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ORIGINAL PAPER

A Review of Some Rock Mechanics Issues in Geothermal Reservoir Development

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Abstract Rock mechanics and geomechanical studies can provide crucial information for economic geothermal reservoir development. Although significant progress has been made in reservoir geomechanics, technical challenges specific to the geothermal area (high temps, data collection, experimentation issues) have prevented widespread use of geomechanics in geothermal reservoir development. However, as the geothermal industry moves to develop more challenging resources using the concept of enhanced geothermal systems (EGS), and to maximize productivity from conventional resources, the need for improved understanding of geomechanical issues and developing specific technologies for geothermal reservoirs has become critical. Rock mechanics research and improved technologies can impact areas related to in-situ stress characterization, initiation and propagation of artificial and natural fractures, and the effects of coupled hydro-thermo-chemo-mechanical processes on fracture permeability and induced seismicity. Rock mechanics/geomechanics research, including experimental and theoretical investigations as well as numerical and analytical solutions, has an important role in optimizing reservoir design and heat extraction strategies for sustainable geothermal energy development. A number of major areas where rock mechanics research can facilitate geothermal systems development are reviewed in this paper with particular emphasis on EGS design and management.

Keywords Coupled processes · Enhanced geothermal systems · Shear slip · Hot dry rock · Hydraulic fracturing · In-situ stress · Induced seismicity · Joints · Mineral dissolution · Fracture network · Fracture permeability · Poroelasticity · Pressure solution · Reservoir geomechanics · Reservoir stimulation · Stimulated volume · Thermal stress · Thermal shock

1 Introduction

The heat of geothermal systems from subsurface hot rocks and geofluids, can be an abundant source of renewable energy in the form of heat or electricity. A total of 24 countries now generate electricity from geothermal resources with a total installed capacity of 10,898 MW, corresponding to about 67,246 GWh of electricity (Bertani 2012). The current installed geothermal electric power production is nearly 3,000 MWe in the US. However, the United States Geological Survey (USGS) estimates that electrical energy producible from geothermal reservoirs to a depth of 3 km exceeds 100,000 MWe for 30 years. In addition, heat recovered from lower temperature geothermal systems may be used for a variety of applications such as heat pumps for heating and

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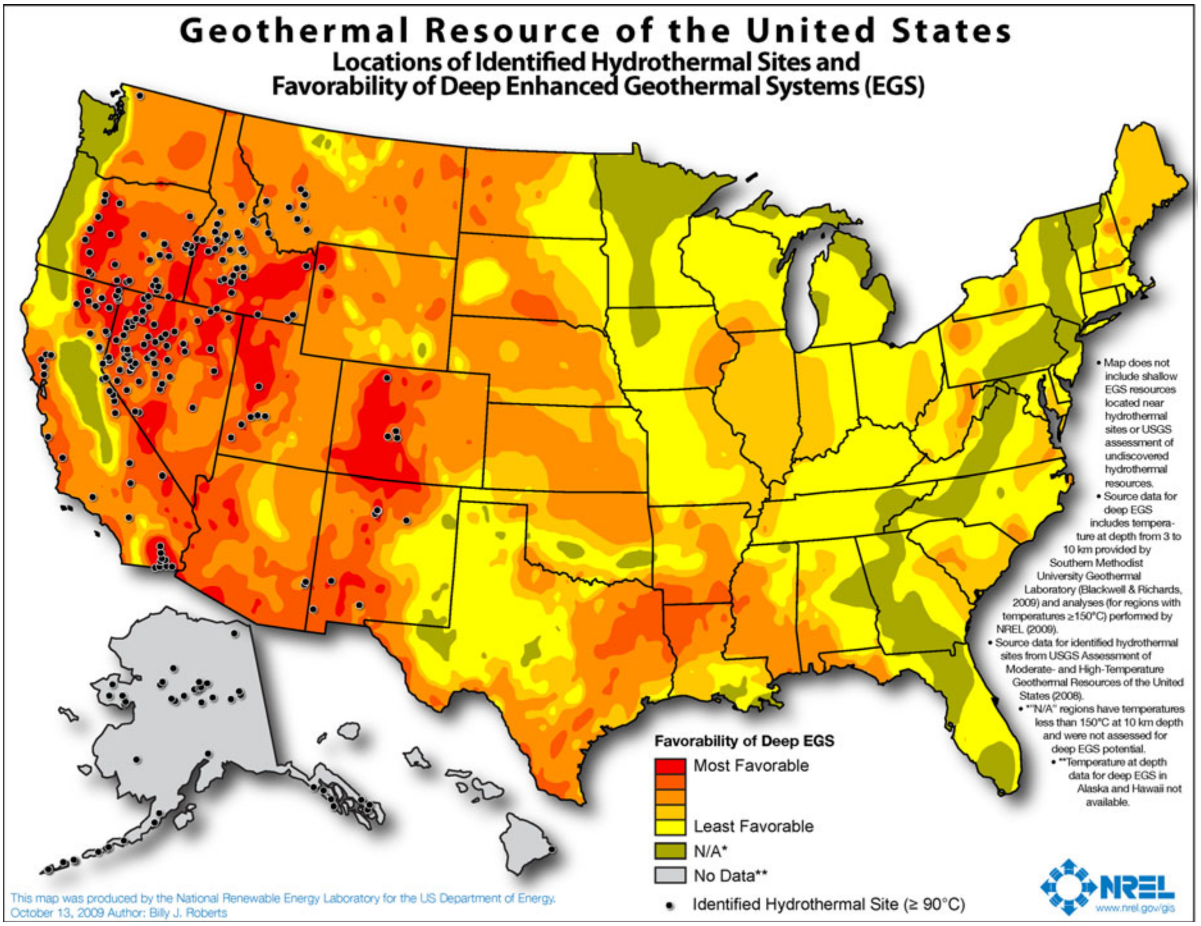
cooling buildings, agricultural green houses, and recovery of oil from tar sands. In fact, direct use of geothermal energy is the most common form application of geothermal energy utilization (Dickson and Fanelli 2003). Lund et al. (2011) report direct utilization of geothermal energy in 78 countries with an estimated installed thermal power of 48,493 MWt, and a thermal energy use of 423,830 TJ/year (117,740 GWh/year. Clearly, it is desirable to have the virtually unlimited heat of earth become an economical source of renewable energy on a broader scale in the US and throughout the world.

