

## Developing Improved Methods for the Assessment of Enhanced Geothermal Systems

Colin F. Williams and Jacob DeAngelo

U.S. Geological Survey, Menlo Park, CA 94025

colin@usgs.gov

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### ABSTRACT

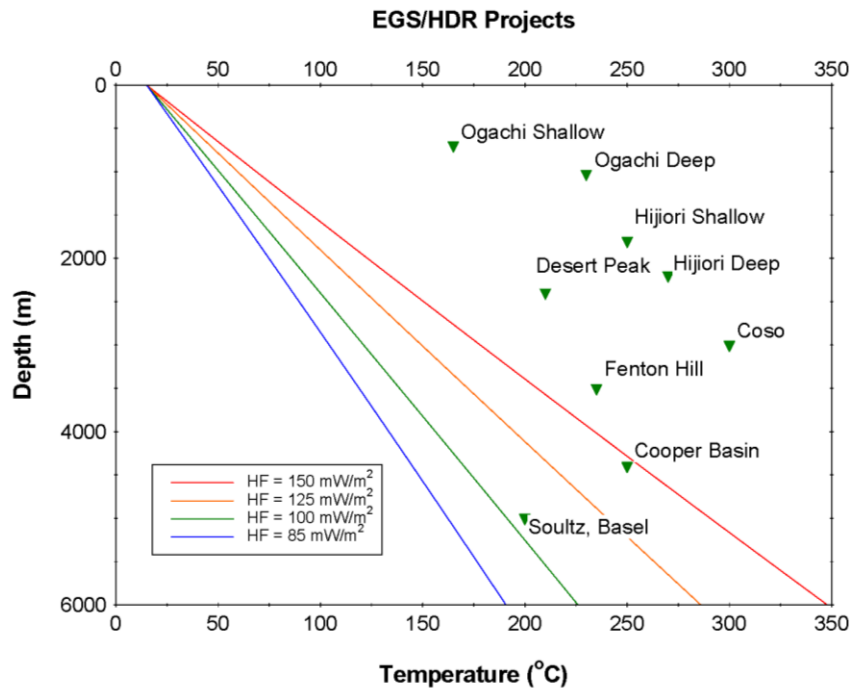
The successful implementation of Enhanced Geothermal Systems (EGS) technology has the potential to dramatically expand both the magnitude and spatial extent of geothermal energy production, and the U.S. Geological Survey (USGS) has been working to improve assessment methodology for an updated EGS resource assessment of the United States. However, a number of outstanding scientific and technical issues must be resolved in order to ensure the accuracy and reliability of this assessment. Among these are determining those conditions under which it is possible to replicate the high average permeability (approximately  $10^{-14}$  to  $10^{-12}$  m<sup>2</sup>) characteristic of natural hydrothermal reservoirs, evaluating the likely heterogeneity of fracture permeability within EGS reservoirs and its influence on the geothermal recovery factor,  $R_g$ , which is defined as the ratio of produced thermal energy to the thermal energy contained in the stimulated volume comprising the reservoir, and improving estimates of temperature in the upper crust to better quantify the thermal energy available at those depths viable for EGS reservoir creation. Models for the development of fracture permeability from the shear slip along pre-existing natural fractures induced by hydraulic stimulation indicate that production from EGS reservoirs will be sensitive to the influence of effective stress and rock properties on the processes of shear fracture formation and closure. Comparison of model parameters with results from EGS field experiments and demonstration projects suggests that sufficient permeability may be difficult to attain through shear stimulation at depths greater than approximately 5 km, particularly in regions characterized by high normal stress on pre-existing faults and fractures. Although there are significant gaps in the spatial coverage of heat flow measurements in much of the United States and some uncertainty in the estimation of thermal properties at depth, analysis of the existing thermal data indicates that even with the possible constraints outlined above, large areas of the western United States will be suitable for EGS development. However, this preliminary interpretation is compromised by the limited number of cases in which model predictions can be compared to laboratory or in situ data. 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 in diverse settings.

### 1. 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 consequence of recent or active faulting. Enhanced/Engineered Geothermal Systems (EGS) are geothermal 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*. A series of resource assessments have highlighted that implementation of Enhanced Geothermal Systems (EGS) technology has the potential to dramatically expand both the magnitude and spatial extent of geothermal energy production, both in the United States (e.g., Tester et al., 2006; Williams et al., 2008) and internationally (Beardmore et al., 2010).

