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STIMULATION TECHNIQUES USED IN ENHANCED GEOTHERMAL SYSTEMS: PERSPECTIVES FROM GEOMECHANICS AND ROCK PHYSICS

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ABSTRACT

Understanding the processes that enhance fluid flow in crustal rocks is a key step towards extracting sustainable thermal energy from the Earth. To achieve this, geoscientists need to identify the fundamental parameters that govern how rocks respond to stimulation techniques, as well as the factors that control the evolution of permeability networks. These parameters must be assessed over a variety of spatial scales: from microscopic rock properties (such as petrologic, mechanical, and diagenetic characteristics) to macroscopic crustal behavior (such as tectonic and hydro-dynamic properties). Furthermore, these factors must be suitably monitored and/or characterized over a range of temporal scales before the evolutionary behavior of geothermal fields can be properly assessed. I am reviewing the procedures currently employed for reservoir stimulation of geothermal fields. The techniques are analyzed in the context of the petrophysical characteristics of reservoir lithologies, studies of wellbore data, and research on regional crustal properties. I determine common features of geothermal fields that can be correlated to spatio-temporal evolution of reservoirs, with particular attention to geomechanics and petrophysical properties. The study of these correlations can then help guide procedures employed when targeting new prospective geothermal resources.

INTRODUCTION

For thousands of years humans have utilized the naturally heated waters of the Earth. While ancient civilizations recognized the therapeutic value of thermal spas, our modern society has realized the potential of these geothermal fluids as a source of energy. To date, research and development activities for geothermal energy have concentrated on geologic terrains having high heat flow (typically associated with a shallow heat source) and fluid-saturated reservoirs having adequate storage capacity and permeability. At issue here is the observation that such conditions are not universally available, thereby restricting the growth of geothermal energy as a commodity. With the advance of technologies and an increased reliance on electrical power, geothermal activities will inevitably seek energy from a range of geologic terrains where heat sources may be cooler, reservoirs are tapped at deeper subsurface levels, or where percolating fluids are absent. To this end, the techniques and concepts employed for enhanced geothermal systems (EGS) are designed to increase the amount of thermal energy extracted from the Earth. The knowledge gained from EGS work may be useful for prospecting new geothermal resources.

I am reviewing results from various EGS sites to assess the universality and relative success of geothermal reservoir stimulation procedures. I then consider the commonalities of current EGS activities and highlight those geomechanical and petrophysical aspects that have relevance to enhanced stimulation of geothermal systems.

SUMMARY OF EGS SITES

In Table 1 I summarize details for a number of geothermal fields for which EGS activities have been tested. For each field, the summary indicates the approximate location, tectonic and/or structural aspects, thermal characteristics, reservoir lithology, and type of EGS research activity.

The chief objective of EGS procedures is to extract thermal energy from existing fields that contain areas of low productivity, or from new geothermal fields that have low capacity for energy production. While this description may include areas of comparatively low geothermal gradient, current research is primarily directed at prospects displaying high temperatures in relatively impermeable rocks (note the lithologies described in Table 1). In such cases it is necessary to improve or create a permeability network with a fluid-rock surface area large enough to efficiently extract the thermal energy. To date, this has largely been achieved by using hydraulic fracturing techniques to stimulate the thermal reservoir (note the stimulation techniques in Table 1).

