the Philippines, Kamchatka, and Indonesia.

2.3 Implementation plan

Success in the JBBP will be aided by close collaboration of Japanese and international geothermal researchers, especially in New Zealand, Iceland, and Russia, all countries with strong motivation for the development of their deep and high temperature geothermal resources. The authors consider that the scheme of The International Continental Scientific Drilling Program is the most suitable for the international collaboration in the JBBP and hold an ICDP workshop, which is the first stage of the ICDP drilling project, in Sendai in March 2013. More than one hundred researchers worldwide participated the 4 day worksop and discussed various issues related to the JBBP. Summary of the WS is available in Muraoka et al.,(2014). The next 2-3 years in the JBBP will be spent on basic scientific research on brittle/ductile rock mechanics, the characterization of ductile rock masses, the development of appropriate numerical simulators, and the investigation of induced/triggered earthquakes. Technological feasibility studies and necessary technology development will be also conducted in collaboration with industry. We expect to drill a 4-5km experimental borehole after the initial work and to make experiments to create EGS reservoirs and to finally demonstrate the practicality and potential of EGS reservoirs in ductile zones. Collaboration with industry will be realized for the transfer of scientific knowledge and technologies to further improve the future commercialization prospects of ductile EGS power generation.

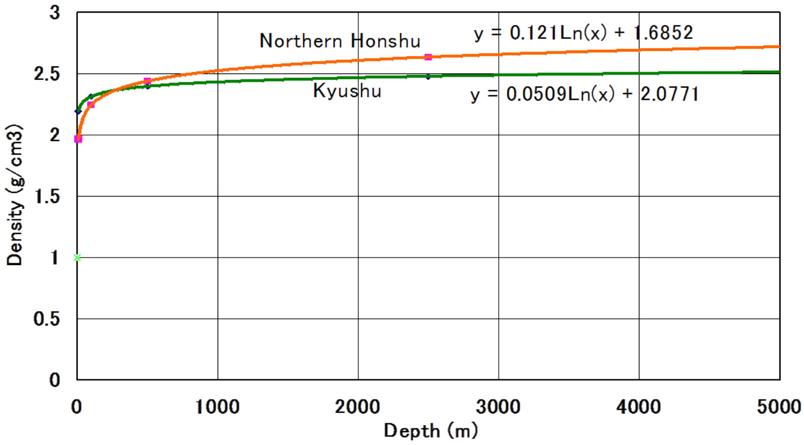

Figure 3: Regression lines of core densities in northern Honshu and Kyushu (Muraoka and Yano, 1998)

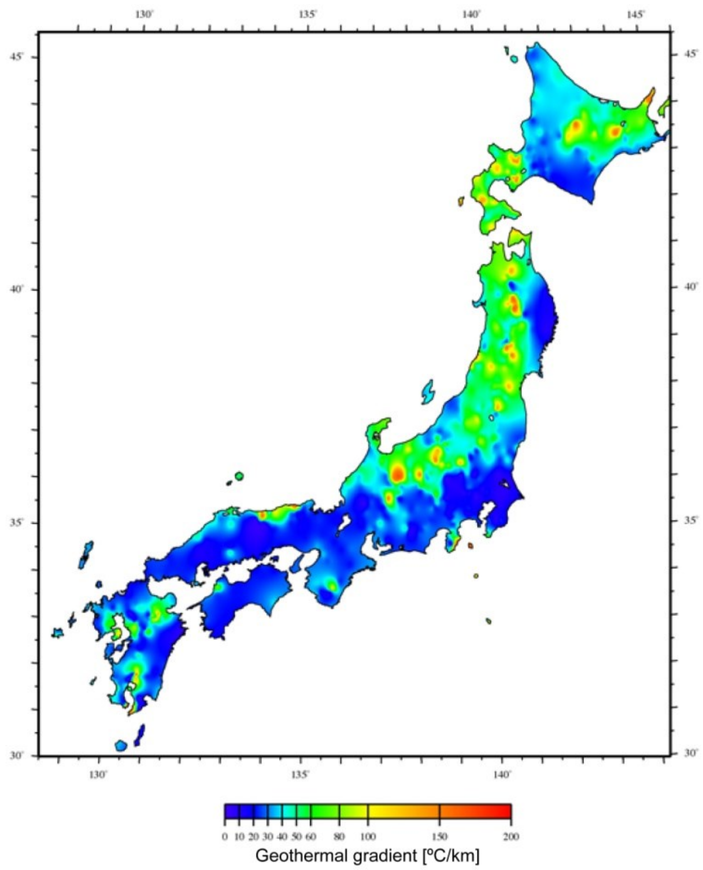

Figure 4: Thermal gradient map in Japan (Yano et al., 1999).

3. SUMMARY

We have described the concept of the "Japan Beyond-Brittle Project (JBBP)" EGS development project which is targeted at the ductile rock masses that are widely distributed at relatively shallow depth (3-4 km) in northeast Japan and other compression tectonic belts. Once the feasibility of the creation of ductile EGS reservoirs and power generation from them has been demonstrated, we expect that many of the currently identified problems associated with geothermal development in Japan, including site dependency, water recovery, sustainability, and economical risk, can be solved. As discussed, this project has just initiated and further scientific/technological investigation is required to validate our concept. We believe that success in the JBBP will lead to rapid increases in geothermal power generation in compression tectonic belts worldwide.

Acknowledgement

The authors would like to acknowledge ICDP (The International Continental Scientific Drilling Program) for their support to hold an international workshop, March 2013. We also would like to thank Dr. Prame Chopra, Earthinsite.com, for his comments and suggestions in finalizing this paper. Part of this study is supported by MEXT/JSPS (Grant-in-Aid for Specially Promoted Research 25000009)

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