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Deep Geothermal: The 'Moon Landing' Mission in the Unconventional Energy and Minerals Space

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ABSTRACT: Deep geothermal from the hot crystalline basement has remained an unsolved frontier for the geothermal industry for the past 30 years. This poses the challenge for developing a new unconventional geomechanics approach to stimulate such reservoirs. While a number of new unconventional brittle techniques are still available to improve stimulation on short time scales, the astonishing richness of failure modes of longer time scales in hot rocks has so far been overlooked. These failure modes represent a series of microscopic processes: brittle microfracturing prevails at low temperatures and fairly high deviatoric stresses, while upon increasing temperature and decreasing applied stress or longer time scales, the failure modes switch to transgranular and intergranular creep fractures. Accordingly, fluids play an active role and create their own pathways through facilitating shear localization by a process of time-dependent dissolution and precipitation creep, rather than being a passive constituent by simply following brittle fractures that are generated inside a shear zone caused by other localization mechanisms. We lay out a new theoretical approach for the design of new strategies to utilize, enhance and maintain the natural permeability in the deeper and hotter domain of geothermal reservoirs. The advantage of the approach is that, rather than engineering an entirely new EGS reservoir, we acknowledge a suite of creep-assisted geological processes that are driven by the current tectonic stress field. Such processes are particularly supported by higher temperatures potentially allowing in the future to target commercially viable combinations of temperatures and flow rates.

KEY WORDS: geothermal energy, enhanced geothermal systems, fracture mechanics, creep, dissolution, precipitation.

0 INTRODUCTION

Deep (unconventional geothermal) energy extracted from hot basement rocks is an international research challenge pushing the frontiers of geosciences and engineering sciences. Australia has proposed to make unconventional geothermal

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energy possible through private money and industry investment with only minimal government support. Unfortunately, although in excess of $0.5 billion have been invested only limited success can be reported. Therefore, private industry has found it difficult of late to attract matching funds for allocated government grants. Clearly, a new strategy needs to be devised acknowledging the fact that the problem of economical extraction of deep geothermal energy cannot be solved by classical concepts. The requirement for large capital investment provides the first part of the analogy to the equally ambitious 'moon landing' mission. This paper mainly addresses the second part of the 'moon landing' counterpart in the energy and minerals space. Unconventional geothermal energy poses a new science challenge that may present unexpected opportunities for deep reservoir engineering and beyond. Strategies have to be devised that acknowledge and are capable to describe the unconventional nature of the material behaviour at high temperature and high depth. We claim that these challenges can only be met by an "unconventional geomechanics" approach. We will first briefly revisit the classical concepts of deep geothermal energy extraction.

The concept of drilling into the hot crystalline basement and extracting heat through an artificially engineered reservoir has remained a challenge for geothermal energy since the early experiments at Fenton Hill, USA. The original idea of a hot dry rock (HDR) reservoir was to create fluid flow paths between an injection and extraction well deep into the crystalline hot rock by hydraulic fracturing. It became clear in early projects that rather than creating new hydraulic fractures, the existing natural fractures provided the flow paths, and their transmissibility was improved by stimulation. This has lead to the use of the term Enhanced (or Engineered) Geothermal Systems (EGS). Numerous projects have been carried out in the USA, Europe, Japan and Australia all facing the same problem. The artificially stimulated flow rates could only be sustained at a maximum of around 20–65 L/s, and only with significant parasitic (energy and water) losses incurred through pumping at high operating pressures. A main lesson learned is the necessity to take advantage of the existing geological inventory and the neotectonic deformation field and target existing fracture zones with existing hydrothermal flow.

The original idea, as put forward by one of the protagonists Don Brown (Brown et al., 1999), was to create an EGS within a previously impermeable body of a hot crystalline basement rock containing an array of re-sealed (and therefore essentially impermeable) joints. The original idea of a HDR reservoir was therefore to create by hydraulic pressurization a deep, multiply jointed rock mass such, that it is totally confined, and enclosed within a "stress cage" as an elastic response to the hydraulic stimulation of the HDR reservoir. The idea was to select the production temperature, by selecting the drilling depth and the size of the reservoir, by the amount of fluid injected. The first reservoir tests in Fenton Hill in 1980 proved successfully that a production flow rate of 5.9 L/s and a temperature of 158 °C can be achieved. The phase II experiments between 1986–1995 improved the production temperature to 190 °C and a production flow rate of 13.5 L/s. Injection water loss was also improved from an initial 0.4 to 0.15 L/s for the phase II testing. However, to date we have not seen a commercially viable operation, which could be achieved if the flow rates are at least quintupled, and the water loss and the excessive pumping power problems overcome.

