Chapter 6
Geothermal Energy

Toshiyuki Hashida

Abstract This chapter focuses on a source of renewable energy which could be very significant in Japan and similar geologically active zones. Geothermal energy has the advantage of heat and electricity with minimal environmental impact. Potentially the available energy exceeds human needs but there remain technical barriers to its economic exploitation on a larger scale away from the most intense sources near tectonic plate boundaries. The role of drilling and fracturing to create Enhanced (engineered) Geothermal Systems (EGS) is described together with the relevant factors for the design of geothermal energy extraction systems. The role of modelling to simulate the effects of fracturing to create flow pathways for heated water is also described.

Keywords Geothermal energy · Hot dry rock · EGS · Hydraulic stimulation

6.1 Geothermal Energy: Current and Future

Geothermal energy exploits the heat from the Earth's crust to generate electricity or provide heat directly e.g. for district heating, hot water, horticulture etc. Ground source heat pumps can also be classified as geothermal energy although not the subject of this chapter. According to the International Energy Agency (IEA 2010a), installed capacity of geothermal energy at the end of 2009 was 10.7 gigawatts (GWe) for electricity generation and 50.6 GWth for direct use as heat. Most recent estimates suggest modest growth in supply, with 11,224 GW of electricity generated in 24 countries in 2012 (GEA 2012).

Currently, geothermal energy is exploited most in the countries shown in Table 6.1. A significant proportion of electricity is generated from geothermal in Iceland (25 %), El Salvador (22 %), Kenya and the Philippines (17 % each), and Costa Rica (13 %). In absolute figures, the United States produces the most geothermal electricity: 16,603 GWh from an installed capacity of 3093 MWe. Japan's geothermal usage is in 8th position globally for electricity and 5th for heat.

T. Hashida (✉)
Fracture and Reliability Research Institute, Tohoku University, Sendai, Japan
e-mail: hashida@rift.mech.tohoku.ac.jp

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Table 6.1 Top 10 Countries using geothermal energy. (IEA 2010a)

Country	Geothermal electricity production GWh/yr	Country	Geothermal direct use GWh/yr
United States	16,603	China	20,932
Philippines	10,311	United States	15,710
Indonesia	9600	Sweden	12,585
Mexico	7047	Turkey	10,247
Italy	5520	Japan	7139
Iceland	4597	Norway	7000
New Zealand	4055	Iceland	6768
Japan	3064	France	3592
Kenya	1430	Germany	3546
El Salvador	1422	Netherlands	2972

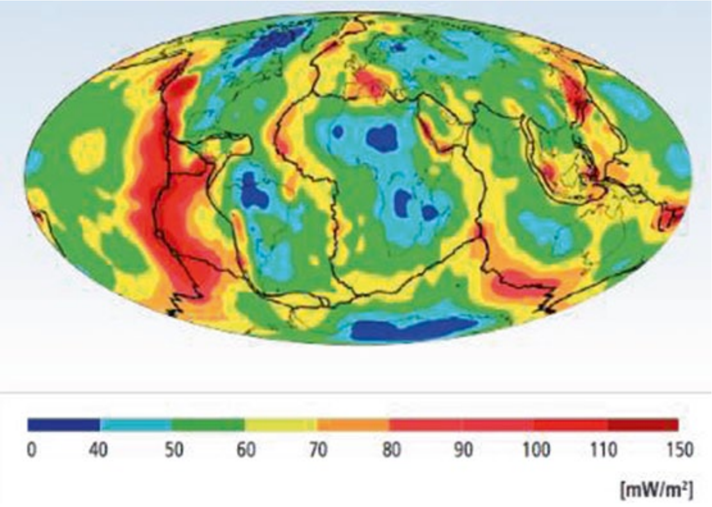

Fig. 6.1 Areas of high geothermal activity due to Tectonic Plate movement. (Source: IPCC 2011)

Geothermal power is potentially cost effective, reliable, sustainable, and environment- friendly but, as can be seen from the location of the main users in Table 6.1, has historically been located at areas near tectonic plate boundaries (Fig. 6.1), where the heat is relatively easy to access—indeed the tradition of hot springs can be traced back thousands of years in some areas.

In recent years, technological advances have dramatically expanded the range and size of potentially viable resources, especially for applications such as home heating, increasing the potential for widespread exploitation. In addition, the technologies of deep drilling and fracturing have improved, and allow the heat present in the crust outside the main plate boundaries to be accessed, thus offering potential

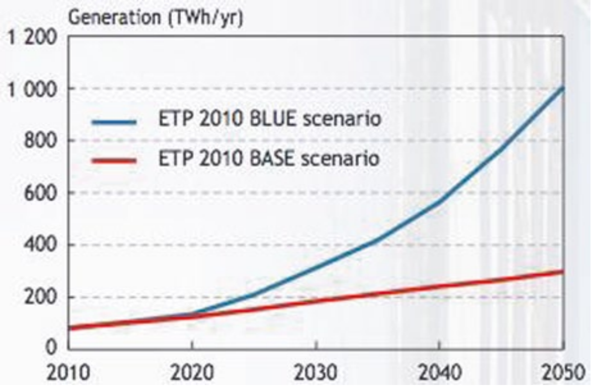

Fig. 6.2 Geothermal energy electricity generation scenarios. (From IEA 2010a)

around the world. These Enhanced (or Engineered) Geothermal Systems (EGS) are the critical foundation for future expansion in geothermal energy.

Regarding future potential, IEA's baseline scenario (IEA 2010b) envisages only modest growth in the role of geothermal energy, suggesting it could provide 1 % (approximately 300 TWh) of global electricity by 2050 (Fig. 6.2). However, if greenhouse gas reduction is afforded the higher priority that would be necessary to meet G8 countries' target of a 50 % reduction in GHG emissions by 2050, geothermal electricity generation could increase up to 1060 TWh/yr by 2050 (the 'blue' scenario in Fig. 6.2). Industry association estimates are that geothermal energy generated electricity and heat will be even higher than the IEA upper estimates.

IEA have compiled a 'Roadmap' for Geothermal (IEA 2011) which indicates a potential to achieve at least a 20-fold increase in global production of heat and electricity from geothermal energy between now and 2050. Through a combination of actions that encourage the development of untapped geothermal resources and new technologies, geothermal energy could then account for around 3.5 % of annual global electricity production and 3.9 % of energy for heat (excluding ground source heat pumps) by 2050.

