

Review of stimulation techniques – State derived from available literature

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Abstract

Chemical and mechanical stimulations are commonly used in order to enhance hydraulic properties of EGS systems. Using chemical acids the reservoir conditions generally improve, however with largely varying success rates. Also, the success of permeability improvement by massive hydraulic injections ("mechanical stimulation") is not easily anticipated. Here, two main mechanisms are to be considered: shear fracturing (or faulting) and jointing (tensile fracture). Both methods increase the pore pressure in the rock, however at different levels. Depending on the stress regime, shear fracturing causes maximum pressures below the minimum stress component ($P \sim \sigma_{\min}$). Slippage is induced in agreement with the Mohr (-Coulomb) Criterion on pre-existing mechanical discontinuities. The displacements generate larger apertures and possibly even new fractures. In contrast, jointing (tensile fracture) develops perpendicular to the least principal stress ($P > \sigma_{\min}$). It is mostly applied in sedimentary rocks. Herewith, a single, far extending fracture can be created.

This paper provides an overview of stimulation techniques used in the past, classify them and define associated mechanisms. The focus is on mechanical stimulation. It describes results obtained through experiments, referenced in literature (using IGA and GRC databases, scientific literature and various reports). The generalization of the results is however not always possible since they depend on each site conditions (history, stress field, temperature...). Chemical stimulation techniques will be shortly examined.

Keywords: HDR, HFR, EGS, stimulation, review, stress field, geothermal

1. Introduction

Reservoir stimulation is a key technology in Hot Dry Rock (HDR) and/or Enhanced Geothermal Systems (EGS) development. Several research projects have been carried

out over the past 30 years at widely different geological conditions and others are being planned.

This review compiles information and results obtained during stimulation campaigns performed since the beginning of HDR/EGS history, in the early 70's. Thus, data recorded and literature written on the following research projects were examined:

- Le Mayet-de-Montagne, France (1984-1987)
- Fenton Hill, New Mexico, US (1970-1993)
- Urach, Germany (1977-1986)
- Rosemanowes, UK (1976-1992)
- Soultz-sous-Forêts, France (1987-)
- Cooper Basin, Australia (running)
- Coso, California, US (running)
- Dixie Valley, Nevada, US (planned)
- Falkenberg, Germany
- Hijiori, Japan (1986-1999)
- Akinomya, Japan (1986-1991)
- Gamma, Japan (1983-1988)
- Ogachi, Japan (1990-1996)
- Fjällbäcka, Sweden (1983-1992)
- Gross Schönebeck, Germany (1990-)

As other sites exist all over the world, it is highly likely that new stimulation experiments will be realised in the next few years - if not months (essentially in Basel DHM, Switzerland and Desert Peak, California, US).

Two main types of stimulation technologies can be considered (Combs et al., 2004): mechanical stimulation techniques or chemical treatments.

Mechanical techniques can be:

- Hydraulic fracturing due to massive fluid injection in the wells

- Explosive fracturing
- Well mechanical treatment: re-deepening, jetting, scraping

Chemical techniques include:

- Matrix acidizing
- Clay shrinking and/or stabilization
- Scale inhibitors

We will here essentially focus on mechanical stimulation techniques.

2. Hydraulic fracturing

If the basic idea of hydraulic fracturing is quite common –high rate injections pressurizes the reservoir, leading to the creation of new fractures or to the enhancement of the permeability of pre-existing ones–, many way of proceeding, unknowns and variable make the results of this kind of stimulation very hazardous to predict.

2.1 Presentation and preliminary classification

Reservoir stimulation mechanisms in Enhanced Geothermal Systems are quite closed to mechanisms described in the petroleum industry (Economides and Nolte, 1989), although a major difference exists between their purpose. Petroleum reservoir stimulation aims at increasing the permeability of a reservoir in order to allow the maximum oil recovery, which stands in rock pores, as geothermal reservoir stimulation aims at optimizing heat recovery, which is stored in the rock matrix.

Identification of stress regime

The main parameter that influences the preponderant failure mechanism in an EGS reservoir may be the stress regime, i.e. the relative values of vertical and horizontal stresses (see Figure 1).