The partial success of the Fenton Hill operation sparked a series of similar attempts (Abe et al., 1999) over the past 30 years in England (Rosemanowes), Sweden (Fjaellbacka), France (Mayet de Montagne, Soultz), Germany (Urach), Japan (Hijori) and Australia (Habanero). Improvements over the Fenton Hill experiment have only been incremental; yet, important lessons have been learned in the European science project in Soultz where a modified concept to the one followed at Fenton Hill was presented.

The European Soultz-sous-Forêts project set out in 1987 with the same geologic target as the Fenton Hill project (the crystalline basement), however, as an alternative choice a geological system, where active normal faults were expected, was chosen. The granitic basement was not 'dry' but contained geothermal fluids migrating along the fault. Therefore the project was labeled an EGS rather than a HDR project. It reached a target temperature of 200 °C and a maximum flow rate of 60 L/s during stimulation. The expected production flow rate for the first geothermal power plant in Soultz sous Forets is 35 L/s at a production temperature of 175 °C (Genter et al., 2010). A challenge was the existence of a seriously damaged granitic reservoir in the area of fluid circulation with a style of "fracturing" that was quite unexpected. Soultz features a number of seriously altered zones of granite, which cannot be interpreted by classical fracture mechanics, but rather appear to be strongly affected by fluid alteration zones. From the appearance of these fluid alteration zones the question is raised; what role do chemical alterations play in a deep crystalline granitic reservoir? Rather than using a simple extension of classical linear elastic fracture mechanics to stimulate a fully elastic "stress cage", a new multi-physics approach was found to be needed where thermal, mechanical, fluid, and chemical processes are considered in a fully coupled manner. The science that deals with quantifying these processes is Thermo-Hydro-Chemo-Mechanical (THMC) reservoir modeling.

In the late 1990's a similar natural fracture based EGS project to the Soultz Project begun in Australia. Initially in 1994 (Somerville et al., 1994), Australian researchers proposed to target pre-existing horizontal fractures likely to be present in a thrust faulting stress environment, rather than pre-existing fractures with a vertical aspect. This approach could have the advantage that, if many such natural fractures can be intersected, heat extraction could be maximized (Abe et al., 1999). This idea was appealing to industry, and as a worldwide first the extraction of heat out of the crystalline basement was tackled as a commercial venture by the formation of Geodynamics Limited, which was listed in September 2002 on the Australian Share Market. Geodynamics targeted a system located in hot granite beneath the Cooper Basin in South Australia with a higher temperature than the European project. Four successful wells were drilled about 4.5 km deep (Habanero 1, 2, 3 and 4). Based on microseismic interpretation, drilling parameters and well logs, the fractures can be traced in two adjacent Habanero wells at ~500 m distance, which intersected the same fracture system. The well observations and the stimulation experiment provided a relatively detailed image of the fractures—identifying three fracture systems. All fractures feature a relatively shallow dip angle (between 28° and 10°), with the fracture system appearing to be truncated at shallower depths. Fractures do not penetrate the top of the granite. The fluid pressure was found to be extremely high about 30 MPa above hydrostatic. This raises the questions on the source of the enormous fluid pressures, which are not recorded in Soultz.

1 KEY PROBLEMS FOR EGS TO BE SOLVED

The foregoing short review of over thirty years of EGS has highlighted the key problem. In spite of the technical feasibility showcased already in the early stimulation experiments at the Fenton Hill, the technology has not made a breakthrough into the energy market. The reason is that little progress has been made in the meantime on (1) achieving the required flow rate through the reservoir (2) solving the water loss problem and (3) keeping the parasitic pumping power to a minimum. Unless there is a breakthrough in solving these three issues, the commercial viability of an EGS play is all about achieving scale. Hence, from simple thermodynamic consideration lower temperatures are currently not viable. We conclude that the target temperature for EGS must be well above 160–180 °C in order to get return on investment.