6.2 Advantages, Disadvantages and Barriers

Some of the pros and cons of geothermal energy are summarized in Table 6.2

A primary advantage is the potential for accessing energy which is currently unused and renewable, since it arises from heat released from the radioactive decay of the Earth's minerals and some residual heat from the original formation of the planet. Contribution to global warming is also low since CO_2 emissions from within geological formations are limited, and most life cycle emissions are those associated with the construction and running of the facility. Life cycle emissions are thus substantially lower than fossil fuels and comparable to solar PV (Table 6.3).

Table 6.2 Advantages and drawbacks in utilizing underground geothermal resources

Advantage	Drawback
Constant and stable	Complexity and heterogeneity
Isolation properties- barriers to gases	Uncertainty and limited information
Renewable and untapped resource	Geological faults (instability, leakage)
Low emissions of greenhouse gases	Cost (construction, maintenance, maintenance of flows)
Safe and secure from threats (terrorism)	Chemical contaminants and scaling

Table 6.3 Life cycle greenhouse gas emissions by electricity source. (Adapted from IPCC 2011)

Electricity generating technology	CO_2 per KWh electricity (mean of available estimates (g))
Hydroelectric	4
Wind (onshore)	12
Nuclear	16
Solar PV	46
Geothermal	45
Natural gas	469
Coal	1001

Further advantages are that geothermal energy provides base load power with no seasonal variation and is not weather dependent. Its resource is also isolated underground which makes it secure and also imparts resilience against earthquakes (as shown in the 2011 Great Eastern Japan earthquake when no geothermal facilities were damaged). In recognition of these advantages, geothermal energy is increasingly included as a desirable renewable energy in some country's renewable energy policies; for instance, it is eligible for Feed-in-tariff (FIT) subsidies in Japan and Germany.

The potential size of the geothermal heat resource can be estimated from the mean temperature depth distribution shown in Fig. 6.3 (Armstead and Tester 1987). The mean surface temperature is 15 ºC, with a thermal gradient of 25 ºC/km near the surface and 11 ºC/km near the 'Moho' where temperature is ~600 ºC at a crustal depth of 35 km (all figures approximate). If we set a maximum depth up to which the underground heat may be extracted (d in Fig. 6.3) as the current depth limit for directional drillings (6 km), the potential geothermal energy resource can then be estimated by calculating the mean crustal temperature up to 6 km, and then calculating the volume that would be required to supply global energy demands. A simple calculation shows that the heat stored in a rock mass of approximately 96 km^2 by 6 km deep is equivalent to the world energy demand forecast for 2030 of 170×10^8 t oil equivalent. We thus see that the potential of geothermal energy is huge and the challenge is to extract it efficiently and economically.

However to realise this large potential, a number of barriers need to be overcome. Those cited by the IEA include public awareness and acceptance, and logistical problems such as insufficient numbers of trained geothermal scientists and engineers. There are also barriers and uncertainties which influence the economics of geothermal energy. In particular these include the rate of failure of drilling to

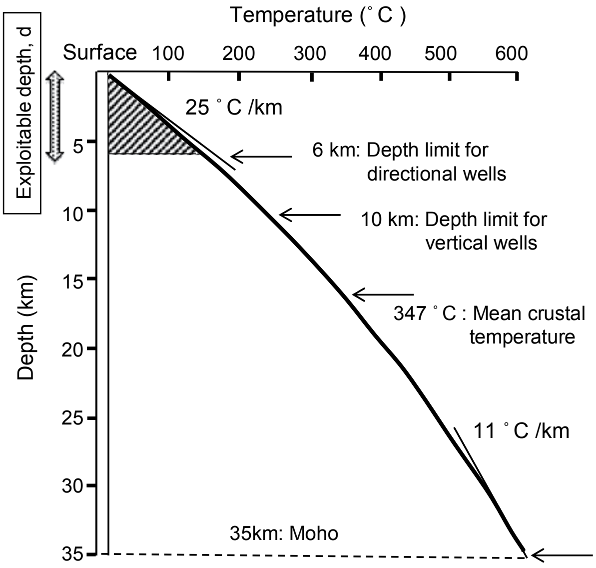

Fig. 6.3 Estimating potential crustal heat resources. (Armstead and Tester 1987)

discover viable reservoirs, which leads to high development costs and risks; another factor is the requirement for deep reservoirs and, even when resources are accessed, insufficient productivity and accessibility in the reservoirs. In addition, maintaining flow rates over time presents many challenges. Moreover, hot water from geothermal sources may hold in solution trace amounts of toxic elements.[1]

A key barrier remains the uncertainty induced by the complex and inhomogeneous nature of rock masses, which imposes a significant challenge to the reliable and extensive use of geothermal resources, and requires the use of EGS, which stimulates subsurface regions where temperatures are high enough to be utilized effectively. A reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells. Heat is extracted by circulating water through the reservoir in a closed loop (see next section). This chapter thus focuses on potential approaches to reduce this uncertainty and contribute to the development of geothermal energy extraction.

6.3 Exploitation of Geothermal Energy

A general diagram showing the penetration of surface water into zones near hot rocks or magma and its return as hot water is shown in Fig. 6.4 (GEA 2012). Also see the literature (White 1967; White et al. 1971) for detailed discussion regarding the characteristics of geothermal reservoirs. In order to exploit this energy, the three necessary conditions are also shown in the Figure; namely high temperature rock,

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[1] Generally cooled geothermal fluids are re-injected underground which may also stimulate production as a side benefit of reducing this environmental risk.