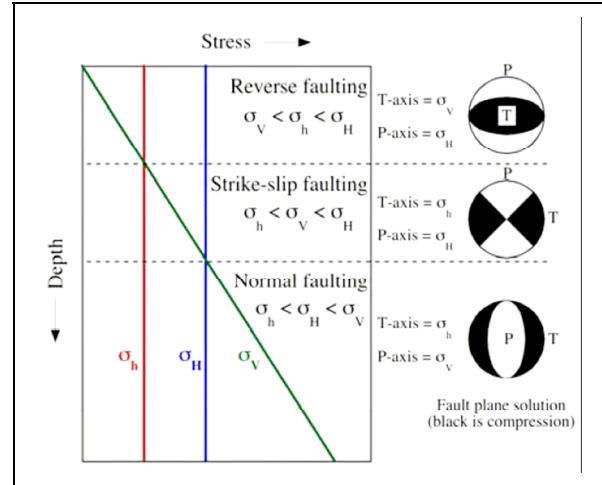


Figure 1: Conceptual representation of different stress regimes possible in HDR reservoirs: reverse, strike-slip and normal faulting (Karner, 2005)

Indeed, failure mechanisms can thus be classified:

Faulting (=shear fracturing)

Failure criterion:

$$\tau < C + \sigma_n' \cdot \tan \varphi$$

$$\Leftrightarrow \frac{\sigma_{\max}' - \sigma_{\min}'}{2} = C \cdot \cos \varphi + \frac{\sigma_{\max}' + \sigma_{\min}'}{2} \cdot \sin \varphi$$

with τ being the shear stress, C the cohesion, φ the Mohr angle, σ_n' , σ_{\max}' and σ_{\min}' the normal, maximum and minimum effective stress.

Jointing

This mechanism is equivalent to tensile failure or extensional fracturing, or hydrofracturing.

Failure criterion:

$$P_{\text{fracture}} > \sigma_{\min} + S + (\alpha P_{\text{pore}})$$

with S being the tensile strength or inherent resistance of the rock to propagation of a fracture and α the poroelastic constant.

Jacking

This mechanism corresponds to hydrofracturing with pre-existing fractures.

Failure criterion:

$$P_{\text{fracture}} \geq \sigma_{\min}$$

As one can observe on these various failure criteria, many parameters play a role in the rupture mechanism that is expected:

- Fluid pressure development in the reservoirs, that depends on:
 - o injection rate,
 - o injection time length
 - o injection through the entire open section of the well, or through perforated casings, or through a casing section isolated by packers, or in a plugged well with sand
 - o fluid type (water, heavy brine, gel of various viscosity, presence of proppants)
 - o fluid temperature, that may induce stress changes in the reservoir
- Stress field, that is different for each EGS site
- Rock and fractures parameters, like cohesion and Mohr angle, may highly influence results obtained, and could be modified by the use of proppant agents or acid treatments

2.2 Results obtained in the past

It is now quite commonly accepted in the scientific community that geothermal reservoir development due to massive hydraulic injections is most of the time due to reactivation of pre-existing fractures by shear of the fracture walls, induced by a diminution of the effective stress in the fracture.

As many stimulation campaigns have been performed on various EGS site all over the world, the purpose of this section is not to give an exhaustive index of the results of each test. The authors want to try to classify the main stimulation phases performed on geothermal reservoirs and the conclusions they led to, according to the considered reservoir properties (stress field, open or closed reservoir...) and to the type of stimulation realized (injected fluid, use of proppant, packers, flowrate...).

Hydraulic stimulation with a proppant agent

Three stimulation with a proppant agent were performed in Urach, Germany, in 1978 (Jupe et al., 1993). The Urach reservoir faces a normal faulting stress field ($\sigma_v > \sigma_H > \sigma_h$), characterized by a very low minimum horizontal stress, and a maximum horizontal stress nearly equivalent to the overburden. Proppant agent concentrations are related to be of 90 and 240 g/l of bauxite sand, in water

or viscous gel. No results were obtained concerning the well injectivity, but the connection between wells could be increased after the last stimulation with proppant agent.