The problem can be rephrased in a different way. It is feasible, but not yet reliable (with our current technologies), to generate hydraulic transmissivity by creating or enhancing existing engineered hydraulic fractures in the reservoirs so that the desired flow rates can be achieved. For such an engineered fracture system to be commercially deployed, the fracture transmissivity must be generated reliably and the resulting transmissivity after stimulation must be sufficiently high to allow commercial circulation rates at relatively small pressure differences. Currently, the stimulation of the reservoir primarily by mobilizing shearing has not provided sufficient transmissivity with the pressure difference required to produce flow through the reservoir requiring the use of high pumping power (1/3 of the electricity produced by the geothermal resource).

2 NEW APPROACH FOR DEEP GEOTHERMAL ENERGY

In order to make deep geothermal energy viable, we clearly have to take a different scientific approach and acknowledge and stimulate the overlooked rich failure modes that are operating at high temperatures and pressures at longer time-scales. In addition to the classical stress controlled fracture processes, that rely on short elasto-dynamic time scales and the conventional fracture modes, a plethora of failure processes exist that rely on thermally activated processes, which macroscopically can be identified as time-dependent creep processes and involve reactivated grain rotations. Rather than relying on new fractures through hydraulic stimulation we consider the natural mode of fractures that are established through geological time. Owing to the longer time scales involved and the low tectonic strain rates these natural modes are often established and maintained through participation of ductile deformation modes facilitated and supported by fluid flow. If these modes can be understood then it appears viable to devise a new engineering framework on how to interact with these fractures on a human time scale.

A comprehensive description of the geological fracture network requires the consideration of the physics and chemistry of concatenated processes across multiple time scales from short classical brittle time scales to longer time-dependent time scales. These are, conversely, also operating on different length scales because of their difference in hydraulic/chemical/thermal diffusivity. Important role might be played by emerging length scales associated with grain rotations and rotational instabilities through the effect of local apparent negative stiffness. Before going into the description of the longer time scales the new ideas on extension to classical fracture mechanics approaches on short time scales are presented.

3 NEW FRACTURE MECHANICS STIMULATION METHODS ON SHORT TIME-SCALES

This is the classical realm of reservoir stimulation. However, we claim that the science has not exploited all of the existing possibilities. A drastic proposition would be, for instance, to stimulate the reservoir by applying an explosive source and thereby irreversibly change the internal structure of the system such that a greater thermal power can be extracted. The advantage of this method is that the science underpinning the fast time-scale alteration of rock properties has received interest from a different field and proceeded very far such that this technology can be controlled in an efficient manner by numerical simulations. The techniques are currently under investigation in the Lawrence Livermore National Laboratory underpinned by technology transfer from unconventional and conventional explosive simulations (Anton Tarabay, pers. comm.). However, explosive stimulation of a large volume of rock typically requires a very close well spacing, which is a challenging task at EGS reservoir depths and may make the economics unfavourable.

Another proposition using fast time-scale processes, often referred to as deflagration, involves using high-pressure gas generated by a rocket propellant to generate a short duration, high pressure gas pulse in the well bore. Fractures generated from such an operation are generally thought be limited to the near well bore region. Such fractures have been shown to grow in a star-burst pattern with 3 to 6 main fractures extending up to 5 m from the wellbore (Cuderman et al., 1981). They can be used as super-perforations or as the main stimulation to connect the well into a natural fracture system, thereby essentially creating a significantly larger well bore effective radius. Current efforts involving this technology are focusing on staged “rocket burns”, where, initially the pressure is raised, and then over a 30–60 s (or longer) duration the pressure is varied by configuring the rocket fuel appropriately based on reservoir properties. It is hoped that further reaching fractures can be created in this fashion.

We are currently following a less drastic approach by proposing a link between fast time-scale processes and long time-scale THMC phenomena described in the next section. The innovation is that a series of fracture modes are stimulated in a time-dependent manner in order to stimulate the wells along the entire reservoir; the stimulation must be directed into targeted sections of the well by effective zonal isolation that is enabled by new approaches to wellbore completion. Given effective zonal isolation is achieved, shear or opening-mode fracture stimulation can be carried out into a number of intervals along the well. Assuming the well is drilled in the direction of the minimum principal stress, opening-mode hydraulic fractures can be extended and are expected to orient transverse to the wellbore. As these fractures grow into the reservoir, they continuously loose fluid into the surrounding fractured rock, creating associated shearing and shear stimulation. This stimulation method would entail placing 10 or more such fractures, successively, along the wellbore. The performance of the reservoir stimulation on the long time scale will rely on the control of the associated shearing over the long time scale such that the fractures are essentially self-propping.