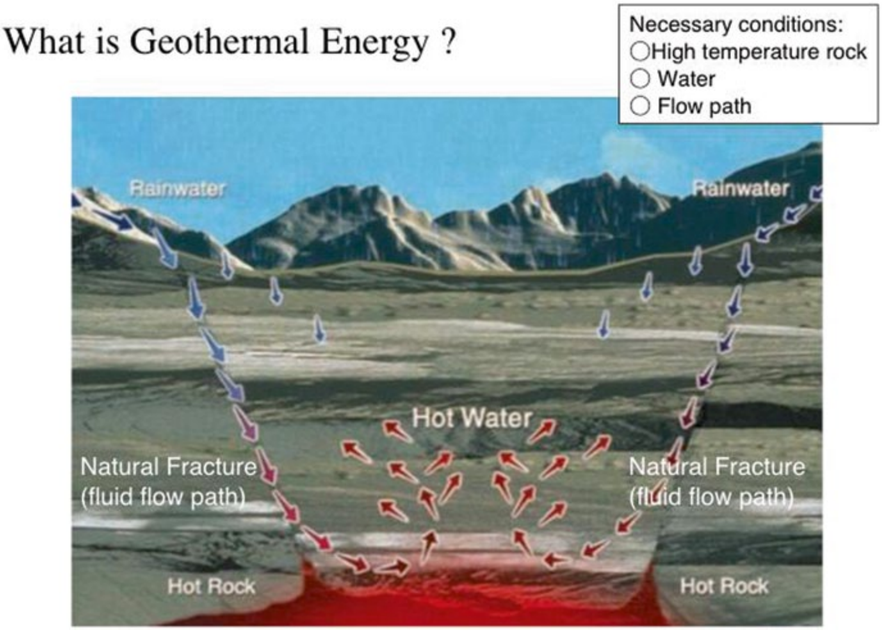
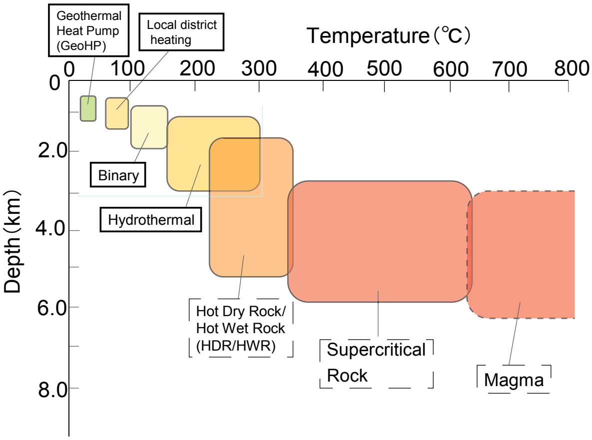


Fig. 6.4 General schematic of geothermal energy reservoir. (Geothermal Energy Association Web site, http://geo-energy.org/basics.aspx)

water which flows from natural sources, and flow paths which allow heated water to flow back through natural fractures.

There are a range of techniques for extracting geothermal energy related to the depths and temperature and nature of the resources involved. Figure 6.5 provides a broad classification of underground heat utilization methods according to their approximate ranges of depth and temperature. The types of underground heat utilized to date include geothermal heat pumps, district heating systems, and steam-based heat and electricity generation systems. Under appropriate conditions, high-, in-

Fig. 6.5 Classification of underground heat utilization methods



termediate- and low-temperature geothermal fields can be utilized for both power generation and the direct use of heat (Tester et al. 2005).

Geothermal heat pumps utilize relatively low and constant temperature ground heat and have been increasingly finding applications as efficient home heating and cooling installations. Hydrothermal power plants are the most typical installation for electricity generation and include two main types: hot water-dominated and steam-dominated systems. The temperature range for the hydrothermal systems is typically 150–300 °C. Binary-cycle power plants may also provide a useful option where low reservoir temperatures (approximately 100–150 °C) are encountered.

Hot dry rocks (HDR) and hot wet rocks (HWR), supercritical rocks and magma energy systems are at the research or development stage. Supercritical rocks refer to high temperature rock masses whose temperature and pressure exceed the critical point of water (374 °C, 22 MPa). In contrast with naturally occurring hydrothermal systems, HDR and HWR refer to geothermal reservoir systems created using artificial methods; these engineered reservoir systems using hydraulic stimulations were first proposed by Tester et al. (1989) and Potter et al. (1974). The aim of geothermal energy extraction using hydraulic stimulations is to mine the heat energy stored in subsurface rocks by creating a system of open, connected fractures through which water can be circulated down injection wells, heated by contact with the rocks, and returned to the surface in production wells to form a closed loop, as illustrated in Fig. 6.6. Following the introduction of HDR, the concept of HWR has been proposed which intends to combine an artificial reservoir system with the existing hydrothermal system (Takahashi and Hashida 1992).

EGS is a newly coined terminology defined as engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources (Fig. 6.6). EGS may refer to geothermal reservoir systems that have been produced by means of artificial and engineering methodologies such as hydraulic stimulation methods in currently non-productive formations and rock masses. In this regard, EGS is an equivalent concept to HWR which aims to improve and enhance the performance of existing reservoirs by use of hydraulic stimulation. HDR may be also included in the EGS concept and in this chapter, the terminology EGS includes both HDR and HWR.

Heat extraction from ultra-high temperature systems such as supercritical rocks and magma may be feasible and attractive in the future, but this chapter focuses on the development of hydrothermal and EGS systems, which are current and near-future heat sources for electricity generation. The reader is referred to Hashida et al. (2000), and Hashida and Takahashi (2003) for the development of supercritical rocks, and Colp (1982), and Teplow et al. (2009) for the exploitation of magma energy.

6.4 EGS Projects

In order to realise the potential of geothermal energy, the 3 pre-requisites already mentioned of high temperature rock, water and flow path are needed. Most current geothermal sources have magma relatively close to the surface and water coming