Geothermal field	Location	Approx. Latitude / Longitude	Thermal reservoir (lithology)	Tectonics & structural elements	Depth to thermal reservoir	Temperature of thermal reservoir	Potential power output	EGS activity	Ref.
Cooper Basin (Habanero)	Approximately 8km SSE of Innamincka, South Australia	27.85 S 140.72 E	Carboniferous granitic intrusives	Permo-triassic basin; intra-cratonic region with evidence for Carboniferous compression	3700 to 4900m	In excess of 240 °C	37 wells to produce an estimated 275 MWe	Hydraulic stimulation of sub-horizontal joints and fractures	1, 2
Coso Geothermal Field	California, USA (Naval Weapons Air Station near China Lake, CA); ~161 km N of Los Angeles, CA	36.00 N 117.75W	Complex, interfingering sequence of Mesozoic diorite, granodiorite, and granite	Situated in major volcanic area with 38 rhyolite domes and abundant basalts; transition between regions of strike-slip and extension.	less than 3000 m	In excess of 300 °C at depths less than 3000 m	240 MWe	Hydraulic fracturing of existing reservoir	3, 4, 5
Desert Peak	Nevada, USA; ENE of Reno, NV	39.76 N 118.92 W	Fault dissected, tertiary volcanics & sedimentary rocks that overlie Mesozoic metamorphics	Humboldt Structural zone (extensional normal faults, strike-slip transfer faults)	762 to 1280 m	~200 °C	9.9 MWe (year 2000)	Hydraulic stimulation	6, 7
Geysers Geothermal Field	California, USA (south of Clear Lake, CA); ~193 km N of San Francisco, CA	38.8 N, 122.8 W	Steam reservoir rocks are typically massive greywacke turbidites of the Mesozoic Franciscan Fm. Underlain by a 2.4-0.9 Ma silicic batholith (felsite).	Fault-bounded, quasi-extensional region; fractures in greywacke are randomly oriented & sub-horizontal, while in the felsite are oriented NW and are near vertical.	60 to ~3000 m	~40 °C at shallow depths to greater than 240 °C in the deepest wells	2043 MWe cumulative installed gross capacity in 1989	Recharge reservoir at depths between 2134-3048 meters.	8,9,10
Hijiori, Japan	south edge of the inner Hijiori caldera, Okura Village in Yamagata Prefecture	38.60N 140.18E	Granodiorite	Max. compressive stress direction is E-W; tectonic regimes are strike-slip and normal faulting	upper reservoir at 1800m; lower at 2200m	~250-270 °C		Hydraulic fracturing and stimulation	11, 12
Larderello, Italy	A few km W of Larderello, Tuscany, Italy	43.25N 10.87E	Upper reservoir has anhydrites and dolomitic lime-stones; quartzites and phyllites in lower reservoir	Structural high; series of nappes with predominant ENE vergence.	~4 km	>400 °C	547 MWe in 1999	Recharge of reservoir by reinjection	13
Rosemanowes Quarry, UK	near Penryn, Cornwall, UK	50.15N 5.1W	Late Carboniferous to early Permian Carnmenellis Granite	No major faults outcrop at Earth surface; sub-horizontal joints near Earth surface; two main sub-vertical joint sets at depth (NE-SW, NW-SE)	Initial borehole depths to 300m; subsequent depths to 2000m	80 °C at 2000m (average geothermal gradient of 35 °C/km)	Not established for power generation	Hydraulic stimulation; explosive stimulation	14, 15
Soultz–sous–Forêts, France	~ 50 km north of Strasbourg, Alsace	48.93N 7.88W	Granites	Local horst structure within the extensional tectonics of the Rhine Graben	3500 to 5000 m	150 °C to more than 200 °C	6 MWe (year 2005)	Hydraulic fracturing and stimulation	16, 17

Table. 1. Summary details for geothermal fields identified as EGS sites. Cited sources are as follows (full details are in the reference section): 1 - Chopra & Wyborn (2003); 2 – Asanuma et al. (2004); 3 – Kovac et al. (2004); 4 – Wannamaker et al. (2004); 5 – Adams et al. (2000); 6 – Faulds et al. (2002); 7 – Tiangco et al. (2004); 8 – Koenig (1992); 9 – Walters & Combs (1992); 10 – Thompson & Gunderson (1992); 11 – Yamaguchi et al. (2000); 12 – Oikawa & Yamaguchi (2000); 13 – Cappetti et al. (1995); 14 – Tenzer (2001); 15 – Parker (1999); 16 – Genter et al. (2000); 17– Durst & Vuataz (2000)

With the exception of EGS sites at The Geysers and Larderello, the reservoir lithologies currently exploited are mainly crystalline, igneous rocks that inherit little porosity or permeability during their formation. Whatever porosity and/or permeability these rocks do have typically stems from post-emplacement deformation (perhaps by contraction during cooling or via tectonic forces). I also note that a majority of EGS sites are located in areas that have experienced at least one episode of tectonism. The imprint of such regional deformation takes the form of fractures and metamorphic features – and it is these fabrics that are exploited by EGS stimulation.

