Challenges in the Assessment and Classification of Enhanced/Engineered Geothermal System Resources

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ABSTRACT

Resource assessment and classification is a key element in the characterization and development of energy resources, including geothermal energy. Stakeholders at all levels of government, within the geothermal industry, and among the general public need to be able to understand basic characteristics of the geothermal resource, such as location, quality, feasibility of development, and potential impacts. A variety of mechanical, chemical and thermal approaches to reservoir stimulation have been proposed and tested over more than three decades of research on Enhanced/Engineered Geothermal Systems (EGS) technology, with the primary focus at present on enhancing fracture permeability by elevating fluid pressure sufficiently to induce shear failure along pre-existing natural fractures. A critical issue in assessing the potential EGS resource is quantifying R_g, the geothermal recovery factor, which is defined as the ratio of produced thermal energy to the thermal energy contained in the fractured volume comprising the reservoir. Recent EGS resource assessments have incorporated one of two approaches. The first approach is based on an analogy with thermal energy recovery from naturally fractured geothermal reservoirs and sets R_g as a constant with a mean value of 0.05. The second approach assumes that a constant amount of thermal energy is recovered during the life of a project, regardless of the temperature of the reservoir. Models for the development of fracture permeability from hydraulic stimulation indicate that production from EGS reservoirs will be sensitive to the processes of shear fracture formation and closure at high levels of effective stress. The implications of these models are that reservoir performance (and consequently R_g) will also depend on in situ stress, depth, and rock properties. This dependence may limit the viability of EGS resource development at great depth in the crust and needs to be incorporated in EGS assessment methods.

Introduction

Conventional geothermal resources are formed due to hydrothermal fluid circulation that results from the convergence of high temperatures and high permeability, typically fracture permeability produced as a result of recent or active faulting. Enhanced/Engineered Geothermal Systems (EGS) are geothermal

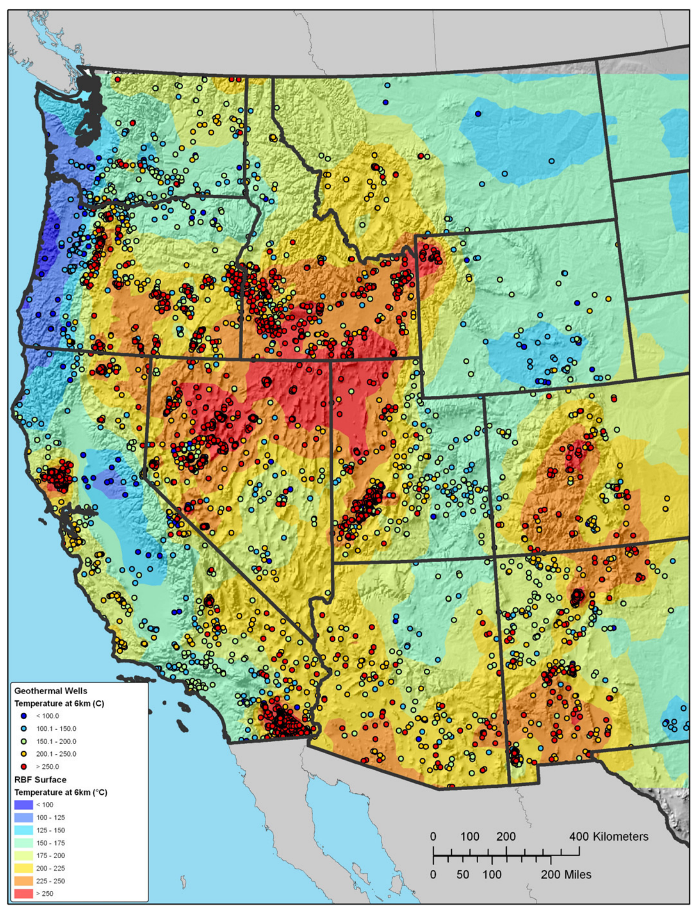

Figure 1. Map showing an example model for the estimated distribution of temperature at a depth of 6 km in the western United States.

resources that require some form of engineering to develop the permeability necessary for the circulation of hot water or steam and the recovery of heat for commercial applications (DOE, 2008). Because exploitation of EGS resources involves the augmentation or creation of permeability *in situ*, the presence of elevated temperatures at drillable depths is the dominant factor controlling the quality of the resource, provided stimulation of the host rock is technically viable.