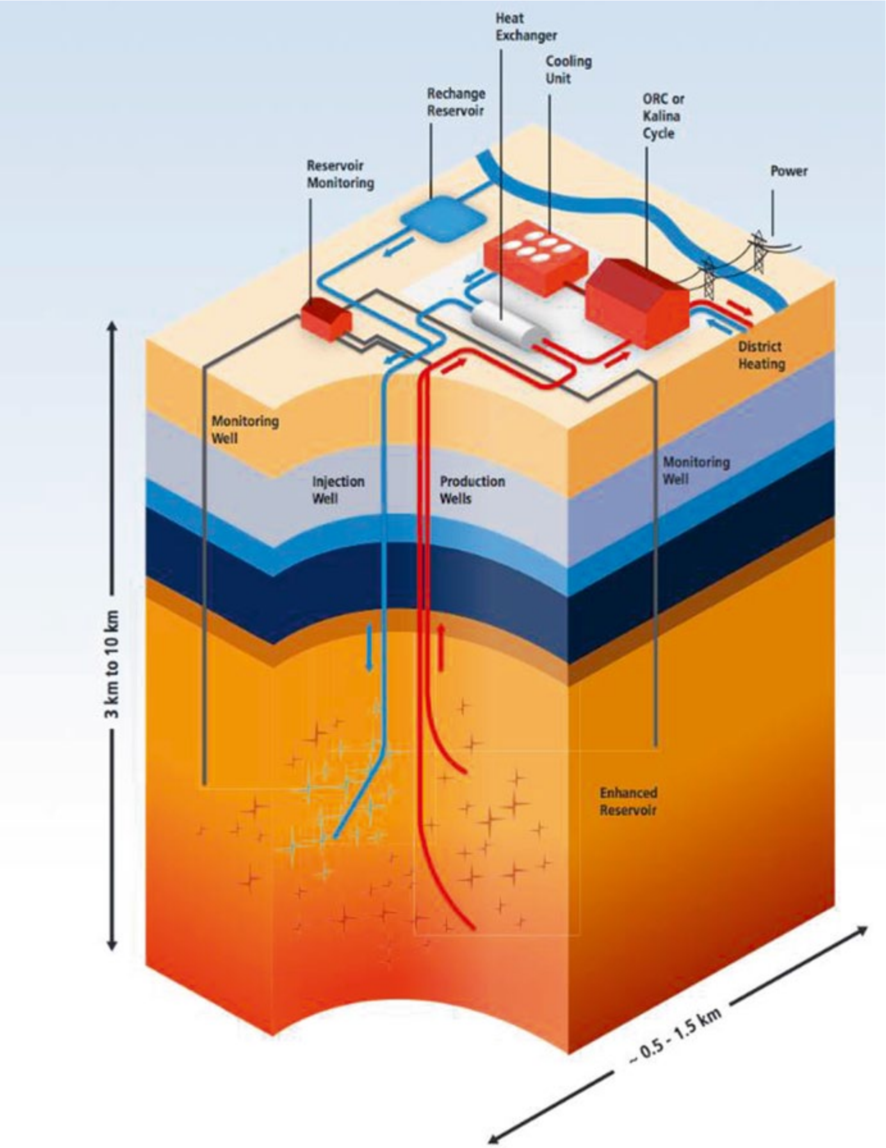


Fig. 6.6 Enhanced or engineered geothermal system (EGS). (Source, IPCC 2011)

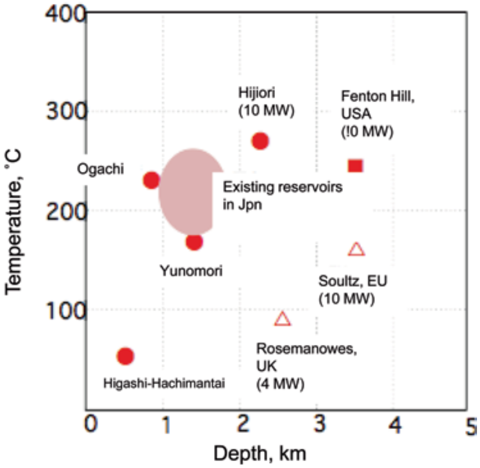
from the surface penetrates to close to the magma area and absorbs the heat. Return flow path is determined by the fractures or faults which exist naturally. When all three conditions are met then a viable extraction is possible, but in many cases all three conditions are not all met at the same time.

Reservoir engineering is designed to determine the volume of geothermal resources and the appropriate plant design for sustainable use and safe and efficient operation. Where flows are inadequate, this may require the creation of an artificial or engineered geothermal energy system of which a critical part is hydraulic fracturing or stimulation. The modern method of estimating reserves and sizing power plants is to apply reservoir simulation technology. A conceptual model is built using available data, it is then translated into a numerical representation, and calibrated to the unexploited, initial thermodynamic state of the reservoir (Grant et al. 1982). Critical parts of the overall reservoir simulation are to model the effects of fracturing in the EGS, to predict the effects of such stimulation and design optimum strategies for the EGS.

Knowledge of temperature at drillable depth is a prerequisite for site selection for any EGS development. The thermo-mechanical signature of the lithosphere and crust are equally important as they provide critical constraints affecting the crustal stress field, heat flow and temperature gradients. Many rocks will already contain natural fractures in the rock mass, and it is imperative to assess their distribution (hole drilling will reveal some of the existing rock characteristics including naturally occurring fractures) which can then inform the design of the fracturing stimulation. Modelling and simulation may play a role and, for the development of mass transport modelling, an artificial geothermal system can be modelled where a reservoir is artificially created by hydraulic stimulation and the fractures connected with two drilled boreholes. Circulation using the reservoir is then performed by injecting cold water into the injection well and recovering it through the production well.

A number of research projects on HDR/HWR have been performed internationally at sites of several countries with various temperatures, depths and locations (Fig. 6.7).

Fig. 6.7 HDR/HWR projects conducted to date



The key challenge for EGS is to stimulate and maintain multiple reservoirs with sufficient volumes to sustain long-term production at acceptable rates and flow impedances, while managing water losses and risk from induced seismicity (Tester et al. 2006). Conventional geothermal resources currently used to produce electricity are either high-temperature systems (>180 ºC), using steam power cycles (either flash or dry steam driving condensing turbines), or low to intermediate temperature (<180 ºC) using binary-cycle power plants. All projects in Fig. 6.7 have succeeded in creating artificial fracturing, and have demonstrated that it is possible to create such an artificial water circulation system in rock masses, with the remaining task to design the reservoir and to predict long-term performance.