Furthermore, these hydraulic fractures should be grown to be approximately parallel to one another, avoiding any tendency for growth toward or away from an adjacent hydraulic fracture (Bunger et al., 2012). Because of the non-planar nature of the opening fracture paths, it is expected that in the presence of shearing the fractures will be self-propping. The processes that contribute to symmetry of the fracture growth for such an array need to be evaluated. The values of conductivity that can be generated and maintained by self-propping need to be determined. Artificial proppants may be required if self-propping is not sufficient. After placement of the array of hydraulic fractures, further shear, chemical, or thermal stimulation can be carried out, if needed, by taking advantage of the conductivity and flow paths provided by the hydraulic fractures.

Another possibility is in inducing a special type of borehole breakouts in the form of compaction bands (e.g., Haimson, 2006) whose propagation is ensured by removing the rock debris by the fracturing fluid. Investigation of this as well as the propagation of the formed normal/shear fractures can be based on our proposed unified rotational mechanism of fracture propagation Dyskin and Pasternak (2014), which can be particularly important if thermal cracking and chemical dissolution mechanisms can weaken the grain boundaries.

Thermal cracking is another overlooked but fundamentally important fast time scale crack nucleation mechanism at elevated temperatures. This has been investigated in time-lapse synchrotron X-ray analyses. The mechanism is based on the differential expansion of the mineral constituents of the granite causing delamination cracks on grain boundaries (Schrank et al., 2012, Fig. 1). Thermally induced cracks can obviously be closed due to mineral precipitation if fluid flow occurs.

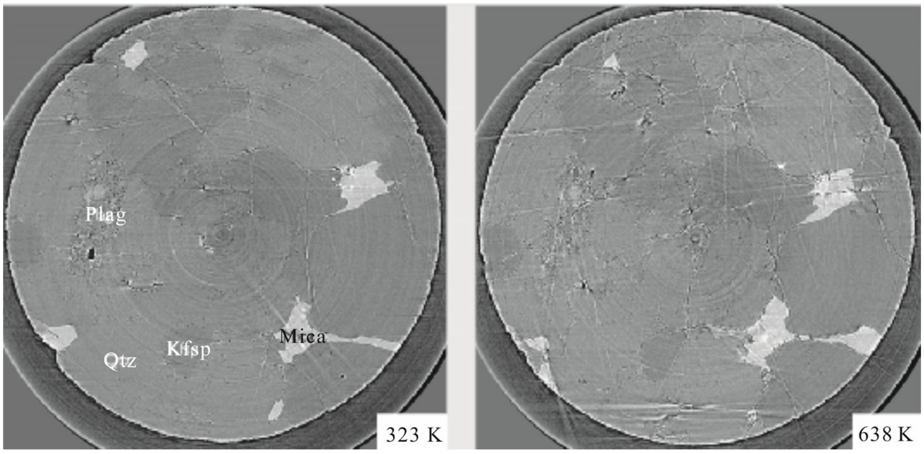

Figure 1. Snapshots of a time-lapse synchrotron heating experiment of a Westerly granite sample showing the importance of thermal-elastically triggered porosity changes. Images are horizontal slices through the sample cylinder with a diameter of 2.5 mm. The microporosity in the plagioclase crystal (Plag, left) at laboratory temperature (323 K) is seen to be reduced due to thermal expansion strain at 638 K while the grain boundary cracks between quartz (Qtz), K-feldspar (Kfsp) and mica are generated as new grain boundary cracks at high temperatures. A finite-element model has successfully reproduced the synchrotron experiment, and the derived thermal cracking model predicts upscaled material properties measured in independent laboratory measurements on larger samples (Schrank et al., 2012).