Under the assumption of successful implementation of EGS technology, provisional estimates of EGS electric power resource potential in the western United States, where high crustal heat flow is most favorable for EGS development (Figure 1), were included in the recent USGS geothermal resource assessment (Williams, et al., 2008a). In this assessment, models for the extension of geothermal thermal energy recovery techniques into regions of hot but low-permeability crust down to a depth of 6 km yield an estimated mean electric power resource on private and accessible public land of approximately 520,000 MWe. This is nearly half of the current installed electric power generating capacity in the United States and an order of magnitude larger than the conventional geothermal resource.

Another recent EGS resource assessment was produced by a panel of experts convened by the Massachusetts Institute of Technology (MIT) under Department of Energy (DOE) sponsorship (Tester et al., 2006). Their report provides estimates of the EGS potential for entire continental United States to a depth of 10 km. The portion of this assessment covering the same western states as the USGS assessment and over approximately the same 6 km depth range varies between 200,000 and 2,000,000 MWe, depending on the assumptions applied for the recoverability of heat from the Earth's crust. Although the mean USGS estimate lies within the range of values produced by the MIT panel, the wide variation highlights significant uncertainties in the potential recovery of useful heat from the Earth's upper crust. Understanding and reducing these uncertainties is of critical importance to the successful development of the EGS resource.

The Recovery of Heat from Geothermal Reservoirs

The potential energy recovery from a geothermal reservoir depends on the thermal energy, q_R, present in the reservoir, the amount of thermal energy that can be extracted from the reservoir at the wellhead, q_{WH}, and the efficiency with which that wellhead thermal energy can be converted to electric power. Once the reservoir fluid is available at the wellhead, the thermodynamic and economic constraints on conversion to electric power are well known (for example, DiPippo, 2005). The challenge in geothermal resource assessment lies in quantifying the size and thermal energy of a reservoir as well as the constraints on extracting that thermal energy. In the approach applied in USGS assessments, the reservoir thermal energy is calculated as

$$q_R = \rho C V (T_R - T_0) \quad (1)$$

where ρC is the volumetric specific heat of the reservoir rock, V is the volume of the reservoir, T_R is the characteristic reservoir temperature, and T_0 is a reference, or dead-state, temperature. The thermal energy that can be extracted at the wellhead is given by

$$q_{WH} = m_{WH}(h_{WH} - h_0) \quad (2)$$

where m_{WH} is the extractable mass, h_{WH} is the enthalpy of the produced fluid, and h_0 is the enthalpy at some reference temperature (typically 15°C). The wellhead thermal energy is then related to the reservoir thermal energy by the recovery factor, R_g, which is defined as

$$R_g = q_{WH} / q_R \quad (3)$$

Inherent in these equations is a geometrical concept of the reservoir that allows calculation of a volume and an estimate of the ability to extract hot fluid from the volume. In ideal cases values for R_g as large as 0.5 to 0.6 have been derived from analytical and numerical models of heat extraction from a geothermal reservoirs through a "cold sweep" process, in which the hot reservoir water is gradually replaced by colder water through natural recharge and/or artificial injection (e.g., Nathenson, 1975; Muffler and Cataldi, 1978; Muffler, 1979; Sanyal and Butler, 2004). Analyses of production data from naturally fractured reservoirs indicate that R_g typically varies between 0.05 and 0.2 (e.g., Lovekin, 2004; Williams, 2004). These lower values for R_g reflect the thermal effects of heterogeneities in the spatial distribution and flow characteristics of permeable fractures in the reservoirs (Bodvarsson and Tsang, 1982; Pruess and Bodvarsson, 1984; Williams, et al., 2007, 2008b).

The 2008 USGS geothermal resource assessment applied this approach for both naturally-occurring geothermal reservoirs (both identified and undiscovered) and EGS. The resource estimate for EGS incorporated three significant changes relative to natural geothermal systems. First, the potential EGS reservoir volume in the western United States for electric power generation was assumed to be the portion of the Earth's crust above 6 km depth in which the temperature exceeds 150°C (Figure 1), reduced by the area occupied by public lands closed for geothermal development, such as national parks. Second, the available reservoir volume was reduced by a factor ranging from 6 to 12 to allow for the fraction of rock in situ that would either be lithologically unsuitable for EGS development or left unfractured for the lifetimes of first generation reservoirs in order to preserve low permeability barriers between zones of contrasting temperature and/or pressure. Third, the value of R_g was varied within the range of 0.025 to 0.075, with an average value of 0.05, at the low end of the observed range for naturally-fractured geothermal reservoirs. This value reflects the observation that, for EGS experiments conducted to date, the stimulated volume indicated by microseismicity during reservoir development is significantly larger than the effective reservoir dimensions under production (e.g., Williams et al., 2008b).