These assessments, although incorporating significant uncertainty in the physical parameters involved in EGS power production, did not include any systematic correlation between the potential EGS geothermal recovery factors and spatial variations in the state of stress and rock composition. For example, for the United States assessments, depth-dependence of production viability due to increasing effective stress and the cost of drilling with depth were incorporated indirectly, in the USGS assessment (Williams et al., 2008) through the restriction to a maximum depth of 6 km and in the MIT assessment (Tester et al., 2006) through the same restriction extended to 10 km. A number of outstanding scientific and technical issues must be addressed in order to improve the accuracy and reliability of future assessments, and the USGS has been working on updated assessment methods that better incorporate the physical constraints on EGS development. Among these issues are (1) identifying and characterizing those parts of the upper crust with temperatures high enough for geothermal power production, (2) determining the conditions under which EGS stimulation can replicate the permeability characteristic of natural geothermal reservoirs, and (3) evaluating the potential for maintaining effective EGS reservoir permeability over the planned lifetime of the reservoir.

Although there are gaps in the spatial coverage of heat flow measurements in much of the United States and uncertainty in the estimation of thermal properties at depth, analysis of the existing thermal data indicates that much of the western United States and large areas in the rest of the country will be suitable for EGS development in both crystalline basement and deep sedimentary basins, provided the rocks at depth are viable for reservoir creation (Williams and DeAngelo, 2011). The longevity of natural geothermal reservoirs, including the successful modification of injection water chemistry to maintain injectivity, suggests that similar procedures will be available to maintain EGS reservoirs. One remaining critical element, and the focus for this paper, is determining those conditions under which it is possible to replicate the high average permeability characteristic of natural geothermal reservoirs.

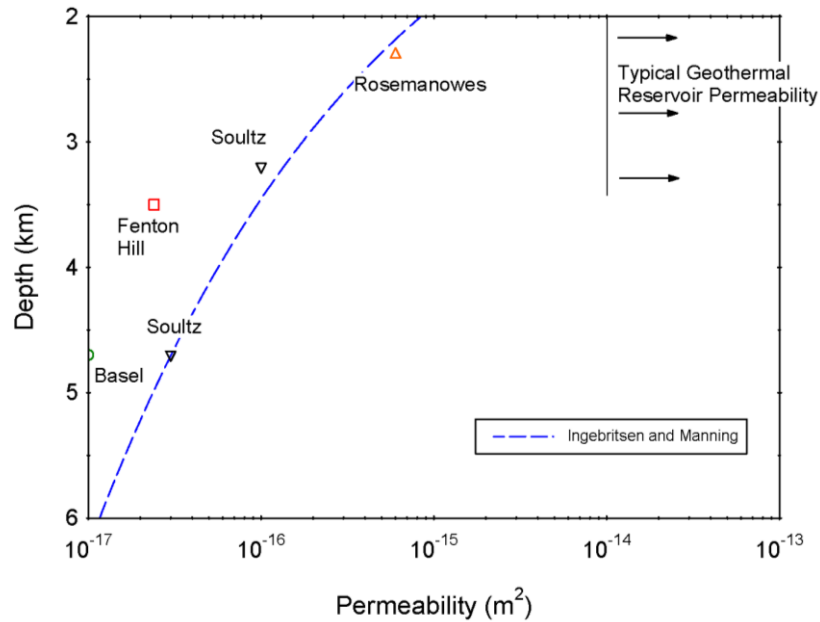


**Figure 1: Temperatures at EGS experiment and development sites, along with example temperature profiles with depth in crystalline basement for different values of heat flow. Note that most EGS sites are in locations with anomalously high temperatures at relatively shallow depths.**