Thus, a clear pattern emerges from the analysis of current EGS research inasmuch as the activities are restricted to hydraulic stimulation of low permeability rocks in areas that are, or once were, tectonically active. To properly assess the efficiency of stimulation procedures it is necessary to consider petrophysical properties of the reservoir, the influence of the present-day regional stress field, the interaction with pre-existing rock fabric, and the spatio-temporal evolution of the permeability network. While I am presently analyzing these details for several EGS sites, I review here some key geomechanical and petrophysical aspects that can be applied to the many of the existing EGS fields.

MECHANICAL CONSIDERATIONS

A fundamental observation from early EGS projects such as Fenton Hill (e.g. Brown, 1995) was that the formation of hydraulically induced fracture networks can be influenced by the regional and/or local stress field, pre-existing fabric (e.g. fractures, foliation), and rock properties. While the geometry of the induced fracture network can be adequately monitored via seismic techniques (e.g. Asanuma et al., 2004), proper modeling of the fracture network generation requires that these various mechanical factors be considered.

Regional Tectonics

Intuitively, the character of the regional stress field can determine the orientation of newly generated fractures. If we assume an Andersonian stress state (with one principal compression stress axis normal to Earth's surface) then compressive, strike-slip, and extensional tectonic regimes develop when the vertical stress (σ_v) is the least (σ_3), intermediate (σ_2), and greatest (σ_1) principal stress, respectively (Jaeger and Cook, 1979; Sibson, 1983). For rock failure via tensional strain mechanisms, simple models indicate that newly generated opening type fractures (Mode I) form approximately perpendicular to the minimum compressive stress, σ_3 (Jaeger and Cook, 1979). Thus, hydraulically induced cracks would be sub-horizontal (i.e. normal to the σ_v) in compressive regions and they would be near vertical (i.e. normal to the minimum horizontal stress, σ_h) in either extensional or strike-slip tectonic regions.

In addition to lateral variations of tectonic stresses, studies of seismic focal mechanisms indicate that stress conditions can vary systematically with depth (e.g. Vetter and Ryall, 1983; Iio, 1996; Bokelman and Beroza, 2000). Such observations can be conceptualized by simple models that incorporate Andersonian mechanics (e.g. Figure 1) by assuming that vertical stress varies linearly with burial depth and that the region is subjected to a uniform horizontal stress field (with maximum, σ_H, and minimum, σ_h, horizontal stresses unequal). This simplified model illustrates that vertical stress can act as either the minimum, intermediate, or greatest compressive stress as depth varies (Figure 1). These systematic variations in tectonic style as a function of depth would be reflected by the various deformation indicators (e.g. seismic focal mechanisms, borehole breakouts) – as can be noted by the transition from reverse to strike-slip to normal faulting in Figure 1). Furthermore, the orientations of hydraulically created fractures would also vary with depth because these cracks are typically generated normal to the least compressive stress direction (i.e. the seismic T-axis). For the conditions shown in Figure 1, fracture orientations would transition from sub-horizontal at shallow depths to near vertical at deeper levels.