Currently, most geothermal systems that generate electricity commercially are the *hydrothermal* type. These systems have adequate permeability and fluids, so that hot water and steam are extracted from the porosity structures (pores, fractures) to generate power. But the hydrothermal systems constitute only a small fraction of the geothermal resources (Fig. 1).

Most geothermal resources are either deficient in water or permeability, or both (the so-called hot dry rock). The production of geothermal energy from these generally dry and low permeability reservoirs can be achieved by water circulation in *engineered* fracture networks consisting of man-made and pre-existing fractures (joints, faults). This is often referred to as enhanced or engineered geothermal systems (EGS). Two or more wells are drilled into the fracture network and cold water is injected into one part of the well system and hot water/steam is recovered from the other (Fig. 2).

A major impediment to accelerated exploitation of EGS is the high cost of reservoir creation (including drilling) and, in certain cases, risks associated with reservoir management. The costs can be reduced and risks mitigated by reservoir development technology based on rock mechanics/geomechanics principles. Such technologies can impact areas related to the in-



Geothermal Resource of the United States

Locations of Identified Hydrothermal Sites and Favorability of Deep Enhanced Geothermal Systems (EGS)

- Map does not include shallow EGS resources located near hydrothermal sites or USGS assessment of undiscovered hydrothermal resources.
- Source data for deep EGS includes temperature at depth from 3 to 10 km provided by Southern Methodist University Geothermal Laboratory (Blackwell & Richards, 2009) and analyses (for regions with temperatures ≥150°C) performed by NREL (2009).
- Source data for identified hydrothermal sites from USGS Assessment of Moderate- and High-Temperature Geothermal Resources of the United States (2008).
- *"N/A" regions have temperatures less than 150°C at 10 km depth and were not assessed for deep EGS potential.
- **Temperature at depth data for deep EGS in Alaska and Hawaii not available.

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. October 13, 2009 Author: Billy J. Roberts

Fig. 1 Map showing the distribution of geothermal resources

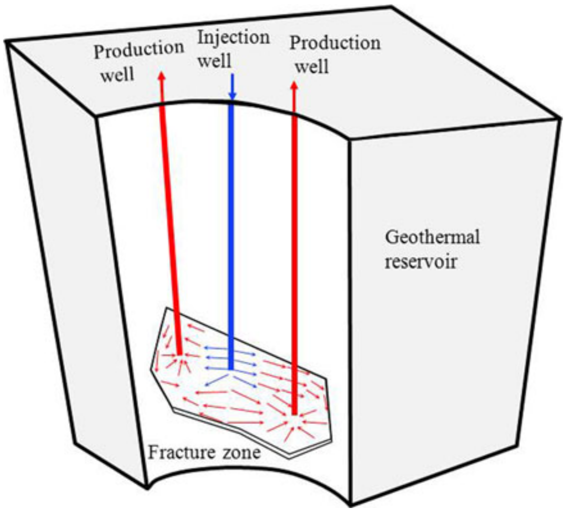


Fig. 2 An illustration of engineered or enhanced geothermal system

situ stress characterization, initiation and propagation of artificial and natural fractures, the role of coupled thermo-hydro-chemo-mechanical (THCM) processes on fracture permeability, and induced seismicity. Rock mechanics research, including experimental, numerical and analytical investigations and solutions, can play an important role in optimizing reservoir design and heat extraction strategies for sustainable geothermal energy development. This paper reviews a few major areas where rock mechanics research has aimed to facilitate geothermal systems development with particular emphasis on EGS design and management.

2 Rock Mechanics Applications in Reservoir Creation and Management

Although significant progress has been made in the area of reservoir geomechanics and its applications over the past two decades, it has been mostly focused on the petroleum reservoirs where the range of encountered temperatures has been relatively low compared to that in geothermal settings. However, as geothermal community has set out to maximize the productivity from conventional geothermal resources and to utilize engineered geothermal systems, improved understanding of geomechanical issues and development of technologies for geothermal conditions has become critical. The specific rock mechanics problems often encountered in geothermal systems development can be broadly divided up into four areas, each of which entails theoretical, analytical, and numerical advancements. This paper provides an overview of these areas, describing the current approach, existing challenges facing the geothermal community, and how geomechanics can contribute in their resolution.

2.1 In-Situ Stress and its Variation in Time/Space

Not surprisingly, a fundamental geomechanical issue in geothermal reservoir design is the reservoir state of stress. The in-situ stress state plays a critical role in well planning and safe economical drilling, reservoir stimulation and permeability evolution, as well as in mitigation of induced seismicity. Knowledge of the stress state in geothermal systems can help delineate fractured zones and zones of possible fluid accumulation and flow. The in situ stress components directly control the pressure required for reservoir stimulation and influence the lateral extent and orientation of the stimulated rock volume. The reservoir stress state is influenced by rock discontinuities, and rheology, heterogeneities, as well as poroelastic, and thermal stresses caused by injection/production operations. Over the years, a number of techniques have been developed for developed to determine the in-situ stress, including mini-frac tests, analysis of breakouts and drilling-induced cracks, hydraulic testing of pre-existing fractures (HTPF) (Baumgartner and Rummel 1989; Cornet and Valette 1984), and focal mechanism inversion. A detailed description of these techniques can be found in Bell (2003), Evans et al. (1999), and Amadei and Stephansson (1997). Usually, the vertical stress (σ_{v}) component is determined using a density log. For determination of the minimum horizontal stress (σ_{h}) one might consider using a leak-off test, or using hydraulic fracturing (micro-frac or mini-frac) to find the closure pressure. The injection rates for leak-off test are in the range of 0.04–0.016 m^3/min for about 1 m^3 total. These values are 0.0038–0.038 m^3/min for micro-frac (0.008–0.38 m^3) tests and 0.795–1.590 m^3/min for mini-frac (1.59–159 m^3) tests (De Bree and Walters 1989). The leak-off test originally was designed to test casing-shoe integrity to ensure safe drilling of the next wellbore section. However, the test has been used for stress measurement by continuing it until the rate of pressure increase declines, and interpreting the departure from linearity of the injection pressure vs. pumped volume as the fracture initiation pressure (Addis et al. 1998). Other interpretations of the test data use the Kirsch's solution to calculate σ_h from the leak-off pressure, or consider the instantaneous shut-in pressure as the value of σ_h. In light of the uncertainties in the leak-off test data, an extended leak-off test has been proposed which involves 3–4 more pressurization cycles over a period of 1 h (Addis et al. 1998). Methods such as leak-off tests, extended leak-off tests and mini-fracs have been used in some geothermal reservoirs to measure stress. However, it is often the case that high temperatures, well completion with slotted liners and rock properties (heterogeneous and fractured) of candidate geothermal reservoirs make zonal isolation using mechanical packers very difficult (Petty 2012). Temperature differences between reservoir rocks and fluids and injected fluids can complicate interpretation of results.