The analysis applied in the 2006 MIT report follows a somewhat different approach in the definition of terms and analysis of power potential, but the basic concepts are similar. For example, the recovery factor was given as

$$F_R = \frac{q_{rec}}{q_{tot}} = \frac{V_{act}(T_R - T_a)}{V_{tot}(T_R - T_{ref})} \quad (4)$$

where F_R is the recovery factor, q_{rec} is the recovered thermal energy, q_{tot} is the total thermal energy in the reservoir, V_{act} is the volume of the active, or producing portion of the reservoir, V_{tot} is the total reservoir volume and T_a is the average reservoir temperature at abandonment (Tester et al., 2006). For quantitative estimates, equation (4) was simplified to

$$F_R = \phi_{eff}\left(\frac{10°C}{T_R - T_{ref}}\right), \quad (5)$$

in which ϕ_{eff} was specified to be either 0.02 or 0.2. In this formulation ϕ_{eff} is equivalent to the volume fraction estimate applied separately in the USGS EGS assessment, and the temperature ratio to the right of ϕ_{eff} represents the true thermal recovery factor within the active reservoir. The most significant difference between the two recovery factor approaches is the role of temperature. In the USGS and other assessments for both natural and EGS reservoirs, the recovery factor has a range of values independent of temperature, whereas the recovery factor used in the MIT assessment decreases with increasing reservoir temperature, resulting in a constant amount of heat recovered at all temperatures.

In both assessment approaches the geothermal recovery factors are insensitive to the state of stress and rock composition. Depth-dependence is only incorporated indirectly, in the USGS assessment through the restriction to a maximum depth of 6 km and in the MIT assessment through the inverse temperature-dependence as an approximate analogue of depth-dependence due to the general increase of temperature with depth in the crust (Williams, 2010). Although they have not been utilized to date for regional resource assessments, existing models for the effect of lithology and confining pressure on the permeability of induced shear fractures provide some quantitative constraints on the relative quality of the EGS resource over a range of depths and contrasting tectonic settings. The section below examines one of these models for induced fracture permeability and evaluates the significance of their predictions for developing an improved EGS resource assessment methodology.

The Potential Influence of Stress and Lithology on EGS Resources

Because of the increase of temperature with depth due to the conductive geothermal gradient, exploiting most of the higher temperature EGS resource involves drilling to greater depth. Consequently, a definitive evaluation of EGS potential should include the full range of thermal, mechanical, hydraulic, and chemical processes that can influence both natural and induced fracture permeability at elevated temperature and stress (e.g., Taron et al., 2009; Taron and Elsworth, 2009). For simplicity this paper focuses on mechanical effects except for the temperature-dependence of fluid density and viscosity.

From the perspective of reservoir performance, the key parameter in evaluating potential stress and temperature sensitivity of potential production is the hydraulic conductivity, K, which is defined as

$$K = \frac{k\rho g}{\mu} \quad (6)$$

where k is the permeability, ρ the fluid density, g the acceleration due to gravity and μ the viscosity. In general, natural fracture permeability decreases with increasing effective normal stress on the fractures (e.g., Walsh, 1981), and this is also true for the permeability of shear fractures induced through hydraulic stimulation (Raman et al., 2002). For these shear fractures, one proposed relationship between permeability and effective normal stress due to dilation of the fracture during slip (Figure 2) is given as

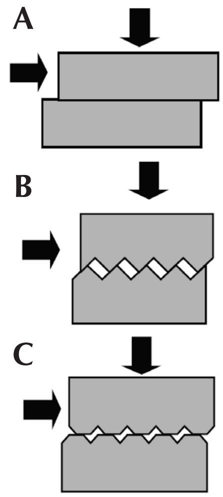

Figure 2. Schematic showing the creation of permeability due to slip on a pre-existing fracture (modified from Hack, 2008). (a) Slip on perfectly smooth surfaces with no dilation. (b) Dilation during the start of slip. (c) Residual fracture porosity after the shearing of asperities during slip.

$$\left(k\right)^{1/3} \propto a = \frac{a_0 + U\tan(\phi_{dil})}{1 + 9\sigma' / \sigma'_{nref}} \quad (7)$$

where a is the fracture aperture, a_0 is the aperture at some reference state, U is the shear displacement on the fracture, ϕ_{dil} is the shear dilation angle, σ' is the effective normal stress on the fracture, and σ'_{nref} is a reference stress defined as the effective normal stress at which the fracture closes to 10% of its original aperture (Willis-Richards et al., 1996). An alternative but similar approach to predicting induced fracture permeability is derived from joint roughness observations (Olsson and Barton, 2000; Barton and Bandis, 1985) but is not included in this paper.