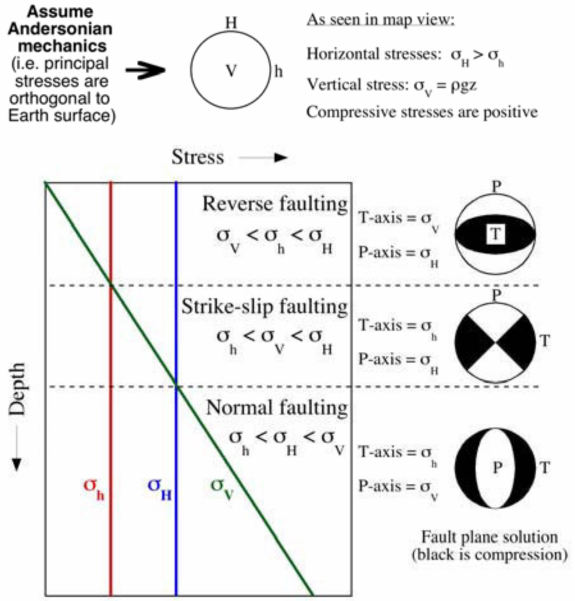

Figure 1. Conceptual model showing the variation of deformation style with burial depth, assuming an Andersonian stress field where only the vertical stress varies with depth. Faulting style transitions from being reverse near the surface, to strike-slip at intermediate depths, and normal faulting at deeper levels. These transitions would be observable from seismic focal mechanisms (with the tensile, T, and compressive, P, axes as shown).

It is important to note that estimates of horizontal stress from geologic data (e.g. Zoback and Zoback, 1980), borehole observations (e.g. Abou-Sayed et al., 1978; Zoback and Zoback, 1980; Zoback et al., 1980; Warpinski et al., 1985; Klee and Rummel, 1993) and seismic data (e.g. Zoback and Zoback, 1980; Sbar, 1982; Vetter and Ryall, 1983; Iio, 1996; Hardebeck and Michael, 2004) exhibit lateral and vertical variations that are more complex than simple models predict (e.g. Figure 1). Thus, studies of 3-D regional stress fields will have strong site-specific aspects. The differences between localities may be attributed to tectonic and burial forces. However, it is important to recall that other factors can significantly alter the stress field – such as crustal thickness, geothermal gradient, style and abundance of damage features, and rock properties (to name a few).

Pre-existing rock fabric

When coupled with Mohr-Coulomb theory, the Andersonian view of brittle deformation in the crust can describe many geologic problems. Yet, several observations indicate the limitations of this simplified view – such as the roles of pore fluids (e.g. Hubbert and Rubey, 1959), stress rotation (e.g. Scholz, 1992), and pre-existing fractures (e.g. Angellier, 1984).

The influence of pore fluid pressure and pre-existing fractures can be understood using a schematic representation of Mohr-Coulomb fracture mechanics (Figure 2). The key to the analysis lies in the fact that while fluids can support compressional forces they cannot support shear tractions. An increase in fluid pressure lowers effective normal stress and does not change shear stress (note the lateral shift in the Mohr circle in Figure 2). The resulting stress state may exceed the material strength and induce failure (e.g. Terzaghi, 1925) and it is this principle that is exploited during hydraulic fracturing of rocks.

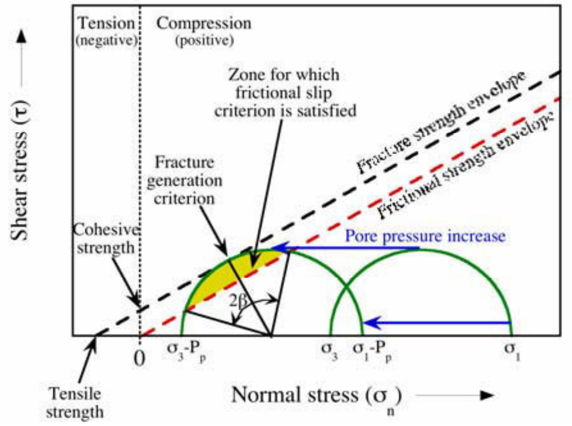

Figure 2. Schematic of Mohr-Coulomb behavior illustrating the role of pore fluid pressure together with a comparison of fracture and frictional strength. Pore fluid pressure acts to reduce effective normal stress. Cracks oriented within the angular range indicated by 2β will fail in preference to creation of a new fracture.

Another important aspect relating to material strength is that of pre-existing fractures (Figure 2). The key here is that cracks exhibit lower frictional strengths than the fracture strength that originally created them. With larger pore pressure, the Mohr circle translates towards the failure envelopes. If a fracture is ideally oriented for failure, then deformation occurs when the stress state satisfies the frictional failure criterion. As Figure 2 shows, the fracture criterion can only be satisfied when pre-existing cracks have orientations that are not optimal for frictional slip to occur.

