Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Stimulating Granites: From Synchrotron Microtomography to Enhancing Reservoirs

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Keywords: multiscale, multiphysics, reservoir modelling, creep fractures, brittle, ductile, coupled processes

ABSTRACT

We present a fresh approach for stimulating granites based on a new multiscale workflow that starts with: (1) an analysis of a fossil geothermal system to assess long time scale processes; and (2) with a time-lapse Synchrotron heating experiment monitored with high-speed microtomographic imaging to analyse the short time scale micromechanisms. (1) The fossil long time scale analysis is based on identification of the thermo-chemo-hydro-mechanical processes leading to formation of fluid transfer zones in granites. These are cast into an upscaled continuum calculation capable of modelling deformation on millions of years time scale. (2) For the short time scale analysis, the propagation of observed fractures through the granite in the Synchrotron heating experiment is reproduced in a numerical experiment to derive the multiphysics processes leading to formation of microcracks. In a final step the calibrated computational model is used to design the stimulation protocol for a reservoir. The aim of this step is to control the coupled propagation of permeability in a virtual experiment prior to any costly field trials. This final step allows the assessment of the physical time and length scales relevant for a reservoir and its surrounding tectonic environment and can be used to optimize the injection strategy. We show a specific example of the workflow applied to granite in Central Australia. Using the above microtomography-based approach, we identify new physics that has previously been overlooked in the formation of the permeability system at depth. This resulting fracture network stems from longer time-scale processes than previously considered. Of particular interest for the injection strategy is that our model predicts a specific depth from which reservoir-scale material response is strongly controlled by thermochemically activated creep processes. These cause fractures that are well known as creep fractures in ceramics. The new physics-based method is promising for characterising and stimulating many other reservoir materials. It may, for instance, also be applicable to unconventional gas plays: clay minerals creep at very low temperatures and can show thermally activated dewatering/degassing-reactions, which generate ductile shear- or compaction- and dilation-aligned porosity.

INTRODUCTION

Exploiting deep geothermal energy from the hot crystalline basement has remained an unsolved challenge for the geothermal industry for the past 30 years. The original idea of a Hot Dry Rock (HDR) reservoir was to create fluid flow paths between an injection and extraction well by hydraulic fracturing deep in the crystalline hot rock. It became clear in early projects that, rather than creating new hydraulic fractures, the existing natural fractures were re-activated as flow paths, and their transmissivity was improved by stimulation. Enhanced Geothermal Systems (EGS) utilise these inherent geological structures for stimulation to achieve better reservoir productivity. It is feasible but not yet reliable with our current technologies to generate hydraulic conductivity by creating or enhancing existing hydraulic fractures in the reservoirs so that the desired flow rates can be achieved. Currently, the stimulation of the reservoir (primarily by mobilizing shearing) has not provided sufficient transmissivity for reliable practical application, with the pressure difference required to produce flow through the reservoir necessitating the use of high pumping powers (approximately 1/3 of the electricity produced by the geothermal resource). In order to make deep geothermal energy viable, we clearly have to take a different scientific approach.

This work presents a fresh approach for reservoir stimulations relying on three key steps: (i) we investigate the micromechanical behavior of the fundamental porosity-forming mechanism in the granite using a Synchrotron-based X-Ray methodology, (ii) we upscale the identified mechanisms using a damage-mechanics approach, and (iii) we develop methods to promote the permeability-generating mechanism that is driven by the present large-scale tectonic stress field.

MICROMECHANICS OF POROSITY FORMING MECHANISMS IN GRANITES

The characterization of micromechanisms of the formation of connected porosity channels in granites allows the development of a new and powerful technique for designing stimulation protocols, provided that an accurate characterization of the physics and chemistry of the micro-porosity/fracture forming processes can be identified. Our goal is to - via a method of upscaling - replace empirical laboratory-based fracturing characterization of the reservoir by physics/chemistry-based methods of reservoir characterization. Although such a micromechanical understanding of the reservoir material is valuable in its own right, the main advantage of the new technique lies in what follows. If one can successfully identify the geological processes that led to the formation of the reservoir a stimulation protocol can be devised. The new method should in principle allow the connection of vastly different time scale processes and lead to better stimulation protocols. It can deal with the interaction of a series of micromechanisms that contribute to the formation of localized zones where the granite can transfer fluids. Through the effective diffusivities of each micromechanism they are expected to have their own characteristic timescale. Thus in short the new technique consists of obtaining a micromechanically-based understanding of the geological processes that led to the original formation of the macroscopic reservoir and a prediction of how the micromechanics interacts with the short time scale engineering micromechanical processes.