Included in these projects is the Hijiori experiment in Japan funded by Japan's New Energy and Development Organization (NEDO). The Japanese work at the Hijiori (10 MW) site has involved EGS using stimulation of subsurface regions where temperatures are high enough for effective utilization. These experiments have successfully generated a reservoir of several 100 m diameter with a thermal output of up to 10 MW. Rock temperatures were generally below 300 and this has allowed the possibility of creating fractured reservoirs to be verified. In these projects, a reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells (see Fig. 6.8). Heat is ex-

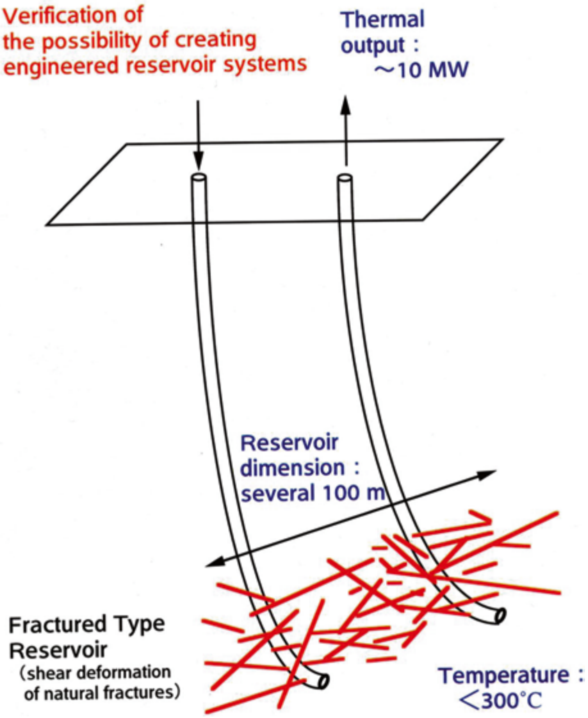


Fig. 6.8 Achievements of the HDR/HWR projects

tracted by circulating water through the reservoir in a closed loop and can be used for power generation with binary-cycle plants and for industrial or residential heating.

These experiments have proved the technical viability of the EGS approach, and confirm that knowledge of temperature at drillable depth is a prerequisite for site selection in any EGS development. The challenge remains to develop methodologies to simulate and design viable economic systems. In this respect, one relevant project being carried out at Tohoku University is the numerical simulator FRACSIM 3-D as one of recently developed analogue and numerical models which provide insights useful for geothermal exploration and production (Watanabe and Takahashi (1995); Willis-Richards et al. (1996); Jing et al. (2000); Jing et al. (2014)). Taking account of fracture distributions, the permeability of the rock before and after fracturing can be simulated. This has been applied to the long-term circulation and heat extraction experiment at Hijori, Japan.

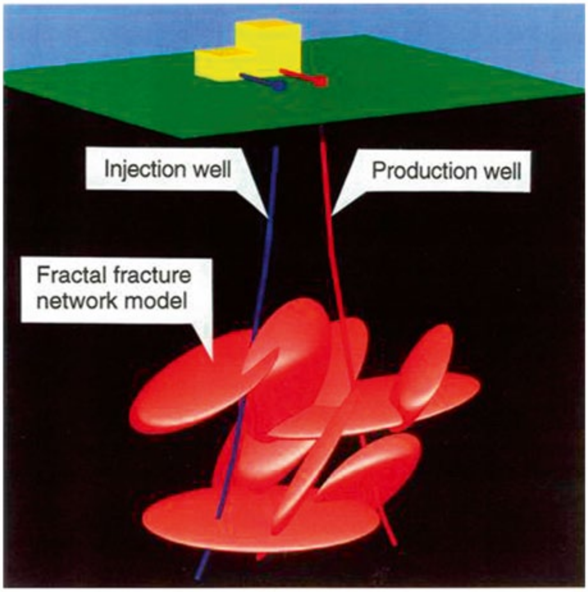
6.5 EGS Modelling

The HDR/HWR projects shown in Fig. 6.7 have confirmed that one of the crucial pre-requisites is to form an extensive fracture network sufficient for sustainable heat extraction. For the formation of EGS, as mentioned previously, it is required to stimulate and maintain multiple reservoirs with sufficient volumes to sustain long-term production at acceptable rates: in other words to establish and maintain the water supply and viable flow paths from the high-temperature rock. A small number of multiple fractures may only result in an early thermal drawdown due to the limited area of heat exchanging surface (hydraulically induced fracture surface). The majority of the rock mass types encountered and/or selected for the sites of the HDR/HWR projects included a number of naturally occurring fractures. Furthermore, hydraulic stimulations conducted have been shown to induce primarily shear dilation (aperture increase due to slip deformation along the natural fracture) rather than formation of new fractures. Thus, based on the experience obtained from the HDR/HWR projects, it appears to be a viable approach to utilize and stimulate a natural fracture system in order to create a water circulation loop with sufficiently high permeability for geothermal energy extraction.

The above-mentioned observation underlines the importance of characterizing and modelling the distribution of natural fractures and their mechanical response for the design of engineered geothermal reservoirs. Figure 6.9 shows a schematic of the fracture network model employed for the development of FRACSIM-3D. FRACSIM 3-D takes into account the complexity of natural fractures, and utilizes the phenomenon of fractal geometry (because most fractures exhibit the characteristics of fractals) to simulate the reservoirs shown in red in Fig. 6.9. In FRACSIM-3D, the reservoir is assumed to consist of a number of circular cracks whose length distribution follows the fractal geometry.

As illustrated in Fig. 6.10, FRACSIM-3D firstly generates a natural fracture network based on the fractal characteristics, which can be obtained from surface observations. Observation of cores and well logs may be used to determine the number