Intuitively, the frictional and fracture envelopes shown in Figure 2 reflect distinctly different strength characteristics. Therefore, cracks in a rock mass may be responsible for anisotropy of material strength. It is important to note here that strength anisotropy can be induced by other factors, such as lithologic variations, sedimentary bedding, foliation, diagenesis (to name a few). Hence, in using the Mohr-Coulomb analysis of rock failure (Figure 2) we should also consider the influence of pre-existing rock fabric.

Rock properties

Results from laboratory deformation experiments show large variations in rock strength depending on the conditions studied. It can generally be concluded that the strength of a rock will change systematically as certain parameters are varied. For example, the compressive strength of a given rock typically increases with the applied confining pressure (e.g. Griggs, 1936; also shown schematically in Figure 2), typically decreases with the presence of water (e.g. Raleigh and Paterson, 1965; Griggs, 1967), and typically increases with increasing strain rate (e.g. Paterson, 1978). However, it is important to recognize that these generalizations are not universal and that other parameters do not systematically influence rock strength (e.g. compositional variations, diagenetic reactions). Yet, the systematics that are observed from laboratory tests can be readily applied to the study of geothermal systems.

Extensional strain tests on necked rock samples have particular relevance to stress orientations estimated from hydraulically-induced fractures. Ramsey and Chester (2004) performed room temperature, room humidity extension experiments on necked (dogbone) samples of Cararra Marble. They explored failure characteristics for a range of confining pressures and observed a systematic change in fracture style and material strength (Figure 3). At low confining pressures, samples failed under extensional stress conditions with tensile strengths compatible with those of previous studies. The through-going fractures associated with sample failure display orientations that are nearly normal to the direction of the minimum stress. At high confining pressures, samples failed with compressive minimum stresses and the extensional fractures form at low angles (<20^{o}) to the minimum stress direction. Further, the high confining pressure fractures have displacements and surface morphologies consistent with opening mode shear fractures. Similar results have been reported for Berea Sandstone (Bobich et al., 2004), indicating that these trends may be observed for a variety of rock types. Measurements of rock properties at a variety of conditions are fundamental for applied research and modeling of geothermal systems. Observations such as those of Ramsey and Chester (2004) and Bobich et al (2004) are particularly relevant for exploration of geothermal resources situated at large depths.