4 NEW STIMULATION METHODS ON LONG TIME-SCALES

The micromechanisms of the formation of long time-scale connected porosity channels in granites can be investigated in natural samples of deformed granites. These samples are extracted from an active or a fossil deformation zone and assessed in the context of their porosity forming mechanism. Ideally this is done for the reservoir rocks and conditions of the geothermal target. Unfortunately, this is a very difficult task in an active geothermal field and we have resorted to sampling a fossil geothermal system in granite. In earlier work we have investigated the fundamental mechanisms of formation of porosity channels in deformed granites at greenschist metamorphic conditions (Fusseis et al., 2009). The samples are from the Redbank shear zone in Australia and were analyzed with synchrotron X-ray micro-tomography. Figure 2 shows a hand specimen featuring a strain gradient from homogeneously deformed granitic gneiss (sample top) into a mylonitic shear zone (bottom). Associated micro-tomograms of host rock and shear zone reveal the formation of a dynamic mode of interconnected porosity network in the mylonite.

Figure 2. Microporosity (red) in a mid-crustal granitic shear zone (X-ray resolution 1.3 µm). Quartz and feldspar are not shown (translucent) while the blue color indicates mica. The percolation threshold for fluid transfer is reached through a shear-assisted dynamic dissolution-precipitation mechanism in the central (ultramylonitic) part of bottom 2 cm of the hand specimen (Fusseis et al., 2009) which has submicron size pores (Fig. 3).

Scanning electron microprobe images (Fig. 3) and NanoSIMS analyses show that the fluid transfer mechanism in the investigated mid-crustal shear zone is dominated by the following dominant K-feldspar mineral dissolution precipitation reaction (K-feldspar plus H^+ dissolves into muscovite plus K^+ and quartz in aqueous solution)

$$3KAlSi_3O_8+2H^+ \rightleftharpoons KAl_3Si_3O_{10}(OH)_2+2K^++6SiO_2\,(aq) \quad (1)$$

Additional mineral dissolution-precipitation mechanism involving the plagioclases may also be contributing. This finding confirms an important creep mechanism for polycrystalline rocks by material transport through a liquid phase (Raj, 1982a). The mechanism has been postulated to be the result of metamorphic fluid breakdown reactions that occur in rocks when the ambient temperature is elevated such as in geothermal conditions. The reactions are triggered by deformation of the solid rock matrix in a tectonic stress field. Figure 3 shows evidence of precipitation of K-feldspar in highly aligned porosity channels in the central part of the shear zone.

Such dissolution-precipitation mechanisms are well known in geology for a whole suite of temperatures relevant for geothermal plays through all temperature conditions from weathering through diagenesis to metamorphic conditions. Different minerals participate in these reactions depending on their thermal activation and reaction kinetics (Zhu and Lu, 2009). In general terms the mechanism relies on a fluid release reaction $AB_S \rightleftharpoons A_S+B_F$ whereby gas or fluids are chemically trapped in a solid component AB_S, which upon critical activation transforms looses its fluid/gas phase B_F and forms the solid A_S. While for the above listed reaction (Eq. 1) the activation temperature is above 200 °C (solid granite) activation temperatures can be much lower for different rock types. Weathered granite, for instance, can—in the presence of water—display the same type of reaction at much lower temperatures. A simple example is the dissolution of feldspar and clay precipitation (Zhu and Lu, 2009). Clay minerals are the ultimate low temperature end-member deforming in a ductile

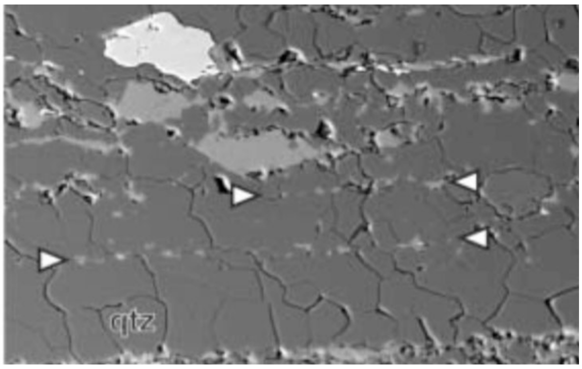

Figure 3. K-feldspar (light grey) precipitation in the central part of the shear zone (Fig. 1). The precipitates follow highly aligned porosity channels that have been argued to be bear evidence of a dynamic fluid percolation associated with creep fractures between the white arrows. The size of the pores (dark spots) is around 1 µm and less. Reproduced with permission from Springer (Regenauer-Lieb et al., 2009).

manner and well known to release their water close to the surface and recapture it below that temperature.