Fig. 6.9 Fundamental design methodology for extraction of geothermal energy



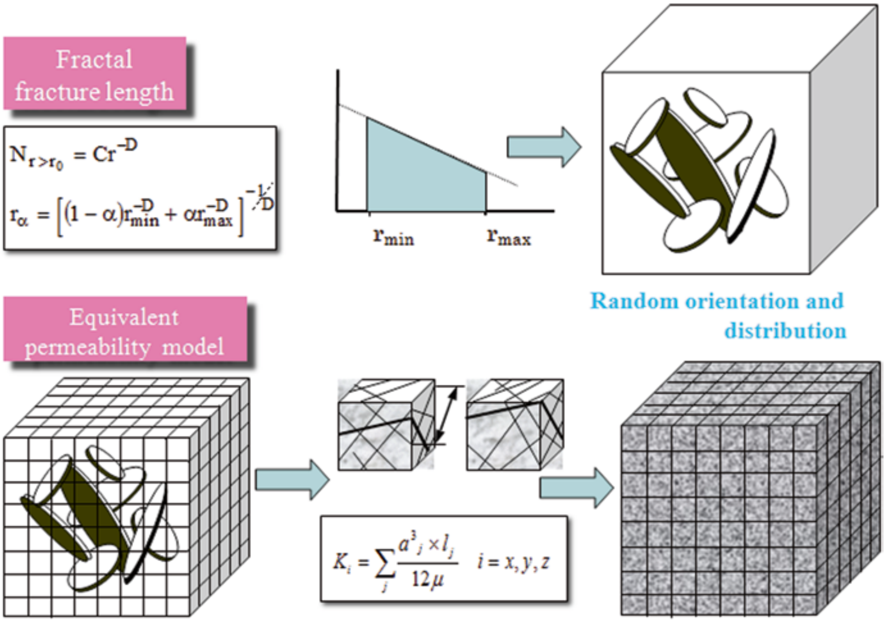


Fig. 6.10 Numerical simulation concept: FRACSIM-3D

of the fractures to be generated in the calculation volume. To conduct fluid flow analysis for hydraulic stimulation and to determine the water pressure within the fractures, the generated fractal fracture network is mapped on a regular cubical grid. Then the equivalent permeability of each block is calculated, based on the sum of the products of the fracture apertures to the 3rd power and length of the intersection of the fracture with the block face. The flow analysis is performed assuming that the calculated permeability controls the fluid flow rate from one block to another block. In FRACSIM-3D, shear dilation mechanism for fracture opening is accounted for, in addition to jacking mechanisms. The fractal nature of the fracture surface roughness is also taken into account in order to predict the shear dilation of fractures. This grid model with a spatial distribution of equivalent permeability is employed to perform numerical computations for mass and heat transfer and to simulate the artificial reservoir formation by hydraulic stimulation and subsequent heat extraction through the man-made water circulation loop in the reservoir. The model can also

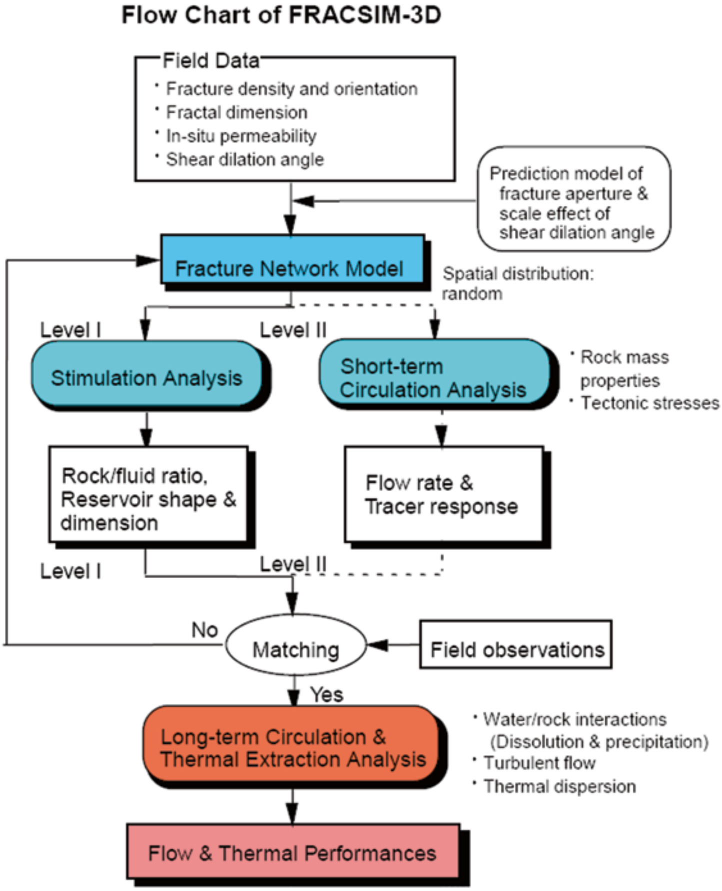


Fig. 6.11 Design methodology for engineered geothermal reservoirs

be utilized to simulate tracer tests. The numerical model for tracer analysis assumes that the migration of tracer species (particles) is dictated by a flow-dependent probability in each grid. The probability of tracer migration for a given orientation is obtained by dividing the flow rate in the direction with the total flow rate for the grid.

Based on the field experience and the development of numerical simulation code, we have elaborated the flow chart for the procedure of FRACSIM-3D shown in Fig. 6.11. Based on field data such as fracture density (number), orientation, and fractal dimension of fracture size, natural fracture networks are generated within a cubic fracture generation volume assuming its spatially random distribution. Field information such as fracture density and orientation can be obtained from the observation of cores and well logs.

It is crucially important to make a good estimate of the initial fracture aperture and shear dilation angle for the fractures having different dimensions in the generated fracture network. A predictive model for fracture aperture and shear dilation angle has been incorporated into FRACSIM-3D. The model predicts the initial fracture aperture based on initial permeability data to be measured in a borehole, and the shear dilation angle of each fracture is estimated numerically on the basis of the fractal nature of the fracture surface.

Because the distribution of natural fractures is a stochastic characteristic, it is not technically feasible to determine *a priori* size and spatial location of each natural fracture in the fracture network generated using the fractal model. Thus, we have proposed a method for determining the natural fracture distribution by comparing numerical predictions with field observations. Specifically, a number of natural fracture networks are generated using random seeds (say 50 realizations in the example to be described below).

First, based on the natural fracture networks generated, we carry out a hydraulic stimulation analysis to compare the numerical outputs with field observations. The field data to be used for this comparison are rock to fluid ratio (RFR), and shape and dimension of the created reservoir. The RFR parameter is a measure of the amount of fracture void space created during hydraulic stimulation, which can be computed from the rock volume stimulated and the injected fluid volume. The stimulated rock volume, and the shape and dimension of the created reservoir may be estimated using field date obtained from microseismic methods. This evaluation step is labeled as Level I. If preliminary and short-term water injection test results such as impedance and tracer responses are available for the site, short-term circulation analyses may be further performed. Flow rates and tracer responses between injection and production wells may be used to compare the numerical outputs with field observations. This assessment stage is denoted as Level II.