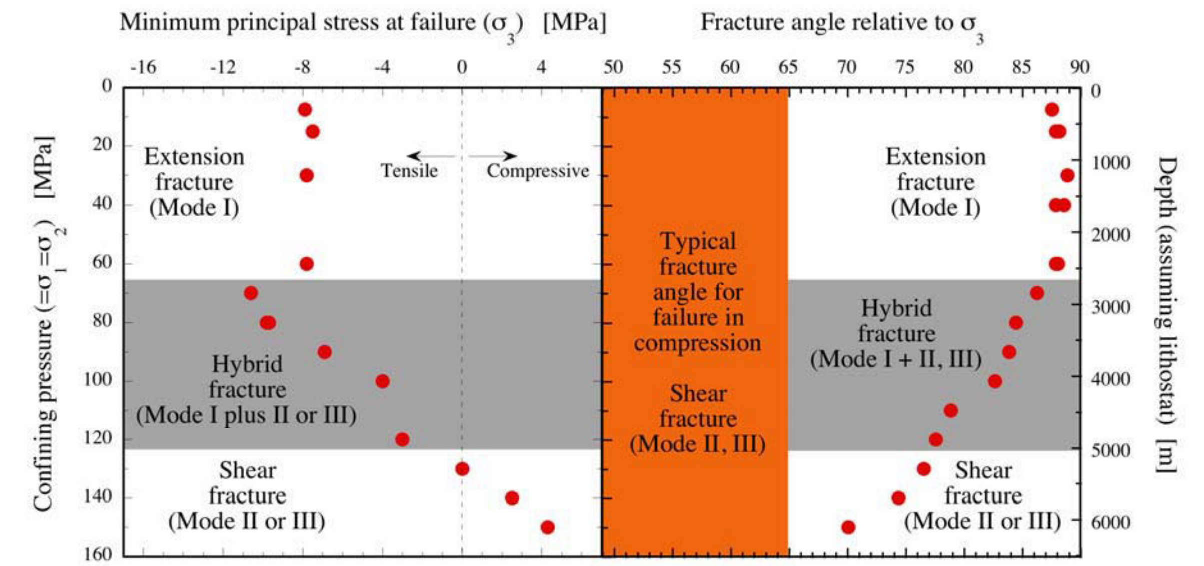

Figure 3. Results from failure experiments on necked (dog-bone) samples of Cararra Marble (modified from Ramsey and Chester, 2004). For all experiments, samples were subjected to tensile strain leading to failure. The minimum compressive stress at failure transitions from tensile to compressive as a function of increasing confining pressure (or depth - assuming a lithostatic gradient of ~24.5 MPa/km). The observed fracture orientation relative to σ_3 systematically decreases with increasing confining pressure. Similar results have been reported from identical tests on Berea Sandstone (Bobich et al., 2004).

Their results also highlight the hazards of applying the common assumption that rock properties are single-valued and static constants. Thus, we must also consider that these properties could vary with a number of factors – such as physical conditions, chemical environment, and time.

TEMPORAL EVOLUTION OF FRACTURES

Concern over fractures in geothermal systems does not end with the successful generation of an interconnected network. When hydraulic stimulation involves pre-existing fractures, an anisotropic stress field, or certain rock properties, the stimulated fractures may experience some portion of the total deformation in the form of shear displacement. The shearing may be contemporaneous with the stimulation process itself, but will likely include a protracted stage of creep following stimulation. Also, as the stimulation and/or production fluids are transmitted through the fracture network they may enter into chemical reactions with the fracture walls. The reaction kinetics and fluid solubilities will control temporal evolution of diagenetic reactions. Such time-dependent deformation and/or diagenetic reactions can influence the temporal evolution of strength and permeability of the fracture network.

Mechanical evolution

Let us consider the mechanical evolution of a hydraulically-induced fracture after it has been generated. Initially, the fracture is held open by the force of the pressurized fluid. With even a small drop of fluid pressure, the stresses within the Earth will act to close the fracture aperture. If closure does not result in perfect mating of opposite sides of the fracture, any rough asperities on the fracture walls will impinge on each other and support part of the normal load. From a mechanical perspective, the material that comprises these asperities will deform over time thereby increasing the real area of contact between the fracture walls. The closure of the fracture and subsequent increase in contact area will not only lower porosity and permeability, but will also increase the cohesive strength of the fracture.

The time-dependent strengthening (or aging) of a fracture is exemplified by results from frictional slide-hold-slide experiments on shear zones that may or may not contain wear material (Figure 4; for a review see Marone, 1998). In these tests, shear zones are deformed at a constant sliding rate (slide) with episodic intervals for which the imposed loading rate is set to zero (hold). During the hold interval, the shear zone supports a residual shear stress that decays exponentially with time due to frictional creep (Figure 4a). On reloading after a hold (slide), the frictional resistance increases to a peak value and subsequently approaches the steady-state sliding value. As the reloading peak is considered to be a measure of static friction levels, then the difference between the peak friction and the steady-state sliding friction level provides a measure of restrengthening. Laboratory slide-hold-slide tests consistently show that frictional strength increases logarithmically with stationary hold time (Figure 4b). For bare sliding surfaces (with no wear material, or gouge), the time-dependent restrengthening is associated with growth of asperity contacts and an increase in adhesion (e.g. Bowden & Tabor, 1954, 1964). When sand layers are sheared (simulating gouge), the restrengthening is associated with compaction (or densification) of the layer (Figure 4c, consistent with the notion that frictional restrengthening is due to time-dependent increase in real area of contact (e.g. Dieterich, 1972).