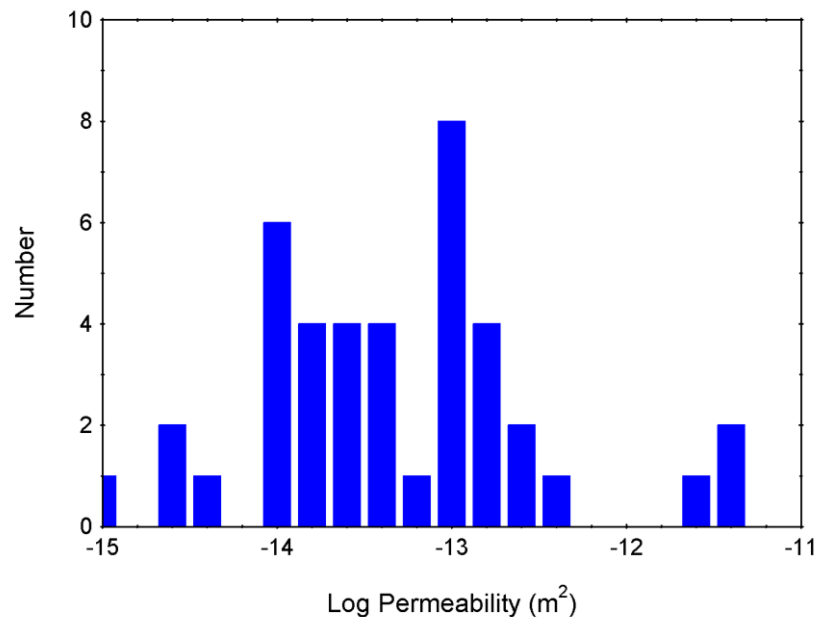
## 2. PERMEABILITY IN THE CRUST: MODELS AND OBSERVATIONS AT EGS SITES

To date, most EGS projects have been located on the margins of hydrothermal systems, where high temperatures are encountered at relatively shallow depths (Figure 1). The crust below ~5km, where most of the conductive EGS thermal resource base resides, is essentially uncharacterized. In addition, with the exception of the Cooper Basin in Australia, which is in a compressional stress regime but with near lithostatic fluid pressures, experimental EGS sites have been located in areas of mixed extensional/strike-slip or purely strike-slip stress regimes. Consequently, our knowledge of the effectiveness of hydraulic stimulation to develop permeability in crystalline basement is limited to conditions of low to moderate effective normal stress. Developing EGS at greater depth or in areas of compressional faulting will require successful stimulation at higher effective normal stress, which highlights the need to characterize pre-existing permeability and stress conditions at depth as well as quantify the effectiveness of EGS stimulation techniques under varying effective normal stress.

Figure 2 shows values for pre-existing permeability at selected EGS test sites from measurements and model estimates as determined by Nathenson (1999), Sausse et al. (2006), and Miller (2014), as well as the general permeability-depth relationship for the upper continental crust developed by Ingebritsen and Manning (1999). The EGS site permeabilities follow the general trend of the Ingebritsen and Manning curve in both magnitude and the rate of decrease with depth, a decrease that most likely reflects combined mechanical and chemical processes reducing fracture aperture due to increasing normal stress and temperature with depth. These pre-stimulation permeabilities are one to five orders of magnitude lower than the natural geothermal reservoir permeabilities reported by Bjornson and Bodvarsson (1990) (Figure 3), highlighting the degree of permeability increase required for EGS reservoirs. It should also be noted that these values of permeability, as well as the values determined post-stimulation, are average values derived for highly heterogeneous fractured media, and as such can have uncertainties of as much as an order of magnitude. 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 next section examines three of these models for induced fracture permeability and evaluates the significance of their predictions relative to observed permeability increases from EGS stimulation experiments for developing an improved EGS resource assessment methodology.



**Figure 2: Pre-stimulation permeabilities (open symbols) at selected EGS sites compared with the average permeability-depth curve for the crust derived by Ingebritsen and Manning (1999) and typical geothermal system permeabilities shown in Figure 3. EGS site permeabilities taken from Miller (2014), Nathenson (1999) and Sausse et al. (2006).**



**Figure 3: Measured permeabilities in natural geothermal reservoirs as compiled by Bjornsson and Bodvarsson (1990).**

### 3. 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 a larger fraction of the higher temperature EGS resource involves drilling and stimulating to progressively 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). As noted above, this paper focuses on mechanical effects as hydraulic stimulation (both tensile and shear stimulation) has been the primary mode of EGS reservoir creation in experiments to date.