This process is repeated for all natural fracture networks prepared, and the fracture model that matches best with the field observations is then selected. An analysis of long-term water circulation is subsequently carried out to predict the thermal extraction performance of the created reservoir, based on the selected best fracture network model for a pair of injection and production wells. Thermal drawdown (time history of water temperature at the production well) can be calculated for the

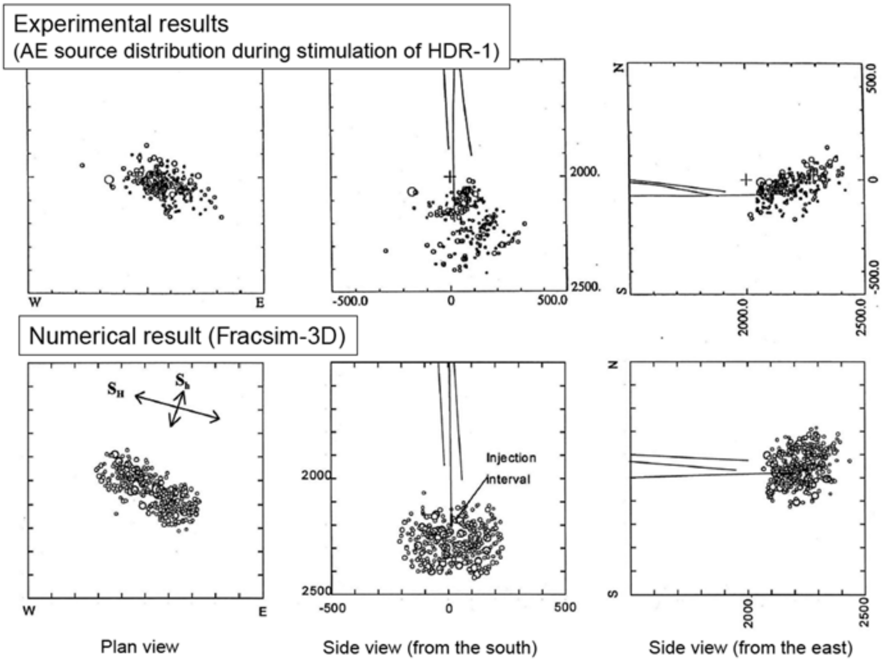


Fig. 6.12 Application of FRACSIM-3D to Hijiori

given circulation conditions such as injection pressure. The numerical result may be utilized to design the operating conditions such as injection rate and pressure for sustainable heat extraction.

The evaluation procedure in Fig. 6.11 has been applied to the Hijiori field experiment (Kuriyagawa and Tenma 1999). The experimental HDR system created at Hijiori comprised an artificial reservoir formed by hydraulic stimulation at a depth of ~2200 m and a water circulation test was performed for 1 year. The results are shown in Fig. 6.12 where the upper row of 3 figures are the experimental results of hydraulic stimulation from 3 directions of view (circles indicate seismic events detected during the hydraulic stimulation process). The lower row of figures gives the simulated results based on the selected best fracture network (circles give the location of the circular fractures whose aperture was increased due to the hydraulic stimulation in the numerical simulation).

In this experiment, 50 natural fracture networks were generated using random seeds and the best fracture network was identified according to the procedure of Level I and II as shown in Fig. 6.11. It appears that the numerical results correspond well with the field data in terms of the shape and dimension of the reservoir created. In particular, the numerical model FRACSIM-3D reproduces the downward migration of the created reservoir as indicated by the experimental results. This comparison may also support the validity of the numerical model.

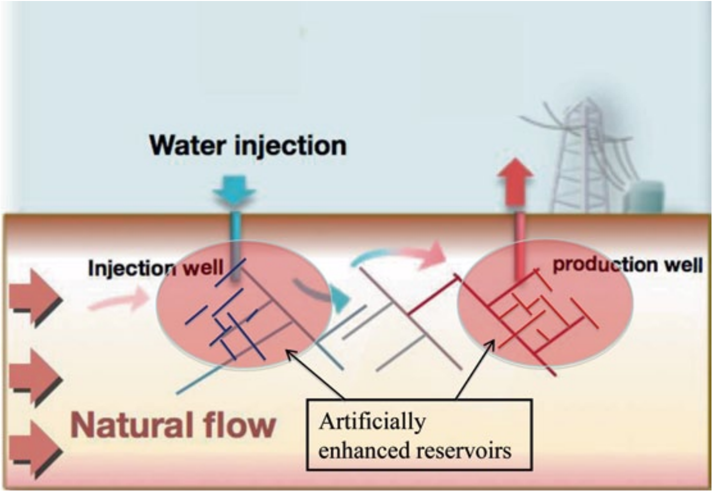


Fig. 6.13 Upstream hydraulic stimulation

Furthermore, it has been demonstrated that the predicted thermal drawdown compared well with the field data from a 1-year circulation test conducted at the Hijiori site.

6.6 Reinjection for Enhancement of Existing Hydrothermal Reservoirs

One remaining area of research is the serious global issue of declining heat production from existing geothermal reservoirs. At the same time, geothermal energy facilities are faced with the challenge of disposing of extractive water after its heat has been used for electricity generation or local heating. Such water can be contaminated with various minerals making their discharge to surface waters an environmental issue. For this reason many administrations have required by law that an injection well must be produced to provide a return path for extracted water, as illustrated in Fig. 6.13.

However there are concerns about the potential cooling effects of re-injected water on the reservoir, since discharged water is generally after passage through the power plant cooling tower, and therefore quite low temperature. For this reason, many geothermal facilities inject the extracted water *downstream* of the reservoir. This avoids the danger of too much cooling in the reservoir but this may lead to inadequate water flows. We thus briefly consider this issue.

The reservoir system with reinjection shown in Fig. 6.13 can be considered as analogous to the artificial water circulation system illustrated in Fig. 6.6. For existing hydrothermal systems, it is thus proposed to utilize the reinjection in order to establish a water circulation loop just like the borehole systems connected with a fractured reservoir created by hydraulic stimulation. The implementation of reinjection should be useful to mitigate and reduce declining heat production in the hydrothermal system provided that the conditions of reinjection (such as temperature and flow rate) and its location are properly designed with respect to the heat extraction rate. The simulation code, FRACSIM-3D as described previously may offer a useful tool for the design of such reinjection strategies.

In addition to numerical simulation code, a mathematical model based on fractional derivatives has been investigated in order to characterize subsurface mass and fluid flow in inhomogeneous and complex rock masses (Fomin et al. 2005, 2011). Numerical flow models which explicitly account for heterogeneities such as natural fractures often require detailed knowledge of the subsurface structure and/or systematic data sets of field flow testing in order to determine the spatial distribution of heterogeneities. Execution of numerical simulations based on such a flow model also requires relatively large computer capacity and long computation times. The fractional derivatives based mathematical model is expected to provide a simple and useful tool to analyze the mass and heat transport in complex reservoir systems.