Even where these techniques can be used to determine the minimum in-situ stress, there are no direct ways to accurately determine the magnitude of the maximum horizontal stress (σ_H). The breakdown pressure (used in calculating σ_H) is rate-dependent, size-dependent, and fluid dependent, and many techniques for its interpretations have been suggested (Guo et al. 1993; Ito and Hayashi 1991).

Another method for estimating the maximum horizontal stress (σ_H) relies on the tendency of a deep wellbore wall to fail in compression where the tangential stress reaches a maximum and overcomes the rock's compressive stress. Such compressive failures around the wellbore are called stress-induced wellbore breakouts (Gough and Bell 1981; Plumb and Hickman 1985; Zoback et al. 1985). Because the possibility of borehole failure depends on the in-situ rock stress and strength, and its location is governed by the in-situ stress and borehole orientation, it is possible to use breakout analysis as a tool to constrain the maximum horizontal in situ stress magnitude (Bell and Gough 1979; Zoback et al. 1985; Zoback and Healy 1992; Brudy et al. 1997) and the in-situ rock strength (Peska and Zoback 1995). In a vertical well, the zone of compressive failure is centered along the azimuth of the minimum horizontal compression. Hence, one can directly deduce the orientation of all principal stresses. However, breakouts may rotate with depth as the wellbore azimuth changes, or as a consequence of change in the petrophysical and structural characteristics of the reservoir. Interpretation of these cases is more elaborate. Qian and Pedersen (1991) proposed a numerical inversion method for estimating the in-situ stress state according to breakout data for inclined wells. Also, Djurhuus and Aadnoy (2003) developed an analytical method to determine the in-situ stress orientations from borehole image logs; however, their method requires knowledge of the magnitude of the in-situ stress.

Most breakout inversion techniques use an isotropic elastic stress analysis which does not consider the progressive breakage of rock. In addition, the effects of coupled thermal and poro-mechanical processes on stability of boreholes in geothermal reservoirs are not considered. When rocks are heated or cooled, the bulk solid and the pore fluid undergo a volume change. A volumetric expansion can result in significant pressurization of the pore fluid, depending on the degree of containment and the thermal and hydraulic properties of the fluid as well as the solid. When heated, water trapped in the pores may undergo pressure increases on the order of 1.5 MPa/°C for conditions typical of earth's upper crust (Williams and McBirney 1979). The net effect is a coupling of thermal and poro-mechanical processes, which occur on various time scales, and the significance of their interaction depends on the problem of interest. For example, when drilling wells in high-temperature rocks, strong coupling between thermal and poro-mechanical effects might develop that can significantly impact the stress/pore pressure distribution around a wellbore and thus borehole failure and fracture initiation. This is caused by the contrast in thermal and hydraulic diffusivities of rock.

The thermo-poroelastic effects on wellbore stability and its use for constraining in-situ stress and rock strength has been considered by Li et al. (1998) and Tao and Ghassemi (2010), respectively using the assumption of rock isotropy and homogeneity. The results showed that poro-thermo-mechanical effects influence both failure potential and mode; cooling tends to prevent compressive failure and radial spalling, whereas heating tends to enhance failure in compression and can cause tensile failure by excessive increase of pore pressure. The inhomogeneous nature of rocks can lead to qualitatively different borehole failure with elongations that are parallel to the maximum horizontal principal stress orientation. These are suggested to be the result of a pervasive, cooling-induced, tensile micro-cracking process prior to macroscopic failure localization (Berard and Cornet 2003). This phenomenon can also influence the validity of using regular breakouts, as thermal stress can change near-wellbore rock properties. Temperature, anisotropy and mismatch in grain thermal expansion coefficient, initial porosity, and grain size contribute to thermal cracking (Fredrich and Wong 1986) in the wellbore region so that Kirsch's solution may not be applicable. The impact of rock strength anisotropy on breakouts was considered by Vernik and Zoback (1990) and was found to be significant. It can be expected that poro-thermoelastic anisotropy can radically change the pattern of pore pressure and stress distributions around the wellbore and thus breakout orientation and size in other situations.

In petroleum reservoir development, interpretation of a mini-frac test to extract the closure pressure is considered an effective method for measuring the minimum horizontal stress, and many techniques have been developed for this purpose (Guo et al. 1993). Therefore, it would seem that integration of minifrac data with other available methods can provide a reasonable estimate of the complete stress state magnitude. Such an approach has indeed been used in e.g., Coso geothermal field (Sheridan and Hickman 2004; Nygren and Ghassemi 2004) and the Desert Peak EGS experiment (Hickman and Davatzes 2010). However, application of the hydraulic fracturing technique for stress measurement in geothermal settings remains difficult mainly because of the high temperatures that impact both its implementation and the interpretation of its results (some operational factors such as cost and potential risk of losing the well are also limiting factors). It is expected that ongoing research and technology development in this area will remove the barriers in the near future.

An alternative approach is the inversion of well-constrained earthquake data from seismic stations. The inversion techniques provide the orientation of the three principal stress axes and the relative magnitude of the intermediate principal stress with respect to the maximum and minimum principal stress (Michael 1987; Gephart and Forsyth 1984). The orientations are determined by minimizing the average difference between the slip vector and the orientation of the maximum shear stress on the inverted faults. But, this approach cannot provide the stress magnitudes, and its effectiveness suffers from uncertainties in earthquake data and its interpretations. Furthermore, the stress state varies with pore pressure and temperature changes accompanying injection/extraction operation. The interactions between the original 3D stress state and rock discontinuities and heterogeneities play an important role both in near-wellbore areas and the reservoir at large.