Three stimulations with proppant agent are also reported in le Mayet-de-Montagne, in France, in 1988 and 1989. This reservoir is quite an open system, with a normal faulting stress regime ($\sigma_v > \sigma_H > \sigma_h$). Each time, between 100 and 200 m³ of water were injected, with a volume of proppant agent (sand) of 2, 7, and 40 tons of sand injected. If the first stimulation with proppant result was not significant, the second stimulation led to a great improvement of the recovery factor between wells, going from 20%, decreasing, to 58%, stable. Though, no improvement of the well injectivity was observed during any of the three stimulation campaigns (Jupe et al., 1993).

Proppant injections also occurred in Rosemanowes, UK. This geothermal reservoir is characterized by a strike-slip stress regime ($\sigma_H > \sigma_v > \sigma_h$). Proppant injections in production well RH15 are related to have had a good influence on the Rosemanowes reservoir responses, increasing the recovery factor from 70% to 85% (Willis-Richards et al., 1995).

Proppant injections also took place in the Gamma project reservoir, Japan (Jupe et al., 1993) and in the Fjällbäcka reservoir, Sweden (in combination with viscous gel injections) (Willis-Richards et al., 1995), that is characterized by an inverse faulting stress regime ($\sigma_H > \sigma_h > \sigma_v$) or a strike slip regime, but few literature was found to conclude on the positive or negative effect of these stimulations.

One could here notice that proppants injections with viscous gels can be performed in sedimentary reservoirs, like in the Rotliegend well situated in the eastern part of Germany (Legarth et al., 2003).

Hydraulic stimulation with a viscous gel

Viscous gels injections are often realized in combination with proppant injections. Low and high viscosity gels injections were performed in le Mayet-de-Montagne; these injections, when realized with a high viscosity gel, are reported to help jacking of fractures connected to the well, but finally quite low results were reported after these injections. High viscosity gels were also used in Rosemanowes, UK (Baria and Green, 1986), in order to increase chances of jacking and opening of fractures in tensile mode more than shearing, but recorded focal mechanisms were in fact consistent with strike-slip shear.

As geothermal conditions are most of the time extreme conditions –high temperatures, high

stresses and highly corrosive fluids, there is a great need of material and techniques development. In that purpose, new gels and stimulation fluids based on saponite and smectite clays are tested (Hirano et al., 2000)

Hydraulic stimulation in a limited section of the well

Stimulation injection in perforated casing was performed in well Habanero 1 in the EGS of Cooper Basin, Australia (Wyborn et al., 2005). This geothermal field is characterized by an inverse faulting regime ($\sigma_H > \sigma_h > \sigma_V$). Following stimulation 1 (realized in the entire well open section), packers were introduced at the top of the well open section, and perforations of the casing above the casing shoe were made. This technique allowed showing up fractures in which inflow could reach 25 l/s during injections phases.

Hydraulic stimulation performed in Falkenberg, Germany took place in a 3 m long packed-off interval, which had previously been identified by core and BHTV logging as the center of a 50m long joint free interval, at 250m depth (Jupe et al., 1993). Falkenberg stress regime changes from an inverse faulting regime above 100 m, to a strike slip regime between 100 and 200 m, and to a normal faulting regime below. This technique allowed the creation of a new hydraulic fracture in the packer interval.

Packers were also tested on the injection well of the Hijori site, Japan, but, as packer rubbers were found to be damaged because of reservoir very high temperatures, no conclusion could be deduced from tests performed in that site. Packers were also used in le Mayet-de-Montagne, France, but their use combined with the injection of proppant makes any conclusion very hazardous.

The technique of injections in perforated and cemented casing was also used during phase 1 of the Fenton Hill project, and packers were used during phase two of the project, with relatively good results after several tests, as injectivity of the wellbore was 2 l/s/MPa and recovery factors was evaluated to 60%. Literature also reports (Jupe et al., 1993) stimulations in perforated casings and using packers in Urach, Germany, and the use of perforated casings was in that case thought to be responsible of high friction losses in the casing.

Another technique that could here be described is well plugging or well sanding/reaming/fracturing. This technique consists, in case of low inflow possibilities in the open section of the well, to sand up the

well open section and then to ream out a part of the casing, in order to perform hydraulic stimulation in the reamed part of the casing. Its application is independent of evaluated stress regime of the reservoir. Such experiments were successfully performed at very small scale (flowrates lower than 3 l/s) in the Akinomiya site, Japan (Jupe et al., 1993). This technique of well sanding was also used in the Ogachi EGS, Japan and is very precisely described in literature (Kaieda et al., 2005). In this site, two reservoirs were successfully created at depth of 719 and 1000 m.