From the perspective of reservoir performance, the key parameter in evaluating potential production viability through hydraulic stimulation is the permeability,  $k$ , which in three-dimensional equivalent continuum models for fractured rock masses is considered

proportional to the cube of the fracture hydraulic aperture (Rutqvist and Stephansson, 2003). 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, Willis-Richards et al. (1996) developed a relationship between permeability and effective normal stress due to dilation of the fracture during the slip induced by elevated the fluid pressure in which the amount of fracture opening is defined in terms of a shear dilation angle. This relationship is given as

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

where  $a$  is the fracture aperture,  $a_0$  is the aperture at some reference state,  $U$  is the shear displacement on the fracture,  $\phi_{dil}$  is the shear dilation angle,  $\sigma'$  is the effective normal stress on the fracture, and  $\sigma'_{nref}$  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 was derived from joint roughness observations by Barton (Olsson and Barton, 2000; Barton et al., 1985) and can be represented as

$$(k)^{1/3} \propto \left( \frac{E^2}{JRC^{2.5}} \right) \quad (2)$$

for which

$$E = E_0 + U \tan \left[ \frac{JRC}{2} \log_{10} \left( \frac{JCS}{\sigma'_n} \right) \right] \quad (3)$$

and JRC is the Joint Roughness Coefficient,  $E$  is the mechanical fracture aperture, and JCS is the Joint Compressive Strength. Walsh (1981) represented the effective stress sensitivity of fracture permeability as

$$\left( \frac{k}{k_0} \right)^{1/3} = 1 - m \ln \left( \frac{\sigma'}{\sigma'_0} \right) \quad (4)$$

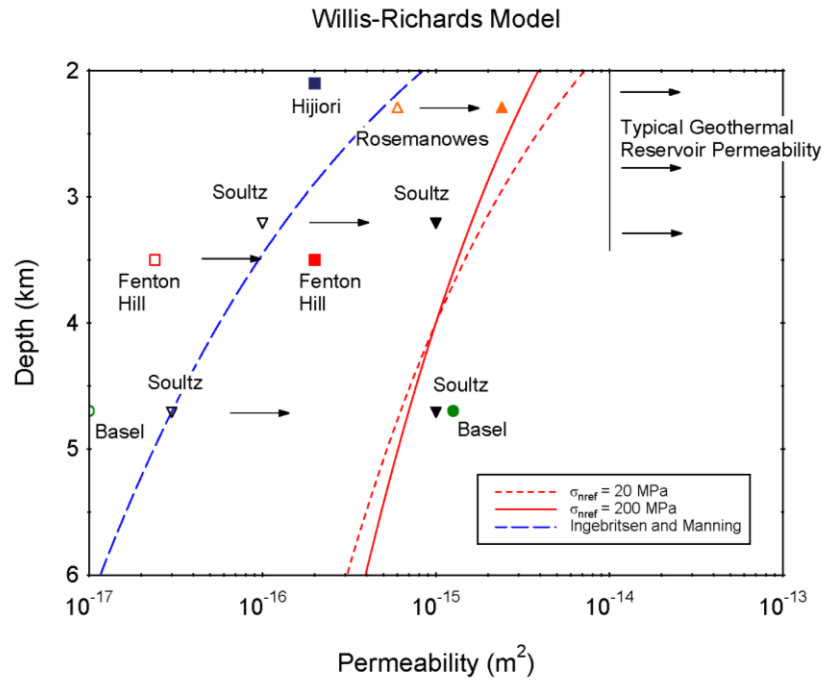
where  $m$  is a material constant influenced by fracture geometry, Young's modulus, and Poisson's ratio (see also Brown and Scholz, 1985 and Cipolla et al., 2008).

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 Equations 1 through 4, 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., 2000) factors such as  $\phi_{dil}$ ,  $\sigma'_{nref}$ , JRC, JCS, and  $m$  are functions of the elastic moduli of the reservoir rock, which in turn are functions of mineral composition, grain size and fabric. For example,  $\sigma'_{nref}$  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,  $\sigma'$  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).