Although the approach is robust in its basic concept the problem lies in extraction of representative samples. Such samples are supposed to be extracted from an active and 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. We have approached this problem from two angles and describe in the following two examples.

Samples from fossil geothermal systems (investigating the geological time-scale response)

In order to assess the long time-scale fluid transfer mechanisms one has to sample 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 1 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 an interconnected porosity network in the mylonite.

Figure 1: Microporosity (red) in a mid-crustal granitic shear zone (X-ray resolution 1.3 micron). Quartz and feldspar are transparent 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 the shear zone (Fusseis et al., 2009).

Scanning electron microprobe images (Figure 2) and NanoSIMS analyses show that the fluid-transfer mechanism in the investigated mid-crustal shear zone is accommodated by the following dominant K-feldspar mineral dissolution precipitation reaction whereby 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 or a suite of diagenetic reactions that happen at lower temperatures may also be contributing. This finding confirms an important creep mechanism for polycrystalline rocks by matter transport through a liquid phase (Raj, 1982a). The dissolution (typically endothermic arrow from left to right) precipitation (typically exothermic arrow from right to left) reaction can be generalized as a solid breakdown reaction with a fluid reaction product of the general style.

$$A_{solid} \rightleftharpoons B_{solid} + C_{fluid} \quad (2)$$

The typical time scale of the reaction is governed by following generalized kinetics:

$$A \rightarrow B \quad , \quad \frac{dA}{dt} = A\, k_0 e^{-\frac{E}{RT}} \tag{3}$$

whereby the temperature is T, the activation enthalpy E and the rate constant is k_0. This implies that the rates of reaction is controlled by the geothermal temperature (faster for higher temperature). An important point is that it is an activated process. It switches on at a critical activation temperature. For a given rate this switch is controlled by the activation enthalpy. Each mineral dissolution-precipitation mechanism is therefore expected to only operate above a given temperature characteristic for the mineral. Judging from the reaction kinetics the rates of the processes are extremely slow and may require months or years time scale.

As the reaction causes changes in the shape of the minerals such slow deformation processes associated with dissolution-precipitation are identified in the upscaled homogeneous description as creep deformation of the general type:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \left[\frac{g}{g_0}\right]^n \left[\frac{\sigma_e}{\sigma_0}\right]^m e^{-\frac{E}{RT}} \tag{4}$$

Whereby the effective strain rate $\dot{\varepsilon}$ of the creep process is now, however, understood to be micromechanically controlled and can be linked to the intrinsic process. The constant k_0 is now replaced by the rate constant $\dot{\varepsilon}_0$ which is a strain rate and the upscaling carries information about the grain-size g and the effective stress as well as the nonlinearities expressed in the power law exponents n, m. g_0 and σ_0 refer to a given reference value of grain size and stress, respectively. Note that this description is in full agreement with the classical empirical fitting of laboratory derived creep laws and it could have been derived without the upscaling step. However, the advantage of the microphysical approach is that it adds physical insight and hence further predictive power. Another advantage is that one can design a suite of laboratory experiments on multiple time scales if multiple dissolution-precipitation reactions are identified. In this case each of the mineral reaction has its own rate constant and activation temperature, characteristic grain size and exponents. The composite law results in an effective strain rate that combines multiple time scale experiments through a simple serial or parallel concatenation, depending on whether the mechanisms operate independently (serial) or depend on each other (parallel).

From a micromechanical perspective the mineral reaction causes a volume change of the solid constituents and an expulsion of a fluid phase. The first condition for the reaction is that for a solid breakdown energy for the endothermic branch must be delivered to the system. This is normally provided by the conversion of deformational work but could also be triggered by another source of heat. Another important constraint is that if the fluid cannot be extracted the reaction must stop. Herein, lies the strong coupling of chemical and deformational processes. One cannot occur without the other.