Hydraulic stimulation with water or brine only

As the cheapest fluid available in high quantity on earth is water, most of hydraulic stimulation phases in EGS were performed using fresh water, or with heavy brines, i.e. NaCl saturated water, reaching a density of 1200 kg/m³ at 20°C. If quantities of available brine are often limited to the capacity of external tanks, one can find evidences that the injection of such a fluid into the reservoir before fresh water injection during stimulation phases can be established (Baujard and Bruel, 2005). Water injections offer the possibility of injecting great volumes of fluids in order to improve well injectivities, productivities or the recovery factor between wells. An other advantage of long-term fresh water injections in the reservoir is that this injected water can temporarily cool down the rock temperatures, leading to a thermal stimulation, due to contraction of rocks.

Though water injections allow high rate injections over long time periods, many uncertainties remain concerning the way of optimizing such injection in order to obtain good stimulation results.

The 5-km depth EGS reservoir of Soultz-sous-Forêts, France, has been developed using essentially fresh water and heavy brine injections, and some acid injections more recently (Baria et al., 2006). Thanks to these operations, connection could be achieved between two wells GPK2 and GPK3, the connection with the last well being problematic for the moment.

Massive hydraulic stimulations were also performed in well Habanero 1 of the Cooper Basin EGS, Australia (Asanuma et al., 2004; Wyborn et al., 2005), in the Ogachi geothermal reservoir (Kaieda et al., 2005; Tenzer, 2001), in the Hijori EGS (Matsunaga et al., 2005), and in Fenton Hill (Robertson-Tait et al., 2000).

Hydraulic stimulation phases are planed in the Desert Peak reservoir, Nevada (Robertson-Tait et al., 2005) and probably in the Coso geothermal field, where low pressure

stimulation experiments were realized (Rose et al., 2006) and stimulation test on shear of the fractures were done on site (Rose et al., 2005).

*Hydraulic stimulation expectations:
information deduced from stimulation
and questions*

Of course, the first purpose of hydraulic stimulation is to enhance reservoir permeability. But, in addition to that, all of the previously defined stimulation techniques induce microseismicity. These microseismic events give extremely important information on reservoir parameters and structures, such as:

- Stress field orientation, thanks to development of microseismicity and orientation of in-situ fractures (Evans et al., 1999)
- Reservoir hydraulic diffusivity, thanks to the speed of extension of seismic cloud generated during stimulation phases (Shapiro et al., 1999)
- Isolation of large scale structures with multiplet clustering analysis (Moriya et al., 2003)
- Velocity structure of the reservoir can also be deduced from microseismic monitoring (Charl  t  y et al., 2005)

On the other hand, very simple questions still remain unresolved:

- What is the exact nature of the link between flow paths and stimulation events ?
- How could high magnitude seismic events be avoided during reservoir development? Are they linked to injected volumes, flowrates, pressure-increase rate in the reservoir or more irrelevant parameters?
- What would be the best strategy to develop a reservoir in an efficient way: short term and very high rate stimulations, long term and moderate flowrate injections, or multi-well injections?

2.3 Microseismicity associated, Example Soutz

As microseismicity is generated during stimulation injections, the most common way to derive information on key reservoir parameters (extension depth, faults) is the determination of magnitude and location of generated microseismic events. These events describe generally local shear failure at individual fracture / fault planes.

Whereas the impact of magnitude from single large events are described only after a careful seismic analysis (i.e. Charl  t  y et al., 2005), a generalization of seismic events can be performed by describing a “seismic density”. Recent studies (Kohl and Baujard, 2006) analyzed the density of the microseismicity recorded in Soutz-sous-For  ts during stimulation experiments in the deep reservoir. Figure 2 shows a transient evolution of the development of the microseismicity in Soutz during each well stimulation.