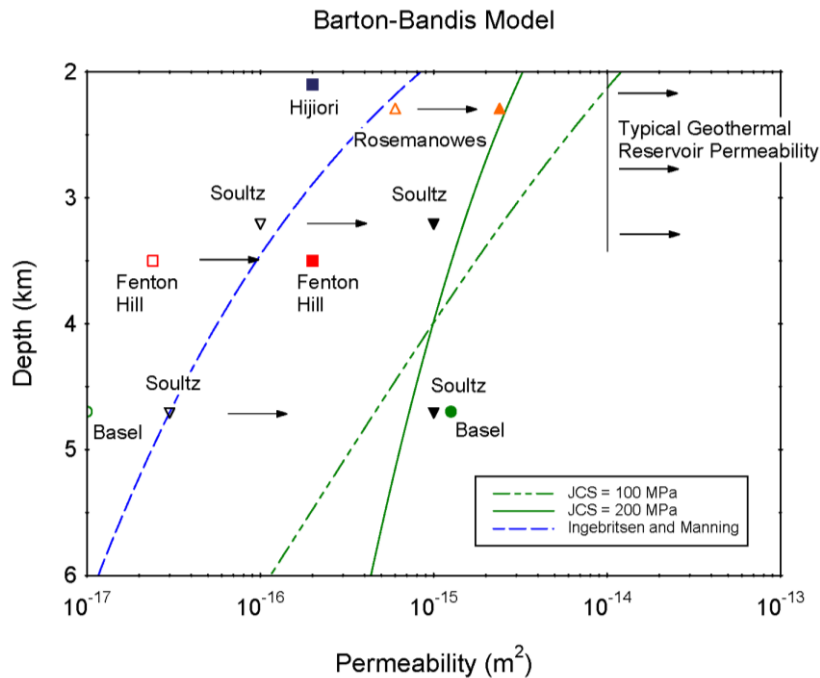
On the basis of these models potential relative changes in EGS reservoir permeability can be evaluated. Figure 4 shows another implication of Equation 1 for changes in relative permeability due to variations in  $\sigma'_{nref}$ . Estimates of  $\sigma'_{nref}$  from EGS sites at Rosemanoes and Fenton Hill average close to 20 MPa (Willis-Richards et al., 1996), but Chen et al. (2000) 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 Stephansson, 2003). Within this potential range for  $\sigma'_{nref}$  of less than 20 to 200 MPa, both the induced shear fracture aperture and resulting permeability vary over a wide range which suggests that higher values of  $\sigma'_{nref}$  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 potential relative change in reservoir flow characteristics with depth is significant.

Similar characteristics are demonstrated for variations in JCS for the Barton-Bandis model (Figure 5) and  $m$  for the Walsh model (Figure 6). All three models provide reasonable fits to the available data, indicating both limitations on absolute permeabilities to values less than natural hydrothermal systems and a significant dependence on effective normal stress. In addition to depth effects, relative changes in permeability due to a changing stress regime 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

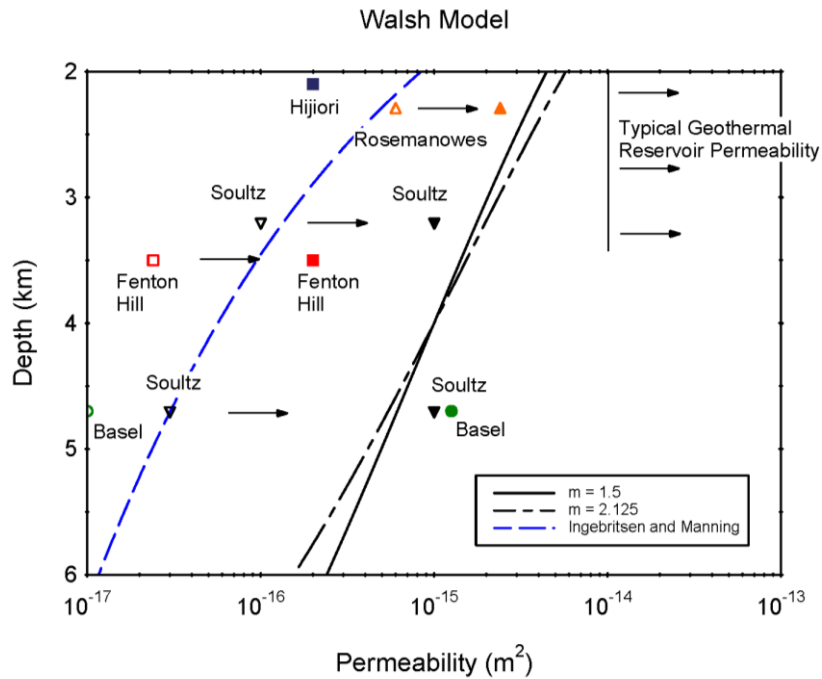
failure with a coefficient of friction equal to 0.6 ranges from  $\sim 8$  (extensional) through  $\sim 15$  (strike-slip) to  $\sim 25$  (compressional) MPa/km (Lachenbruch and McGarr, 1990). The potential relative effects of this variation in  $\sigma'$  on permeability are shown in Figure 7.