The above-described dissolution-precipitation creep mechanism has therefore been postulated to be the result of diagenetic or 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 2 shows evidence of precipitation of K-feldspar in highly aligned porosity channels in the central part of the shear zone. In the figure one can see some open pores (dark spots) and some fossil fluid channels with K-Feldspar precipitates indicating a dynamic process or possibly pulses of highly active fluid transfer indicated by the white arrows and interpreted here as creep fractures.

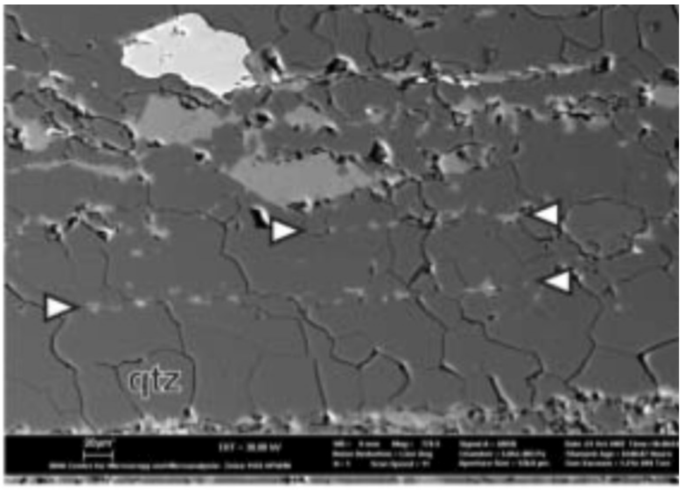

Figure 2: K-feldspar (light grey) precipitation in the central part of the shear zone (Figure 1). The precipitates follow highly aligned porosity channels that have been argued to be bear evidence of a dynamic fluid percolation associated with creep fractures between the white arrows. Reproduced with permission from Springer (Regenauer-Lieb et al., 2009).

Although such 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 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 and is important element of a granitic geothermal reservoir. Because this mechanism requires an active deformation field, it needs to be driven by the current tectonic stress field. This relies on the afore mentioned observation that the fluid-assisted feldspar breakdown reaction is an endothermic process and requires energy input from tectonic deformation. 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.

Sample deformed in the laboratory (investigating the engineering-time scale response)

The short time scale response of a granitic reservoir host rock to engineering intervention at elevated temperatures has been investigated in time-lapse Synchrotron X-ray experiments, where we have identified thermal-elastic cracking. This mechanism is based on the differential expansion of the mineral constituents of the granite causing delamination cracks on grain boundaries (Schrank et al., 2012). For an introduction into the numerical upscaling technique of the 4-D experiment the reader is referred to the article (Schrank et al., 2012). We wish to highlight here that in contrast to the above described creep fractures thermal cracking operates on short time scales. Thermally induced cracks can obviously be closed due to mineral precipitation if fluid flow occurs.