2.2 Reservoir Stimulation

In hydrothermal systems, fluids are re-injected for pressure maintenance and resource sustainability (Axelsson 2010; see other papers in the same Geothermics issue for case histories). On the other hand, energy production from dry and low permeability reservoirs is achieved by water circulation in an engineered network of natural and/man-made fractures. Therefore, certain aspects of reservoir stimulation are of interest to both conventional and engineered or enhanced geothermal systems. For the latter, the permeable zone is created by stimulation, a process which involves fracture initiation and propagation and/or reactivation of discontinuities such as joints and faults due to pore pressure and the in situ stress perturbations. Although conventional hydraulic fracturing has been used for nearly 60 years in the petroleum sector, the distinct characteristics of geothermal systems make a direct application difficult (see Sect. 2.1). Better understanding of fracture *initiation and propagation* behavior in geothermal rock masses in response to different loads is needed for effective geothermal reservoir stimulation. This is the case in the realm of both the physical processes and modeling. Many features and processes important to geothermal reservoir development such as multiple fracture interactions and mixed-mode propagation have not been implemented in existing fracture models. Rock fracture mechanics can provide insight into significant questions related to engineering of multiple fractures in geothermal reservoirs. In particular, it can guide efforts in controlling fracture spacing and location and fracture propagation in the presence of natural fractures.

Numerical modeling of reservoir stimulation must rely on a realistic conceptual model because the stimulation design and its interpretation strongly depend on the particular geological and geomechanical setting. For example, in the German HDR project at Falkenberg, Bavaria (Jung 1989), a single planar fracture was created and used as the heat exchange surface. Also, conventional stimulation has been carried out in Groß Schönebeck in northern Germany (Huenges et al. 2004) to enhance hot water production. The Los Alamos HDR experiment has shown that creation of an efficient heat transfer area requires a very large fracture, e.g., a circular fracture would have to have a radius of 580 m (Kappelmeyer and Gerard 1987). Hence, a number of parallel fractures connecting two wellbores might be considered as an alternative. Other experience shows that stimulation of a naturally fractured rock can be achieved by extension of existing joints or multiple natural fractures to create the desired heat exchange surfaces. Examples include the HDR project of Mayet de Montagne, France (Cornet 1987), Cooper Basin HDR (Asanuma et al. 2005; Baisch et al. 2006), deep heat mining project at Basel, Switzerland (Haring et al. 2008), and Soultz-sous-Forets European project (e.g., Baria et al. 1999; Bruel 2002). Reservoir design by a combination of tensile mode fracturing and shear stimulation can also be envisioned. An example is the Coso EGS experiment (Megel et al. 2005; Nygren and Ghassemi 2005; Sheridan et al. 2003) whereby evidence of both mode I propagation and shear slip have been reported (Julian et al. 1998, 2006). Regardless of the particular conceptual model deemed appropriate for stimulation design in a given geothermal setting, understanding of fracture propagation and interaction, possibly under mixed mode loading, is needed.

Early models of conventional hydraulic fracturing relied on elastic two-dimensional semi-analytical models (e.g., Perkins and Kern 1961; Geertsma and de Klerk 1969) and neglected poroelastic and thermoelastic effects. A thermoelastic analysis of a fracture in hot dry rock was presented by Abe et al. 1983, and Perkins and Gonzalez 1985 considered the possibility of secondary cracks during cold water injection in petroleum reservoirs. These studies involved a single two-dimensional vertical fracture and determined fracture volume and length. Hayashi et al. (1990) and Abe et al. (1995) examined fracture stability by considering a natural fracture as the heat exchange surface. Examining the conditions for the joint extension revealed that crack growth can be unstable when the inclination of the weakness plane is large; and that crack closure is possible, leading to splitting of the reservoir into isolated sections. Thermal processes and their contribution to variations of reservoir state of stress were not considered in those work. During extraction of heat, the surface of the fracture is cooled by the fluid and results in thermal contraction and increase in fracture width, which can in turn cause fracture propagation or formation of secondary cracks. A realistic analysis of this problem must rely on numerical modeling.

Early numerical modeling of stimulation in geothermal systems considered hydrothermal effects while generally neglecting rock mechanical aspects (GEOCRACK-Swenson et al. 1997; Hopkirk et al. 1981, Kohl et al. 1995). The advances in computers and computational techniques have lead to the development of a number of numerical models for analysis of more complex forms of reservoir stimulation (Sesetty and Ghassemi 2012; Weng et al. 2011; Zhang and Jeffrey 2006; Koshelev and Ghassemi 2003); however, these elastic models neglect the details of fracture propagation and interaction. Other approaches have used complex and real variable boundary element methods (Olson 2008; Dobroskok et al. 2005; Bobet and Einstein 1998) to model fracture coalescence. Poroelastic and thermoelastic displacement discontinuity methods (Zhou and Ghassmi 2011; Ghassemi and Zhou 2011; Ghassemi and Roegiers 1996; Carter et al. 2000) or the finite element method (FEM) (Boone et al. 1991), extended finite element method (XFEM) (Yazid et al. 2009) have also been developed. These approaches have been useful for studying near wellbore, and planar fracture propagation and help to better understand aspects of fracture intersection, but none can handle the complex problem of multiple fracture initiation and propagation.

Moreover, experimental analysis (Finnie et al. 1979) and analysis of cooling by injection (Perkins and Gonzalez 1985; Ghassemi and Zhang 2006) show that high stress zones develop in the vicinity of the main fracture, indicating potential for multiple initiation and propagation events. Cooling induced stresses cause a complete rotation of the stress field such that stress parallel to the secondary cracks becomes the in-plane major principal stress (higher than the component in the normal direction) and may exceed the in situ stresses of the geothermal reservoir (Perkins and Gonzalez 1985). The cracks can propagate into the rock matrix perpendicular to the main fracture and increase the permeability of the reservoir (Fig. 3). Such secondary cracks can be particularly important in reservoir development in view of their

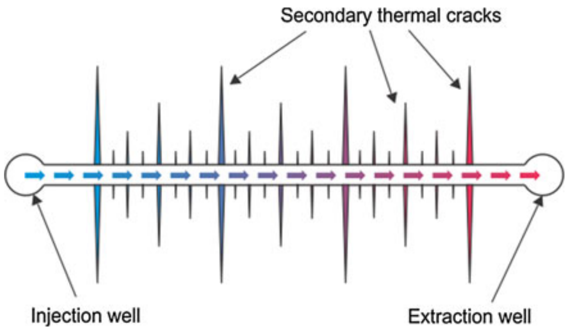


Fig. 3 Formation of secondary thermal cracks perpendicular to the main fracture cooled by injected water

potential role in enhancing the heat exchange area or increasing fluid loss. To increase heat extraction, the secondary thermal fractures should be sufficiently long and open to allow the fluid to flow deep inside the reservoir matrix where the heat is stored.