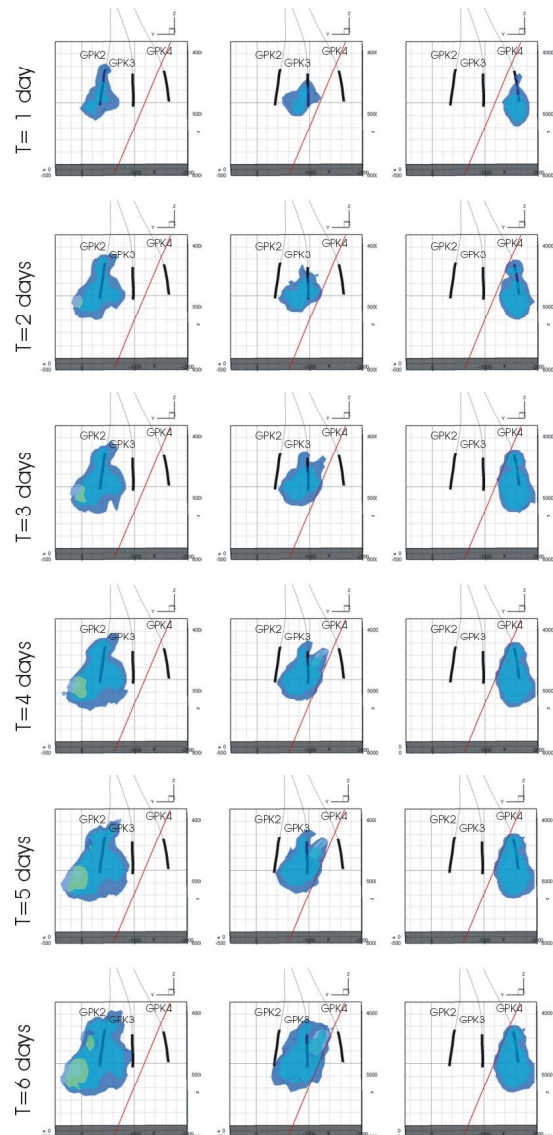


Figure 2: transient development of GPK2, GPK3 and GPK4 microseismic density distribution ($\Delta x=100$ m); Blue envelope: $d = 3$ events per 50 m side length cube; green envelope: $d = 15$ events per 50 m side length cube. Time is from beginning of injection.

Numerical analysis of this density of microseismicity development pointed at an

aseismic zone at between GPK3 and GPK4, of orientation 96N64W, which may explain very poor hydraulic connection and low tracer recovery between these two wells. Microseismicity can be considered as a filter that favors the visualization of features parallel to S_{max} . However, faults perpendicular they may also have high hydraulic conductivity remains invisible. Yet, this kind of microseismic analysis is cannot provide non-unique information on the type of the hydraulic structure (drainage or no-flow boundary).

3. Other mechanical stimulation techniques

3.1 Explosive stimulation

Explosive well stimulation is a quite common technique of the petroleum industry. The use of explosive in geothermal wells is quite dangerous due to the instability of explosives at high temperatures in the wells, which represents a non-negligible danger for on-site workers. So far, this kind of treatments have been performed in a few geothermal wells and results were in fact very hazardous.

Explosive pre-treatment of well

An explosive pre-treatment of well was conducted on the site of Rosemanowes, UK. There was some microseismic evidence to suggest that this explosive stimulation may have acted as the focal point for subsequent growth of the reservoir during later stimulation phases (Jupe et al., 1993). No real conclusion on efficiency of this well pre-treatment was clearly showed out.

Explosive well stimulation

An explosive well stimulation was lead in several Geysers wells and is mentioned in literature (Hanold, 1980; Mumma et al., 1982). It is also reported that these explosive stimulation experiments resulted in a significant decrease of the well transmissivity, attributed to a possible blockage of two deep steam entry zones by rubble from the explosions (Entingh, 2000).

3.2 High energy gas fracturing

Realizing that explosives generally act so fast that they mainly pulverize and compress rock, Sandia scientists pursued the development and use of propellants that burn more slowly as a means to force fractures at least some distance from wellbore. This was called "high energy gas fracturing" (HEGF). The purpose of HEGF methods is to develop multiple, radial fractures around a borehole using a rapid

pressure load. The advantage of this technique is that it was demonstrated that HEGF methods were likely to create fractures in every wanted direction, including in a direction perpendicular to the main stress direction, which could allow newly created fracture to intersect many hydraulically important fractures (Chu et al., 1987; Entingh, 2000).

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