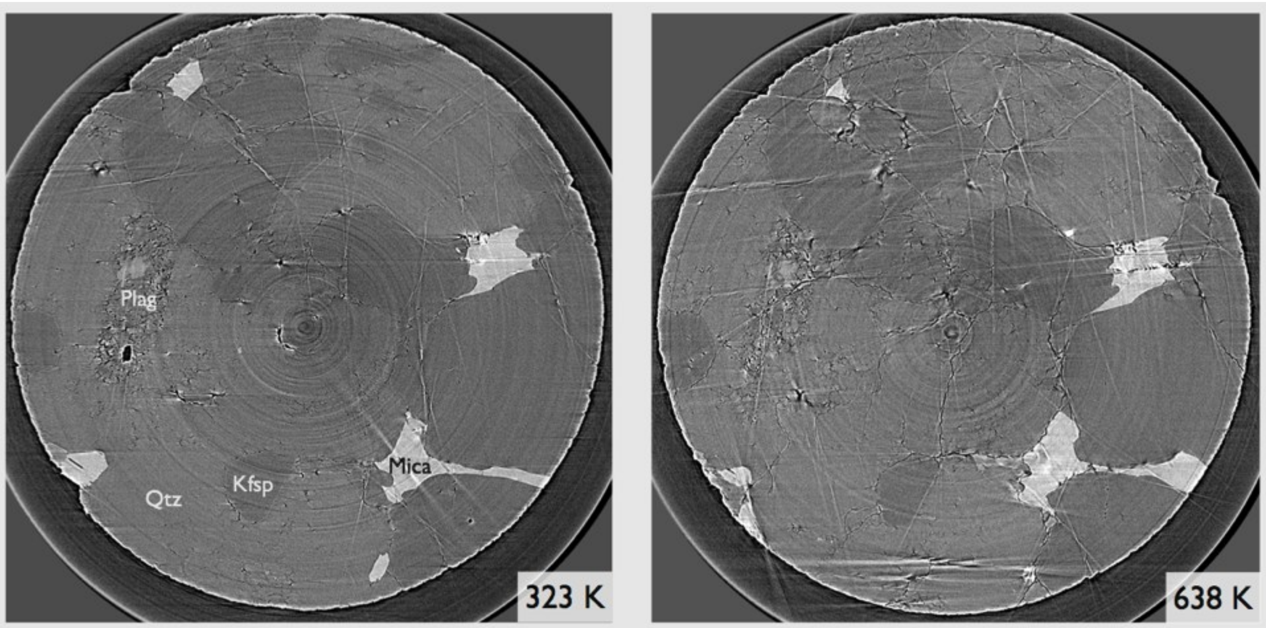

Figure 3: Snapshots of a time-lapse Synchrotron heating experiment of a Westerly granite sample showing the importance of thermal-elastically triggered porosity changes. Images are horizontal slices through the sample cylinder with a diameter of 2.5 mm. The microporosity in the plagioclase crystal (Plag, 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. The Synchrotron experiment has been successfully reproduced by a finite-element model, and the derived thermal cracking model predicts upscaled material properties measured in independent laboratory measurements on larger samples (Schrank et al., 2012).

DAMAGE MECHANICS APPROACH

We described two important mechanisms of crack/pore generation in granites that are currently overlooked in the classical hydraulic fracture stimulation protocols: thermal elastic cracks and creep fractures. 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 several mineral breakdown reactions which can be lumped together macroscopically in a viscous grain boundary sliding creep law (Raj, 1982a). The other process is a fast process but can be retained on long geological time scales. The third important porosity generation mechanism is that of a brittle fracture 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 microscopic level using current computational power available for modeling the reservoir. Such a simulation requires time steps to go from milliseconds to million 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 processes.

This approach is well established in material sciences and known as a smeared-crack, or damage mechanics 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., 2011; Karrech et al., 2014). 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.

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

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). We have extended the classical damage mechanics approach to incorporate the energetics of the chemical breakdown reactions leading to a fluid release (Liu et al., 2014). The new development was successfully tested for the problem of melt generation at the base of the lithosphere. Another extension relevant for more realistic modeling of geothermal reservoirs is the consideration of anisotropy in the damage mechanism. This has been shown to be particularly important for more detailed modeling of geomechanics around a wellbore (Gaede et al., 2013).

MODELLING SLOW TIME SCALE PROCESSES

In order to make deep geothermal energy viable, we propose a new approach that is based on stimulating 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. These require the consideration 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. The processes can be incorporated into the above-described continuum damage mechanics formalism(Regenauer-Lieb et al., 2013a; Regenauer-Lieb et al., 2013b).

As these time-dependent processes are driven by plate tectonics, the identification of the neotectonic large-scale driver enabling the background fluid flow network of the geothermal reservoir depth is important. In the case of Australia the driver can be identified to be the collision of Australia with Papua-New Guinea between 5-10 Ma ago (Sandiford and Quigley, 2009). Sandiford and Quigley conclude that as response to the collision Australia is slowly deforming at convergent strain rates around 10^{-16} s^{-1}. The above-described formalism has been implemented into a finite element approach and is currently being tested for deep geothermal reservoirs under the slow deformation resulting from the collision of Australia with Papua-New Guinea. 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 are currently being confirmed in the natural geological examples as part of our ongoing research.

DISCUSSION AND CONCLUSION

The logical prediction of our approach is that classical hydraulic fractures are not ideal for flow assurance and improvement in such high-temperature reservoirs. 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 of 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.

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