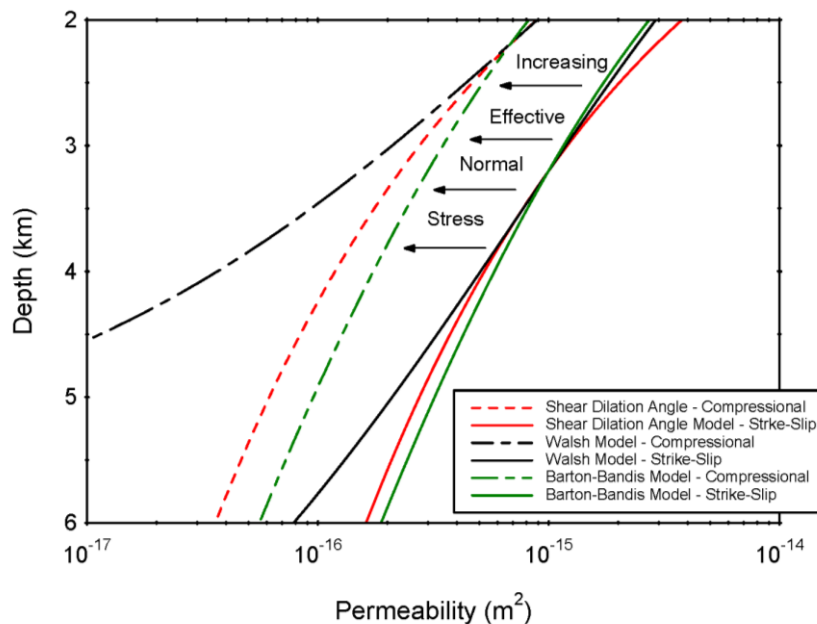
**Figure 4:** Pre- (open symbols) and post-stimulation (closed symbols) permeabilities at EGS sites along with the Ingebritsen and Manning crustal permeability curve and a model for the variation of stimulated permeability with depth in a strike-slip stress regime matched to the mean stimulated Soutz permeability at a depth of 4 km and with parameters derived from Willis-Richards et al. (1996).



**Figure 5:** Pre- (open symbols) and post-stimulation (closed symbols) permeabilities at EGS sites along with the Ingebritsen and Manning crustal permeability curve and a model for the variation of stimulated permeability with depth in a strike-slip stress regime matched to the mean stimulated Soutz permeability at a depth of 4 km and with parameters derived from Olsson and Barton (2001).



**Figure 6:** Pre- (open symbols) and post-stimulation (closed symbols) permeabilities at EGS sites along with the Ingebritsen and Manning crustal permeability curve and a model for the variation of stimulated permeability with depth in a strike-slip stress regime matched to the mean stimulated Soutz permeability at a depth of 4 km and with parameters derived from Cippolla et al. (2008).



**Figure 7:** Result of changing the stress regime from strike-slip to compressional and thus increasing the mean effective normal stress on fractures favorably oriented for shear failure for the three permeability models shown in Figures 4 through 6.