In actual EGS stimulation operations, the reservoir scale change in permeability will be the result of a large number of individual slip events of varied size occurring on fractures of diverse characteristics which can best be modeled in a statistical fashion (e.g., Kohl and Megel, 2007). However, to the extent that large-scale variations in crustal properties will influence the distribution of fracture aperture changes through relationships like Equation 7, investigating the sensitivity of the relevant factors to these variations will provide insights into the processes controlling the quality of the EGS resource.

Specifically, although the exact relations are not well-constrained (e.g., Willis-Richards, 1996; Chen et al., 2001) U, ϕ_{dil} and σ'_{nref} are functions of the elastic moduli of the reservoir rock, which in turn are functions of mineral composition, grain size and fabric. For example, σ'_{nref} should be sensitive to Young's modulus and Poisson's ratio (Brown and Scholz, 1985). Under the assumption that the state of stress in the crust is near or at the point of frictional failure for the local tectonic stress regime, σ' should reflect the normal stress on pre-existing shear fractures, which will be determined by the predominant mode of faulting (e.g., Lachenbruch and McGarr, 1990).

On the basis of these observations relative changes in EGS reservoir permeability can be evaluated. For example, in the transition from extensional through strike-slip to compressional tectonic environments, the vertical gradient of the normal stress on fractures optimally-oriented for shear failure with a coefficient of friction equal to 0.6 ranges from 8 (extensional) through 15 (strike-slip) to 25 (compressional) MPa/km (Lachenbruch and

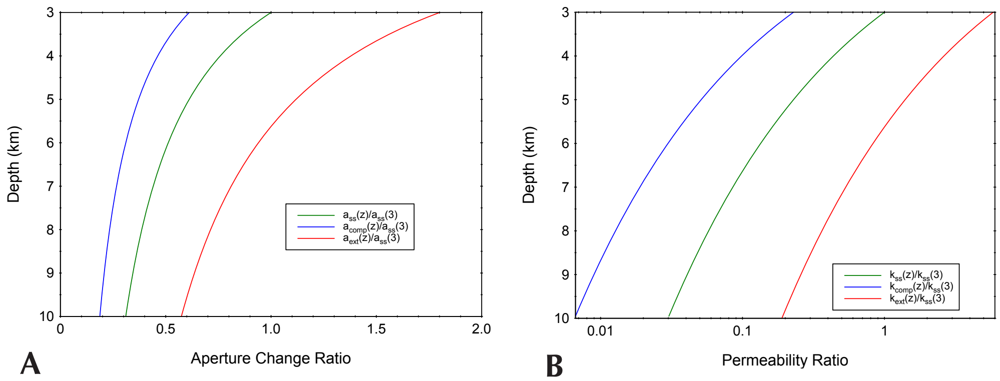

Figure 3. Change in (a) fracture aperture and (b) permeability with depth for three stress regimes expressed as a ratio relative to the value for a strike-slip regime at a depth of 3 km.

McGarr, 1990). The relative effects of this variation in σ' on fracture aperture and permeability is shown in Figure 3, with the results shown as a ratio relative to the value at a depth of 3 km in a strike-slip faulting environment. The results show the potential for changes in induced fracture permeability of more than an order of magnitude at a given depth solely due to the effects of changing stress regime and over the depth range from 3 to 10 km for the same stress regime.