The reaction can be generalized for all rock types/mineral compositions (including sediments) as a thermally activated process where the reaction rate is kinetically controlled (Fowler and Yang, 2003) by the temperature T, the activation energy E and the rate constant k_0

$$AB_S \rightarrow A_S, \quad \frac{\mathrm{d}A_S}{\mathrm{d}t} = A_S k_0 \mathrm{e}^{-\frac{E}{RT}} \tag{2}$$

where k_0 is the rate constant for the reaction. The dissolution kinetics is thus rate limited by an activation barrier and it requires energy input (usually mechanical deformation) to cross the barrier. Another important point is that dissolution-precipitation can only take place if fluids can flow. The dissolution-precipitation reaction is therefore an ideal illustration of a thermo-hydro-mechanical-chemical (THMC) coupled process. The reaction cannot take place if there is no energy input into the system and thus it requires a driving force, provided in the field by a tectonic stress field. The result is a slow creep process that is based on a THMC coupled permeability network. Macroscopically, this relationship is traditionally modelled by either an exponential, linear or a power law relationship between effective strain rate and effective stress (see Table 3 in Gratier et al., 2013).

Although creep fractures are particularly prominent in chemically aggressive environments (Raj, 1982b) and are well known in material sciences (Ashby et al., 1979; Ghandi and Ashby, 1979), they have only been introduced to geosciences relatively recently through theoretical considerations (Regenauer-Lieb, 1999), controlled laboratory experiments (Rybacki et al., 2007) and the above described synchrotron analysis of a naturally deformed granite in the Redbank shear zone (Fusseis et al., 2009). We postulate here that thermally and tectonically activated permeability generation processes by dissolution-precipitation creep form the natural network of fluid transfer in high-temperature granites. Because this mechanism requires an active deformation field, it needs to be driven by the current tectonic stress field. This is because the fluid-assisted feldspar breakdown reaction is an endothermic process and requires energy input from tectonic deformation. A feldspar breakdown that is simply driven by additional thermal energy without tectonic alignment on shear planes, would result in diffuse and pervasive reaction front unlike the localized reaction sites seen in Fig. 3. It follows that any fluid release from older deformation histories will most likely have precipitated and will not form a permeable network for circulating geothermal fluids. However, active tectonic stress fields can generate grain-boundary weakening, release thermal stresses frozen at grain boundaries by mineral dissolution reactions or simply cause dissolution-precipitation creep with grain boundary sliding. All of these mechanisms can trigger unconventional fracture mechanisms that involve small grain boundary rotations. Such rotational mechanisms require modifications of classical fracture mechanisms and extension to a new unified fracture propagation criterion.

5 UNIFIED FRACTURE PROPAGATION CRITERION

The unified fracture growth criterion is based on two premises (Dyskin and Pasternak, 2014, 2013): (1) Reactivation of grain rotation caused by damage accumulation due to compressive loading or differential thermal expansion; (2) mutual rotation of grains leads to bending of the inter-grain links with subsequent development of flexural microcracks in the links and their final breaking (Fig. 4). The bending is effected by moment stress concentration at the fracture tip (Fig. 4). It was shown that the effect of moment stress is an order of magnitude larger than that of the conventional stress concentration. As a result, practically the same moment stress concentration would be required to produce en-echelons of microcracks effecting in-plane propagation of tensile (Mode I) fractures, anti-Mode I fractures (compaction bands) and Mode II fractures, Fig. 4.

The technical means for implementing the unified criterion of fracture propagation is provided by the theory of the small-scale Cosserat continuum (Pasternak and Dyskin, 2012b; Dyskin and Pasternak, 2010, 2008). The theory is based on the notion that in particulate materials such as the rocks the Cosserat length scales are commensurate with the grain size and therefore microscopic with respect to the length scales involved in the fracture propagation. This opens a way to use asymptotics of small Cosserat lengths. Subsequently, the main asymptotic term can be obtained by using the conventional elastic solutions for the stress intensity factors and displacement field around the crack tip followed by using the displacement gradients to determine the rotation field and then the Cosserat constitutive equations to determine the moment stress distributions. This approach can be used for both obtaining closed form solutions and for implementation in any fracture mechanics enriched finite element calculations.