The formation and propagation of thermal fractures in response to cooling has been treated theoretically (Bažant and Ohtsubo 1977; Bažant et al. 1979; Nemat-Nasser et al. 1978). These stability analyses predict that many small cracks appear shortly after cooling of the surface; however, some of them will be arrested upon further cooling. In these studies it was concluded that because the growth of one crack will suppress the propagation of its nearest neighbors, only every second crack will grow further until the next bifurcation point is reached. However, these analyses did not include the high compressive in situ stresses which are typical for geothermal applications. Barr and Cleary (1983) numerically studied the effect of thermal crack penetration into a geothermal reservoir by assuming parallel fracture geometry without considering the propagation in time of many thermal cracks at unequal rates. As pointed out by Nemat-Nasser (1983), a more complete analysis would consider the possibility of unequal crack growth. Recently, Tarasovs and Ghassemi (2010) developed a complex variable boundary element numerical method for investigating the growth behavior of many cracks under the influence of a nonstationary thermal field resulting from cold water injection (Fig. 4), and a compressive stress field. The model has been used to study the influence of the main physical parameters of the system on the length and spacing of thermally driven fractures.Several simulations for various combinations of relevant parameters were performed. Figure 5 shows the crack length vs. cooling depth for three different minimum

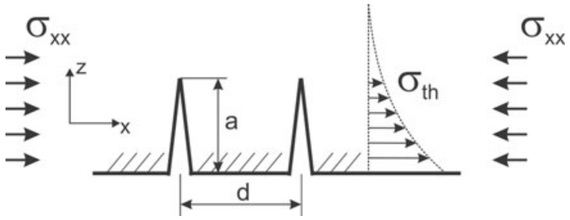


Fig. 4 An array of edge cracks loaded by thermally induced stress σ_{th} and a far-field compressive stress σ_∞

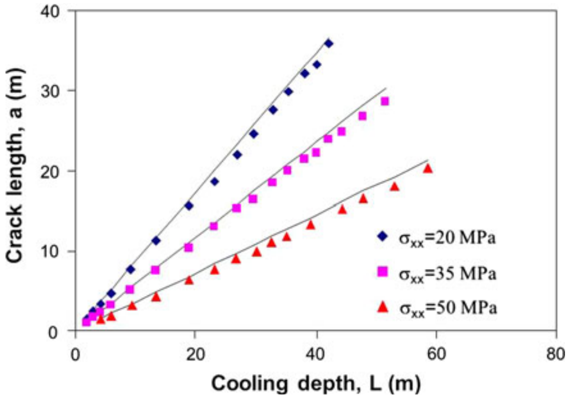


Fig. 5 Crack length as function of cooling depth *L*. *Dots* represent results of simulation, *lines*—approximation by an analytical expression for a cooled infinite space (Tarasovs and Ghassemi 2010). Note that σ_{xx} is the far-filed stress component perpendicular to the crack (see Fig. 4)

compressive in situ stress values (20, 35 and 50 MPa). The results for a random array of cracks in a half-space under uniform cooling show the cracks' length to be approximately proportional to the cooling depth *L*, or proportional to the square root of time. For a given cooling depth, a larger in situ stress results in smaller fracture lengths. The process of crack pattern formation is self-similar, i.e., the crack pattern repeats itself on different time and length scales, and depends on the parameter $\xi = \left(\frac{K_{IC}}{\frac{E\alpha_T\Delta T}{1-\nu}+\sigma_\infty}\right)^2$. The characteristic length ξ, is the ratio of the energy required to create a new crack surface and the energy that is generated in the solid by the thermal shock in the presence of in situ stress. A typical crack pattern is shown in Fig. 6.

Although 2-D analyses of fracture propagation such as those described above are useful and provide some basis for design, reservoir rock and in situ stress heterogeneity often result in fracture propagation involving tensile, shear and tearing modes [e.g., Healy

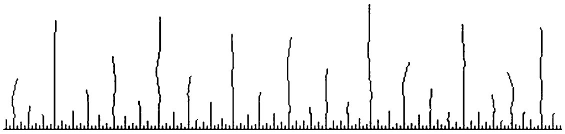


Fig. 6 Simulation results showing a typical crack pattern that developed with uniform cooling of the main crack

et al. (2006)], so 2-D numerical modeling is insufficient and a 3-D numerical analysis is required. New methods that can overcome some of the difficulties of modeling multiple propagation modes of fracture clusters are being developed to accurately predict geothermal reservoir stimulation. Some novel approaches are being considered such as peridynamics (Maceka and Silling 2007); virtual multi-dimensional internal bond (Gao and Klein 1997; Klein and Gao 1998), which is based on a philosophy similar to the cohesive surface method (Xu and Needleman 1994; Camacho and Ortiz 1996) but without its limitations (Zhang and Ge 2005a, b, 2006; Zhang and Ghassemi 2011); the variational approach (Bourdin et al. 2008), and damage mechanics (Tang et al. 2002; Yuan and Harrison 2006; Min and Ghassemi 2011). These methods offer the advantage of considering heterogeneity and propagation involving tensile, shear and tearing modes. But, issues related to mesh dependency, lack of existence of necessary functions in the methodology (variational), and distinguishing a fracture based on the degree of damage need to be overcome.

2.3 Role of Rock Discontinuities

Natural fractures in rock such as joints and faults have a major and perhaps dominating impact on the success of engineered geothermal systems through their effects on flow, heat extraction and induced seismicity. The latter is often attributed to shear slip on natural fractures caused by a reduction of the normal effective stresses across them, in response to an increase in the pore pressure field and/or thermal stress (Cornet and Jianmin 1995; Segall 1989). The shear slip on fractures can also increase the fracture permeability as a result of shear dilation. As reservoir pressure varies with injection and production, the effective stress in the reservoir also changes, leading to both fractures and matrix deformation. Generally, rock fractures are more deformable than the matrix and thus are more sensitive to pressure, temperature, and stress changes than the matrix. Therefore, fracture permeability dominates the flow behavior, so that joint deformation and strength characteristics are needed for analytical and numerical modeling of a reservoir's response to fluid injection and extraction.