It is often pointed out that the flow behaviour in the vicinity of wellbores dominates the overall flow impedance of the hydrothermal system because of its concentrated and high flow rate. Mineral depositions and plugging may be anticipated to take place along the flow path at wellbores, reducing permeability. Thus, an improvement in permeability near the wellbore is expected to enhance greatly the fluid conductance of the reservoir. Hydraulic stimulation of wellbores may provide a very effective approach for this purpose. The operation of hydraulic stimulation is expected to increase the aperture of pre-existing fractures intersecting the wellbore and to connect the wellbore with isolated natural fractures, leading to enhanced water permeability in the vicinity of the wellbore. Hydraulic stimulation may be useful not only for the stimulation of production wells, but also in reinjection wells. Thus, the technology developed for creating man-made reservoir systems and relevant numerical simulation models can be utilized to combine the existing reservoir with an artificial fracture system in order to mitigate the decline in the heat production. This strategy would reduce the uncertainty associated with the development of many geothermal energy extraction systems.

6.7 Conclusion

It has been said that the underground (or ‘inner space’) just below us is less studied than the universe. One of the primary reasons for this may be its uncertainty due to the complexity of the subsurface structure including the complicated distribution of natural fractures. Nonetheless the underground provides a safe and resilient space for energy systems which can be truly harmonized with the environment. This chapter describes a methodology for the development of geothermal energy extraction with a special focus on designs for engineered geothermal reservoirs. It is emphasized that the engineering methodology enables artificial reservoir systems to be created in the subsurface structure. A numerical simulation model which expresses the complex distribution of natural fractures on the basis of fractal geometry has been introduced and applied to field experiment with the objective of developing a quantitative basis for designing geothermal reservoirs in the complex natural system. It is also proposed that this engineering methodology could also be applied in order to tackle the common issue of the declining heat production in existing reservoirs.

References

Armstead, H., and J. Tester. 1987. *Heat mining—A new source of energy*. New York: E. & F.N. SPON.

Colp, J. L. 1982. Final report—Magma energy research project. Sand 82-2377, Sandia National Laboratories, Albuquerque, NM.

Fomin, S., V. Chugunov, and T. Hashida. 2005. The effect of non-Fickian diffusion into surrounding rocks on contaminant transport in a fractured porous aquifer. *Proceedings of Royal Society A* 461:2923–2939.

Fomin, S., V. Chugunov, and T. Hashida. 2011. Non-Fickian mass transport in fractured porous media. *Advances in Water Resources* 34:205–2114.

GEA. 2012. Geothermal Energy Association. Geothermal basics. http://geo-energy.org/reports/Gea-GeothermalBasicsQandA-Sept2012_final.pdf. Accessed 21 Nov 2014.

Grant, M., I. Donaldson, and P. Bixley. 1982. *Geothermal reservoir engineering*. New York: Academic Press.

Hashida, T., and T. Takahashi. 2003. Supercritical water/rock interactions and generation of artificial geothermal reservoirs in deep-seated high temperature rock masses. Proceedings of International Conference on coupled T-H-M-C processes in Geo-systems: Fundamentals, modelling, experiments & applications, 659–664.

Hashida, T., K. Hayashi, H. Niitsuma, K. Matsuki, N. Tsuchiya, and K. Nakatsuka. 2000. Investigation of heat extraction from supercritical geothermal reservoirs. *Proceedings of World Geothermal Congress* 2000:3725–3730.

IEA. 2010a. Geothermal essentials.

IEA. 2010b. Energy technology perspectives, 2010. OECD/IEA, Paris.

IEA. 2011. Technology roadmap—Geothermal heat and power. http://www.iea.org/publications/freepublications/publication/Geothermal_Roadmap.pdf. Accessed 21 Nov 2014.

IPCC. 2011. Summary for Policymakers. IPCC special report on renewable energy sources and climate change mitigation. Cambridge University Press.

Jing, Z., J. Willis-Richards, K. Watanabe, and T. Hashida. 2000. A three-dimensional stochastic rock mechanics model of engineered geothermal systems in fractured crystalline rock. *Journal of Geophysical Research* 105 (B10): 23663–23679.

Jing, Y., Z. Jing, J. Willis-Richards, and T. Hashida. 2014. A simple 3-D thermoelastic model for assessment of the long-term performance of the Hijiori deep geothermal reservoir. *Journal of Volcanology and Geothermal Research* 269:14–22.

Kuriyagawa, M., and N. Tenma. 1999. Development of hot dry rock technology at the Hijiori test site. *Geothermics* 28:627–636.

Potter, R., E. Robinson, and M. Smith. 1974. Method of extracting heat from dry geothermal reservoirs. US Patent #3.786.858.

Takahashi, H., and T. Hashida. 1992. New project for Hot Wet Rock geothermal reservoir design concept. Proceedings of the 17th workshop on geothermal reservoir engineering, Standord University, 39–44.

Teplow W., B. Marsh, J. Hullen, P. Spielman, M. Kaleinkini, D. Fitch, and W. Richard. 2009. Ductile melt at the Puna Geothermal Venture Wellfield, big island of Hawaii. *GRC Transactions* 33:989–994.

Tester, J., D. Brown, and R. Potter. 1989. Hot dry rock geothermal energy; a new energy agenda for the 21st century. LANL Report, LA-11514-MS.

Tester, J., et al. 2005. *Sustainable energy—Choosing among options*. MIT Press, 850 pp. ISBN 0-262-20153-4.

Tester, J., et al. 2006. The future of geothermal energy: Impact of enhanced geothermal systems on the United States in the 21st century. Massachusetts Institute of Technology, 358 pp. geothermal.inel.gov/publications/future_of_geothermal_energy.pdf.

Watanabe, K., and H. Takahashi. 1995. Fractal geometry characterization of geothermal reservoir fracture networks. *Journal of Geophysical Research* 100:521–528.

White, D. 1967. Some principles of geyser activity, mainly from Steamboat Springs, Nevada. *American Journal of Science* 265:641–684.

White, D., L. Muffler, and A. Truesdell. 1971. Vapor-dominated hydrothermal systems compared with hot-water systems. *Economic Geololy* 66 (1): 75–97.

Willis-Richards, J., K. Watanabe, and H. Takahashi. 1996. Progress toward a stochastic rock mechanics model of engineered geothermal systems. *Journal of Geophysical Research* 101 (B8): 17481–17496.