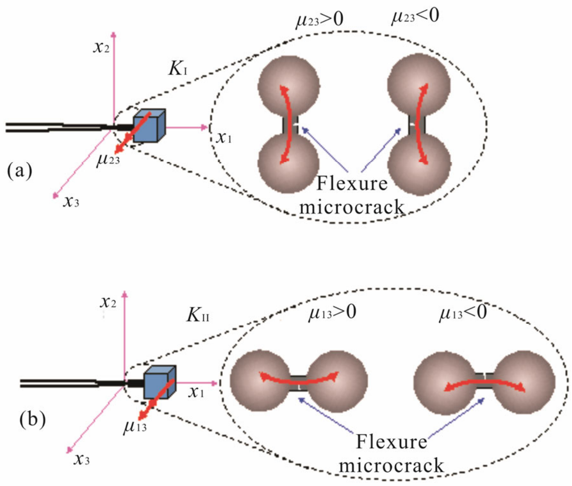

Figure 4. Unified mechanism of in-plane fracture propagation. (a) Tensile fracture, K_I, $\mu_{23}>0$ and compaction band, K_I, $\mu_{23}<0$; (b) shear fracture.

6 MICRO-SEISMIC MONITORING OF RESERVOIR STIMULATION

Reducing the total cost of geothermal development begins with an efficient exploration process leading to resource discovery, evaluation and quantification. We describe in the following a new approach where the above-described unconventional micro-mechanisms of fracture may be detected through their particular geophysical signal during stimulation. Reservoir stimulation using fracturing fluid can involve the production of tensile or shear/dilatant hydraulic fracture or a propagating compaction band. The type of the fracture produced and thermo-mechanical processes involved will influence the type and spatial distribution of microcracks produced. This gives rise to the use of micro-seismic methods to monitor the type of fracture. The determination of microcrack distribution normally requires a multichannel seismic recording system capable of accurately locating the sources associated with the fracture/band. We developed a new method, which potentially requires only a single channel to determine the type of distribution.

The method is based on analyzing the arrival times, $\Theta=\{t_1, t_2, \ldots t_M\}$, of the micro-seismic events using what can be called the 'spectrum of arrival times' and its energy in the frequency range $(0, \Omega)$

$$\begin{aligned} & S(M,\Theta,\Omega) \\ & =\int_0^{\Omega}\left|\sum_{m=0}^{M}\exp(-it_m\omega)\right|^2 d\omega \\ & =(M-1)\Omega+2\sum_{m=2}^{M}\sum_{i=1}^{m-1}\frac{\sin(t_m-t_l)}{t_m-t_l} \end{aligned} \tag{3}$$

Different types of distribution of the micro-seismic events lead to different spectra. In particular, the transition from randomly generated events to the events emitted form the crack contour leads to the shift of the spectrum to the higher frequencies—the blue shift (Dyskin et al., 2013; Pasternak and Dyskin, 2012a, c). Quantifying the blue shift is done through the blue shift indicator

$$\sum\nolimits_n(M,\Theta,\Omega)=\frac{S(M,\Theta,\Omega)-S_r(M,\Omega)}{S_r(M)} \tag{4}$$

where $S_r(M)$ is the energy of the arrival times of randomly generated micro-seismic events, Ω is the maximum frequency of the part of spectrum for which the energy is calculated.

The Blue shift indicator allows one to determine the type of micro-seismic event distribution and, ultimately, the type of fracture.

7 NEW DAMAGE MECHANICS APPROACH

We have described above short and long-term mechanisms of crack/void generation in granites that are currently overlooked in the classical hydraulic fracture stimulation protocols. One mechanism requires a long time scale creep process and is expected to be restricted to a regime above a critical temperature for thermal activation of the mineral breakdown reaction. The other process is a fast process but can be retained on long geological time scales. Here we describe a computational approach that can describe the interaction of these new classes of fracture with the classical important porosity generation mechanisms, i.e., those of brittle fractures such as triggered by the hydraulic stimulation or a natural seismic event.