The effect of stress change on the aperture and permeability of a single fracture has been well investigated in the laboratory, and a number of empirical models for joint closure have been developed (Iwai 1976; Goodman 1980; Bandis et al. 1983; Barton et al. 1985). The experimental data show a nonlinear relation between normal stress and fracture closure. For shear deformation, experimental data show an approximately linear relation between shear stress and shear displacement before yielding, followed by a more complicated response. Also, laboratory experiments and field observations have been used to develop peak shear strength criteria (Goodman 1980; Ladanyi and Archambault's 1970). Shear deformation can induce fracture opening as the opposing fracture asperities slide over each other and cause an increase in aperture (dilatancy). A simplified dilatancy model was proposed by Goodman and St. John (1977) based on the assumption of infinite stiffness; these and other re-interpretations (Fortin et al. 1988; Saeb and Amadei 1990) have the limitation of not considering the variable rock stiffness. Furthermore, real rock joints often are not isotropic and display roughness anisotropy (Grasselli 2006; Grasselli et al. 2002; Grasselli and Egger 2003; Fardin et al. 2001a; Kulatilake and Um 1999) and mechanical characteristics (Grasselli and Egger 2003; Jing et al. 1992). Kulatilake et al. (1995) have suggested a general relation for taking into account joint peak shear strength anisotropy.

Establishing relationships between joint surface characteristics and joint geomechanical parameters under appropriate boundary conditions (stress or displacement) can improve understanding of rock mass hydromechanical behavior. This can be achieved by integrated laboratory and field investigations that consider filling material, friction, roughness, and the stress state. Such data will help improve the ability to model how natural fractures influence hydraulic fracture propagation. An important issue that must be emphasized is that joint mechanical and hydraulic properties are scale-dependent (Fardin et al. 2001b). Experimental results (Barton and Choubey 1977; Bandis et al. 1983; Barton et al. 1985) show that larger samples display a lower peak shear stress and lower elastic shear stiffness, and that fracture permeability increases with sample size (Barton and Bakhtar 1982; Neuzil and Tracy 1981).

Natural fracture behavior during injection depends on effective stress, and the stress near a hydraulic fracture is influenced by slip on natural fractures. This interaction has a role in the formation of fracture network. Indeed, laboratory and field investigations have shown that departure from an ideal hydraulic fracture geometry is very likely in the presence of discontinuities, as evident by micro-seismic and tiltmeter fracture mapping and mine-back experiments (Jeffrey et al. 2010; Warpinski and Teufel 1987). Joints, faults, other structural feature give rise to fracture complexity. The evolution of this complex network is not well understood. Much development is needed to clarify the roles of shear and pure tensile failure during hydraulic fracturing and coalescence of hydraulic and natural fractures in EGS, and to quantify the evolution of the resulting fracture network permeability in response to coupled processes.

2.4 Coupled Processes and Permeability Variation Evolution

The geological conditions favorable for an engineered geothermal system include pre-existing, critically stressed and optimally oriented fractures that can be made more permeable through various stimulation techniques such as hydraulic, thermal, and chemical treatments. Given these conditions, a requirement for economic production of energy is high flow rates while avoiding short circuiting and rapid thermal drawdown. The porosity and permeability of induced and natural fractures are sensitive to chemical, thermal, and pressure disequilibria that arise from fluid circulation. The impact of these sensitivities of natural fracture aperture must be adequately understood. In particular, it is necessary to quantify the fracture closure and shear deformation in response to coupled hydrological, thermal, chemical, and mechanical processes over the reservoirs life span (a few tens of years).

The hydro-mechanical coupling in fractured rock has been the subject of many studies (see e.g., Rutqvist and Stephansson 2003) and it has been established that the aperture of natural fractures and micro-cracks are strongly stress dependent (Gale 1982; Raven and Gale 1985; Jones 1975; Cook et al. 1990). This dependency is rooted in the mechanical deformation of fracture asperities as well as the filling material or propping agents that are used (mostly in petroleum industry) to keep the fractures open. The hydro-mechanical characteristics of joints are also affected by thermo-poroelastic processes and free-face mineral precipitation/dissolution (Laubach and Tushman 2009; Ghassemi and Kumar 2007; Dobson et al. 2003; Singurindy and Berkowitz 2003; Rabemananaa et al. 2003; Martin and Lowell 1997).

The problem of isothermal and non-isothermal reactive flow in natural fractures has been studied in the context of geological problems as well as geothermal reservoir development (Pruess 1991; Xu and Pruess 2001; Wells and Ghiorso 1991; Lowell et al. 1993; Steefel and Litchner 1998) with emphasis on free-face dissolution of silica. These studies indicate that when the initial rock temperature and silica content are higher in the rock than the fluid, dissolution increases the fracture aperture near the inlet while precipitation decreases fracture width near the extraction point. An important factor in the manner these effects evolve is solute diffusion into the rock matrix. This is because the coupling between the fracture and matrix affects the thermal regime and the rate at which the concentration gradient between them influences the opening/closure of the fracture aperture (i.e., fracture permeability). This is particularly important for reservoirs having small fracture aperture (low aspect ratio) as in this case, solute and heat transport are diffusion dominated (as opposed to convection dominated fluid flow in highly porous and permeable reservoirs).

Because of the complexities in numerical modeling, kinetic effects are often neglected in studies of reactive transport through fractures, assuming that equilibrium thermodynamics is a suitable basis for calculating chemical interactions. However, incorporation of kinetics into models provides a more complete understanding of temporal evolution of fluid/rock systems. In fact, Steefel and Lasaga (1994) questioned the validity of maintaining equilibrium between dissolved silica and quartz on the fracture walls. A numerical study incorporating kinetics and matrix diffusion carried out by Suresh Kumar and Ghassemi (2005) showed that the diffusion of silica into and out of the reservoir matrix lowers the net mass of silica retained in the fracture. This enhanced dilution of silica in the fracture fluid favors less aperture change by free-face dissolution/precipitation while it prolongs the time needed to attain the equilibrium concentration in the fracture. Typically, higher initial water velocity, higher initial fracture aperture, lower reservoir thermal conductivity, lower reservoir porosity and lower effective matrix diffusion coefficient would lead to a higher degree of silica dissolution and a lower filling of the fracture near its outlet, thus lowering the flow impedance between the injection and production wells.