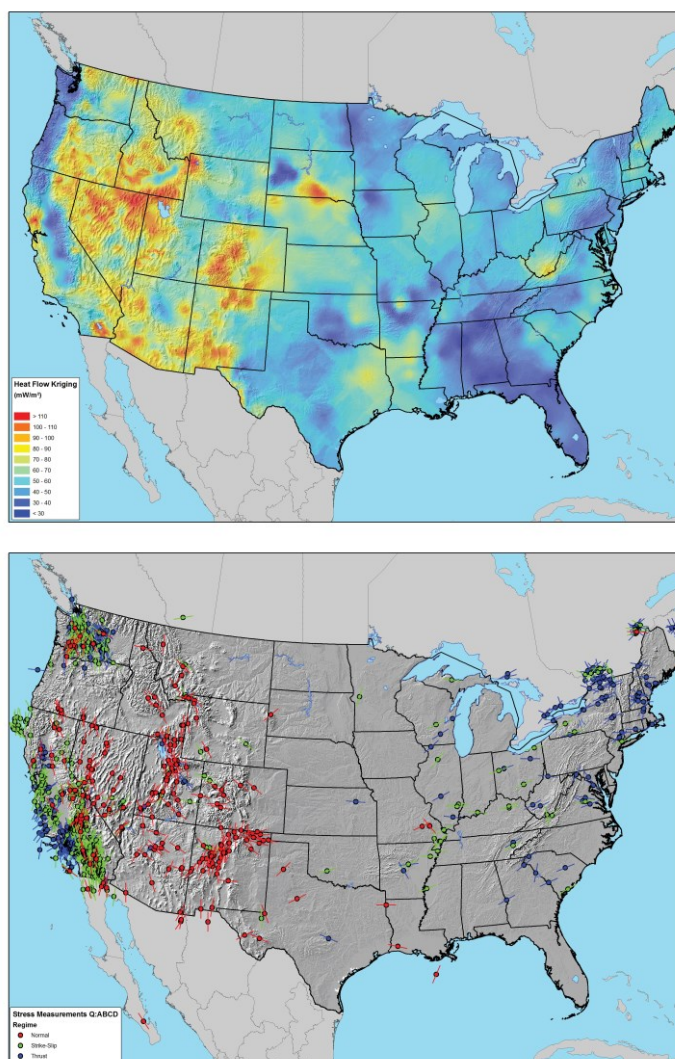
**4. IMPLICATIONS FOR EGS ASSESSMENT METHODOLOGY**

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. However, the limited information available from EGS experiments is a start on developing quantitative constraints on the EGS resource until a comprehensive suite of laboratory and field experiments on varied rock types over a range of stress states and pre-existing permeabilities can be conducted for site-specific, quantitative predictions. Even though existing modeling results are limited to a narrow range of reservoir conditions and

rock properties, in the absence of long-term EGS field experience it can be stated at this point 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).

For example, if the model curves shown in Figures 4 through 7 are reasonable approximations of actual permeabilities, and multistage stimulations will be capable of attaining adequate flow rates by increasing the permeability-thickness ( $kh$ ) of EGS reservoirs (Petty et al., 2013), then permeability in the range of  $10^{-15}$  to  $10^{-14}$   $m^2$  can be used as a threshold requirement for successful EGS reservoir stimulation. In extensional to mixed extensional/strike-slip stress regimes, the available evidence suggests permeability greater than  $10^{-15}$   $m^2$  can be attained at depths as great as 5km. However, increasing effective normal stress on shear surfaces by transitioning to other stress regimes could raise the depth of this threshold to approximately 3 km (compressional). Both mixed compressional and strike-slip stress states and relatively low upper crustal temperatures (Figure 8) characterize most of the eastern United States as well as parts of the central and western, indicating that EGS development in crystalline bedrock (as opposed to sedimentary basins) using only hydraulic stimulation technology will be limited to the predominantly extensional, high-temperature regions of the western US.

In identifying those favorable regions, the appropriate procedure to follow for EGS resource assessment will be (1) estimating temperatures in the crust to constrain the thermal resource base, (2) determining the orientation and magnitudes of the principal stresses at depths characterized by temperatures of interest for geothermal power production, (3) developing three-dimensional geologic models to describe lithologic variations at those depths, (4) applying calibrated models for permeability creation using the available information on stress and lithologic properties at depth, and (5) determining the recoverable heat and power from those potential reservoir volumes with sufficient permeability creation potential.



**Figure 8: Maps of heat flow (Williams and DeAngelo, 2011) and stress state (Reinecker et al., 2005) in the lower 48 states of the United States.**

## 5. CONCLUSIONS

A survey of models for the development of fracture permeability from shear slip along pre-existing fractures by hydraulic stimulation indicates that production from EGS reservoirs will be sensitive to the influence of effective stress and rock properties on shear fracture formation and closure. Calibration of model parameters to EGS field experiments suggests that sufficient permeability may be difficult to attain through shear stimulation at depths greater than approximately 5 km, particularly in regions of reverse faulting, which are characterized by high normal stress on pre-existing fractures. As a result, away from areas of hydrothermal and volcanic activity with anomalously high temperatures at shallow depths, the most promising targets for EGS development in crystalline bedrock may be restricted to areas of both high conductive heat flow and extensional to strike-slip faulting, which in the United States are essentially restricted to the western part of the country. The development of new technologies for reservoir development, such as chemical stimulation, could easily alter this conclusion. At this point any interpretation is limited by the relatively small number of cases in which model predictions can be compared to laboratory or in situ data. 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 in diverse settings.

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