It is difficult to describe all of the above-described mechanisms explicitly at current computational power available for modeling the reservoir. Such a simulation requires time steps to go from milliseconds to millions of years and micrometer-level to hundreds of kilometers. We therefore suggest a simplification and use an implicit description of the microporosity generation processes by integration over several cycles of the microporosity generation using an approach that relies on the basic micro-physics and micro-chemistry of the porosity generating mechanisms. The models are then upscaled on selected subscale models, delivering a better confidence in classical damage mechanics approximations. The damage mechanics approach is well established in material sciences and known as a smeared crack approach. Rather than modeling each individual microcrack an assembly of microcracks is modeled and their effect on the mechanical behavior of a representative volume element (REV) is assessed (Karrech et al., 2014, 2011). The long time scale behavior of the REV is subsequently modeled using a thermodynamic evolution law based on the sum of the individual microporosity generating mechanisms cast into a microstructurally enriched continuum formulation (Regenauer-Lieb et al., 2013a, b)

$$\dot{W}_{diss}=\chi\dot{W}_{mech}+\sum_{i=1}Y_i\dot{D}_i \tag{5}$$

where the total dissipated work rate $\dot{W}_{diss}$ is dissipated as heat $\chi\dot{W}_{mech}$ plus the rate of the microporosity generating damage mechanisms, $\dot{D}_i$ multiplied by the associated thermodynamic force Y_i. In the case of a classical brittle fracture the thermodynamic force is the fracture stress and the damage parameter is the percentage of crack volume generated (1 is the total volume of the REV). In the case of a creep fracture the damage force is derived from the partial derivative of the stored energy (Helmholtz free energy) over the creep damage parameter (microporosity generated by the creep fractures). An extension to anisotropic damage mechanics for more detailed modeling of geomechanics around a wellbore has been developed (Gaede et al., 2013). The approach has also been extended recently to involve fluid breakdown reactions such as occurring during partial melting (Liu et al., 2014).

The above-described formalism has been implemented into a finite element approach and is currently being tested for deep geothermal reservoirs. Key model predictions such as fluid transfer zones, fluid chemistry, high fluid pressure and the expected breakdown of the mechanism below a critical activation temperature need to be confirmed in the natural geological examples. The subsequent step for the ductile stimulation method is as following. The logical prediction of our approach is that classical hydraulic fractures are not enough for flow assurance and improvement in such high-temperature reservoirs. While the stimulation may, profit from hydraulic fractures we suggest that the reservoir is best stimulated by a slow injection protocol that considers the critically activated processes and the linking of the above described mixed mode brittle and ductile micro-porosity processes to a mesoscopic and macroscopic overall ductile stimulation protocol. In a nutshell our suggestion for a new paradigm for reservoir stimulation can be described by reactivating pre-existing faults at reservoir scale in an aseismic, ductile manner. A side effect expected from the new "soft" stimulation method is that owing to the design specification of a macroscopic ductile response, the proposed method offers the potential of a safer control over the stimulation process compared to conventional stimulation protocols such as shale gas reservoirs.

8 DISCUSSION

We have proposed a fresh approach for unconventional reservoirs subject to higher temperature and pressures than usual. The approach relies on modeling and identification of new micromechanisms of brittle and ductile fracture involving grain boundary processes through thermal cracking and dissolution-precipitation creep (Alevizos et al., 2014; Poulet et al., 2014; Veveakis et al., 2014). We have presented a unified fracture propagation criterion and a continuum 'smeared crack' approach that can be used to upscale the rotational degrees of freedom encountered in the fracture process and help to design stimulation protocols based on the rate competitive processes in the microfractures. Without going into the necessary details of large scale modeling we have emphasized the implicit need for identifying the large scale tectonic driver as the novel stimulation protocol is based on the fault reactivation of geological structures through the background tectonic stress field.

It is worth noting that the permeability network of the geological structures establishes itself on time scales of years and requires an extremely slow background strain-rate. A thorough empirical study duplicating geological processes is not possible in the laboratory. As an example experiments on dissolution precipitation for plagioclases and its secondary mineral precipitates have been analyzed over several thousand hours (Zhu and Lu, 2009), for one particular setting. These experiments cover just one aspect of the THMC coupled phenomenon. Because a traditional laboratory approach is difficult to achieve we propose to change the classical empirical geomechanics approach by a physics based unconventional geomechanics framework using multiscale modeling of THMC coupling.

Deep geothermal energy extraction is figuratively speaking a "moon landing mission" in the energy space. Not everyone may see the benefit in geothermal research. However, EGS projects provide a laboratory deeper and hotter in the Earth than ever before achieved. The science may well deliver insights into problems spanning an unexpectedly wide spectrum; from the elusive question of understanding the mechanisms of earthquakes to practical fields such as the discovery and production of conventional and unconventional mineral and petroleum resources.

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