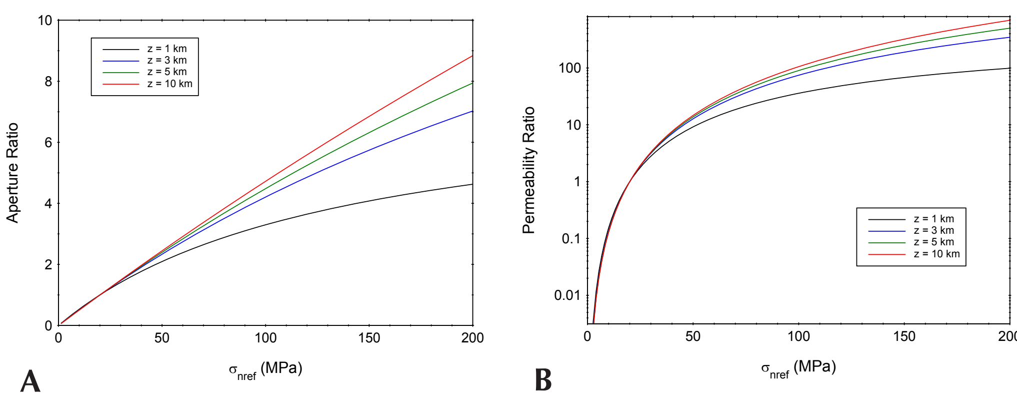

Figure 4. Change in (a) fracture aperture and (b) permeability with σ'_{nref} relative to a reference value of σ'_{nref} =20 MPa and a depth of 3 km.

Figure 4 shows another implication of Equation 7 for changes in relative permeability due to variations in σ'_{nref}. Estimates of σ'_{nref} from EGS sites at Rosemanoes and Fenton Hill average close to 20 MPa (Willis-Richards et al., 1996), but Chen et al. (2001) suggest that true values may be an order of magnitude greater, a result consistent with the inferred characteristics of natural, partially mineralized fractures (Rutqvist and Stephensson, 2003). Within this potential range for σ'_{nref} of less than 20 to 200 MPa, both the induced shear fracture aperture and resulting permeability vary over a wide range and suggest that higher values of σ'_{nref} will be necessary for EGS reservoirs to be viable at great depth. Even allowing for the effect of temperature and pressure on water density and viscosity in the hydraulic conductivity (Wakasugi, 1990), the relative change in reservoir flow characteristics with depth is significant (Figure 5).

The potential relative changes in permeability predicted by sensitivity to effective normal stress and fracture compliance need to be quantified in absolute terms before they can be incorporated into predictive models for EGS potential based not only on subsurface temperatures but also the regional state of stress and the elastic moduli of crustal rocks in situ. The limited information available from EGS experiments is a start on developing quantitative constraints on the EGS resource, but a comprehensive suite of laboratory and field experiments on varied rock types over a range stress states and pre-existing permeabilities, is necessary for site-specific, quantitative predictions. With existing modeling results limited to a narrow range of reservoir conditions and rock properties and the absence of long-term EGS field experience, the most that can be stated at this point is that a significant decrease of induced permeability with depth could hamper efforts to extend EGS technology to depths beyond the deepest existing natural geothermal reservoirs, which have yet to be exploited below approximately 6 km (Kobayashi, 2000).

Conclusions

Modeling studies and limited field observations indicate that, in addition to in situ temperature, variations in rock type and in situ stress will have a significant impact on the quality and potential development of the EGS resource. The geothermal recovery factor, R_g, is likely to decline with increasing effective stress, and to the extent that the increase in effective stress with depth corresponds with increasing temperature in the Earth's crust, the exploitation of deep, high-temperature EGS resources may be limited. The key challenge for improved EGS resource assessments is acquiring and interpreting comprehensive laboratory and field data that can provide quantitative constraints on the recovery of heat from EGS reservoirs.

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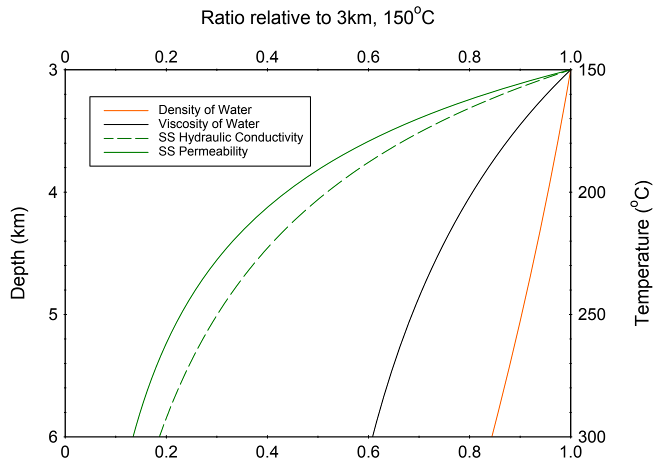

Figure 5. The relative change in hydraulic conductivity profiles for EGS reservoirs based on modeled profiles for permeability, water viscosity and water density over the depth and temperature interval from 3 km and 150°C to 6 km and 300°C for a strike-slip faulting regime.

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