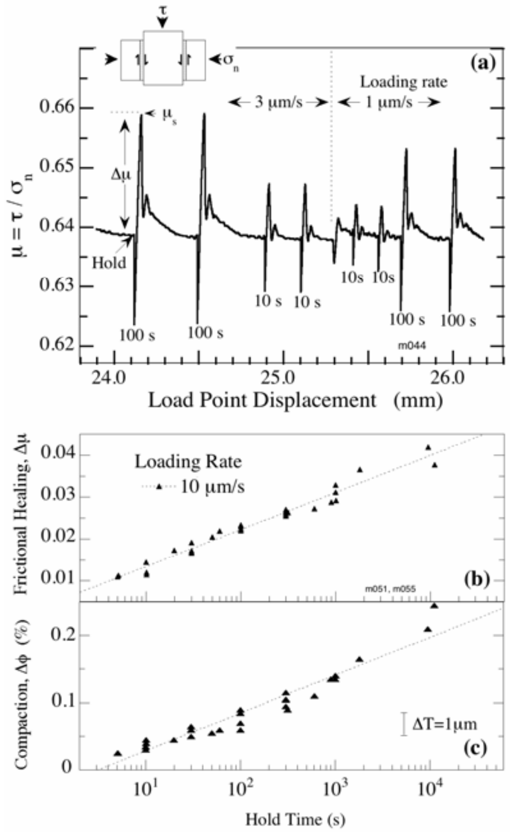

Figure 4. Results from slide-hold-slide shear tests in quartz sand (modified from Karner and Marone, 1998). Holds start when loading rate is to zero. In holds, stress-relaxation occurs (Figure 4a) with compaction of the layer (Figure 4c).Friction restrengthening occurs on reloading (Δμ; Figure 4a) and this scales with the logarithm of hold time (Figure 4b).

Geochemical evolution

While fractures can obtain greater adhesion (hence, strength) via mechanical deformation of contacting asperities, fracture strength can also be influenced by pressure solution of contacting asperities or by diagenetic precipitation of cements bonding fracture walls (e.g. Karner et al., 1997; Tenthorey et al., 2003). Further, the permeability of porous media has been observed to vary as hydrothermal diagenesis proceeds (e.g. Karner and Schreiber, 1993, Tenthorey et al., 2003). This is because geochemical reactions are inherently rate-dependent.

At low temperatures (less than ~400^{o}C), the strength of aqueous silicate-bearing shear zones (i.e. quartz, feldspar) generally increases with longer reaction time (e.g. Karner et al., 1997) while the permeability typically decreases (e.g. Tenthorey et al., 2003). At high temperatures (greater than ~400 ^{o}C), silicate shear zones may show little to no time evolution in strength (e.g. Karner et al., 1997) and permeability reduction may be enhanced. However, it is important to note that these generalizations may not be universal. For example, common by-products from low temperature diagenesis are clays – which have been shown to dramatically reduce frictional strength of shear zones (e.g. Marone, 1998). Thus, the temporal evolution of strength, porosity, and permeability of fractures in geothermal systems will likely be determined by a variety of site-specific properties (e.g. physico-chemical environment, lithology and/or mineralogy, fluid composition).

CONCLUSIONS

I have researched several existing EGS sites to analyze reservoir stimulation procedures. To date, stimulation activities have primarily focused on hydraulically creating or enhancing a permeable network of fractures in low porosity/permeability reservoir rocks (typically crystalline) – many of which are imprinted by past episodes of tectonic deformation. With this in mind, I have described various mechanical and geochemical issues that must be considered when establishing geothermal fields. A better understanding of the generation and temporal evolution of geothermal reservoirs can be achieved when these aspects are coupled with results from remote sensing techniques (e.g. monitoring micro-seismicity, electrical conductivity, fluid geochemistry). With such knowledge in hand, the success of hydraulic fracturing can be adequately evaluated compared to predicted successes of alternate stimulation practices (e.g. explosives, high-energy gas gun, acid-treatment).

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