Another coupled chemo-mechanical mechanism that exerts a strong influence on fracture permeability is pressure solution (Revil 1999; Yasuhara et al. 2003; Yasuhara and Elsworth 2006 Bernabé and Evans 2007), a process that is driven by stress-induced gradients in chemical potential and by diffusion-controlled reaction rates along a fracture or fracture zone. As the mineral dissolves at stressed contacts, it is carried along a thin film of water along the joint (fracture) and is deposited elsewhere on the fracture surface. It is worth noting that in contrast to permeability increase with free-face dissolution, some lab (Elsworth and Yasuhara 2009) and field evidence suggests a loss in permeability with pressure dissolution. Many phenomenological and theoretical models have been developed to describe dynamics of this mechanically and chemically dependent behavior (Lehner 1995; Revil 1999; Yasuhara and Elsworth 2006; Liu et al. 2006) that can occur in fractures.

The precipitation/dissolution process in fractures is more complex for two-phase flow where one phase can become entrapped as a residual phase within a variable aperture fracture (Glass et al. 2003). If the reaction kinetics at mineral surfaces are fast relative to the dissolution of the trapped phase, preferential flow paths can develop. Experiments in rough-walled glass fractures (Detwiler et al. 2003; Detwiler 2010) show that in the presence of an entrapped phase, dissolution channels form much earlier and with higher mean aperture than fully saturated fractures.

The problem of reactive flow in fractures is further complicated when thermo-poroelastic deformation influences the fracture aperture. The individual effects of chemistry and thermoelasticity have been studied by Lowell (1990) with respect to seafloor black smokers. It was shown that as hydrothermal fluid entered cooler rocks, the resulting thermal stresses could contribute to the narrowing of the fracture openings and thus focus the upflow. Lowell and Germanovich (1995) suggested this effect could help stabilize hydrothermal output from the black smokers. Using a decoupled chemistry and thermoelasticity, Lowell et al. (1993) showed that the permeability reduction resulting from silica precipitation occurred about an order of magnitude slower than that caused by heating-induced expansion of fracture surfaces. However, as shown by Ghassemi and Suresh Kumar (2007), the rate and the time scale of each phenomenon can vary under different flow conditions.

Although some hydromechanical aspects of natural and induced fractures (e.g., in the context of “huff and puff”) have been studied using simple analytical models (Wessling et al. 2009), consideration of coupled processes in fractures relies on numerical modeling. Poroelastic behavior of joints has been considered using plane strain and axisymmetric geometries and the finite difference and finite element methods (Swenson and Hardemana 1997; Rutqvist et al. 1998; Guiducci et al. 2002; Svenson et al. 2007). A 3-D poroelastic displacement discontinuity method was developed to analyze the temporal variations of the fracture opening and slip upon sudden application of a fluid pressure (Ghassemi and Zhou 2011). The impact of poro-thermoelastic loading caused by injection/extraction in joints has been analyzed (Ghassemi et al. 2008). These studies show that under most EGS conditions, the fracture pressure and aperture away from the injection point are influenced by the poroelastic effect during the early injection stage. The thermoelastic stress becomes dominant after a long time of fluid injection. As different points on the fracture plane can experience different cooling and pressurization histories, they undergo different stresses and thus display different aperture variations (Rawal and Ghassemi 2012).

2.5 Reservoir Geodynamics and Induced Seismicity

The stimulation of the reservoir rock mass is often accompanied by multiple micro-seismic events. Micro-seismic events characteristics such as their locations, pattern, spatial distribution, and the temporal relation between the occurrence of seismicity and reservoir activities are often studied for design of EGS. Microseismic signals contain information about the sources of energy that can be used for understanding the hydraulic fracturing process (Pine and Batchelor

1984; Niitsuma et al. 1999; Julian et al. 2006; Warpinski et al. 1996) and the extent of the created reservoir and its permeability.

The occurrence of micro-seismicity in conventional geothermal fields, and the existence of a temporal relationship between injection/extraction operation and seismicity have been known for many years (e.g., Majer et al. 2007). In EGS, micro-seismic events detection and interpretation is used for estimating the stimulated volume and fracture growth, resulting reservoir permeability, geometry of the geological structures, and in-situ stress state (Warpinski et al. 2001; Gutierrez-Negrin and Quijano-Leon 2003; Pine and Batchelor 1984). The process commonly is referred to as *seismicity-based reservoir characterization* (Shapiro et al. 1999; Rothert and Shapiro 2003). Increased interest in efficient EGS development and the recent field experience with induced seismicity in Basel (Haring et al. 2008) have stimulated interest in investigating the potential for large seismic events.

Micro-seismic events are believed to be associated with rock failure in shear, and shear slip on new or pre-existing fracture planes (Pine and Batchelor 1984; Pearson 1981) and tensile fracture initiation (Foulger et al. 2004). Both failure modes can be related to injection induced pore pressure increases in a critically-stressed rock. However, a clear relation between the location of the micro-earthquakes and the fluid flow has not been established. As pointed out by Majer (2007), examination of the spatial and temporal rate of change in seismicity can be used to rule out or confirm some of the mechanisms. Evans et al. (2012) have documented and reviewed 41 European case histories of seismic response of crystalline and sedimentary rocks to fluid injection. The review showed that that generally sedimentary reservoirs tend to be less seismogenic than crystalline reservoirs. Also, according to Evans et al. (2012), induced seismicity has been observed in all cases of injection into crystalline rocks, but no correlation can be readily observed between the MEQ (micro-earthquake) strength and stress criticality. The indication is that in addition to critical stress levels, other rock mass conditions and processes contribute to felt MEQ.

Thermo-poromechanical processes not only change reservoir permeability, but also can cause micro-seismicity through induced in situ stress variations. Both phenomena have been observed during injection/extraction in the Coso and the Geysers geothermal fields (Petty 2002; Rutqvist et al. 2006; Majer 2007). Injection and withdrawal of fluids lead to poroelastic and thermoelastic stressing (e.g., Segall and Fitzgerald 1998; Mossop 2001; Ghassemi and Zhang 2004a, b; Rudnicki 1999). The thermo-poroelastic effects on reservoir seismicity can be viewed from two related standpoints: (a) the impact on the large scale in situ stress state and (b) the influence on the local fracture and fracture zone behavior, with emphasis on fracture opening, slip, and/or propagation. Segall and Fitzgerald (1998) investigated both poro- and thermoelastic induced stresses and their impact on the reservoir, with the conclusion that thermoelastic stresses associated with steam production are more significant for geothermal reservoirs. Mossop (2001) and Bruel (2002) studied thermal stress associated with injection and suggested that it contributes to reservoir seismicity.

The study of thermal stresses, as well as its application to geomechanics, has long been of interest. Thermoelasticity has been used to study inter- and intra-granular thermal cracking in certain igneous rocks (Fredrich and Wong 1986). There have also been a number of early investigations of thermoelastic effects in geothermal systems. Bodvarsson (1976) derived the stress field and surface deformation due to temperature changes in a geothermal system, and their impact on fracture aperture. Elsworth (1989) used a 1-D heat transfer model to study the impact of thermal stress on fractured rock permeability. Nygren and Ghassemi (2005) investigated the role of combined injection-induced thermoelastic and poroelastic stresses on joint slip, opening, and injection pressure, using semi-analytical models of 1-D heat and fluid diffusion into the rock matrix. The 1-D approach to fracture opening in response to cooling predicts an unbounded fracture opening as time increases, so that at least 2-D elasticity is necessary to obtain a physically realistic long term behavior.

The magnitudes of the 3-D thermal stresses associated with advective cooling was obtained by Mossop (2001) for an axisymmetric model of injection into a reservoir, and a coupled hydro-thermo-mechanical FEM was developed by Kohl et al. (1995) for a planar fracture. Willis-Richards et al. (1996) and Megel et al. (2005) studied the problem of injection pressure variation in a fractured geothermal reservoir using a finite element model and a statistically generated fracture network. In these studies, the temperature field and the thermal stresses in the rock mass have been modeled using a 1-D approach. A 1-D heat transport model can underestimate the heat transfer from the rock to the fluid (Ghassemi et al. 2003), and a 1-D treatment of the elasticity problem does not predict the correct distribution of thermal stresses. A 3-D heat extraction/thermal stress solution coupled to a 3-D elastic stress/displacement analysis was developed by Ghassemi et al. (2005, 2007) to obtain the opening and ride of a fracture under a given in situ stress field in response to cooling of the rock. The case of multiple intersecting fractures has been also considered (Safari and Ghassemi 2011).

Poro-mechanical and thermo-mechanical processes occur at different time scales, depending on the problem of interest and the rock mass properties. For example, the thermomechanical coupling is important during injection on the time scale of months to years (Ghassemi and Zhang 2006). It can be expected that changes in pore pressure may influence deformation of a rock discontinuity much more rapidly than temperature (Read 2004). This supports the notion that injection related seismicity is due to shear slip on natural fractures in response to a reduction of the normal stress across the fractures due to an increase in pore pressure. Consequently, it is commonly suggested that micro-seismic activity is indicative of water flow and enhanced permeability. But as it has been pointed out (Cornet and Jianmin 1995; Cornet et al. 1997), a pore pressure increase does not necessarily correspond to the existence of flow. Furthermore, injection pressure in geothermal reservoirs is often insufficient to open a fracture, pointing to the importance of thermal stresses (Bruel 2002; Stark 1990). Stark (1990) reports that half the earthquakes in the Geysers geothermal field (northern California) appears to be related to cold water injection at less than critical injection pressures.

Although progress has been made in quantitative and qualitative analysis of reservoir stimulation using MEQs (Shapiro et al. 1997, 1999, 2002; Cornet 2000; Rothert and Shapiro 2003; Parotidis et al. 2004), the fundamental mechanisms still are not adequately understood and several key questions remain unresolved in the analysis of micro-seismicity, namely the variation of seismic activity with injection rate, delayed micro-seismicity, the relation of the stimulated zone to the injected volume and its rate, the connectedness of the fractures hosting micro-seismic events and the resulting reservoir permeability. In addition, the longer term impacts of stimulation including continued seismicity, the healing or alteration of newly permeable fractures and the persistence of fracture permeability and its evolution remain to be investigated to better understand and manage the frequency and magnitude of MEQ and optimize reservoir development. Analytical, numerical and experimental rock mechanics research is particularly useful in guiding reservoir development and management and will help reduce the levelized cost of electricity from EGS.

3 Closure

The ability to engineer a stimulated volume of rock consisting of a network of natural and man-made fractures that provides fluid flow pathways and heat exchange surfaces for decades, would significantly increases geothermal energy reserves. An important step towards removing barriers to EGS development is minimizing uncertainties in reservoir structure and its dynamics. Such an effort must rely on reservoir geomechanics principles conditioned to geothermal settings. Therefore, rock mechanics/geomechanics experiments, modeling and analysis dealing with fluid/rock interactions constitute an integral part of a comprehensive approach to geothermal reservoir characterization and development. This is particularly true for complex hydrothermal reservoirs and enhanced geothermal systems in crystalline rock systems.

Expectedly, the reservoir stress state is of fundamental importance to many aspects of geothermal energy development such as optimum drilling trajectory, borehole instability, stimulation, and fluid loss, all of which impact economic geothermal energy production. High temperature tool development and modeling advancements will contribute to reducing the operational difficulties in applying hydraulic fracturing to stress measurement in geothermal settings.

Geomechanical data such as matrix and natural fracture mechanical properties and their dependence on coupled thermo-poro-chemo-mechanical processes are needed for rock mechanics and reservoir modeling and analysis that aim to enhance and sustain flow into the production well with minimum hydraulic and thermal drawdown. Existing coupled constitutive relations need to be evaluated and multi-scale geochemical/geomechanical relations for matrix and fracture permeability evolution to be developed. Also, it is necessary to quantify the uncertainty in computational predictions of permeability evolution and performance of EGS projects.

Fluid injection/circulation and heat extraction processes affect reservoir geodynamics. The interaction between strain localization (in the form of rock matrix strain, fractures and faults), fluid flow, and heat transfer is manifold and complex; understanding this interaction and its role in reservoir evolution and induced seismicity is critical to successful implementation of EGS concept. Therefore, the relation between size and spatio-temporal distribution of MEQs accompanying injection/extraction operations in reservoirs must be further studied to establish the relationship between seismic energy release and injected volume and pressure for various lithological and tectonic settings.

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