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Observations of hydraulic stimulations in seven enhanced geothermal system projects

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A B S T R A C T

Numerous stimulation tests have been performed on Enhanced Geothermal System (EGS) or Hot Dry Rock (HDR) projects during the past three decades, however, there is much room for improvement in our knowledge and understanding of the mechanisms of stimulation. This paper investigated the hydraulic stimulation tests carried out on seven EGS or HDR projects where massive volume of fluid was injected into the long open section of the well with interval of tens to hundreds of meters in the crystalline formation. The key characteristic test and performance parameters were defined and collected through extensive survey of stimulation results. Attempts were made to carry out comparative analysis on reservoir conditions, test parameters and test observations. The analysis and discussion suggest that 1) the reservoir stress regime impacts the growth of stimulated region and the reverse faulting stress regime can be favorable for the layout of multiple well system as it may lead to a horizontally or sub-horizontally oriented stimulated zone; 2) the injection pressure for activating shear slip and the associated onset of seismicity is mainly field stress controlled; 3) there is strong dependency of injectivity on injection pressure and a high pressure makes a better hydraulic injectivity during stimulation and consequently afterwards for circulation; 4) the stimulated region and number of induced seismic events are mainly injection volume controlled and the potential strategy to reduce seismic risks is either to extend stimulation in time or to separate stimulation in space; and 5) the differential stress condition is one of the necessary factors to raise a large magnitude event (LME) and the difference of maximum injection pressure achieved over that at onset of seismicity is an important additional factor to induce LMEs.

1. Introduction

Ever since the first geothermal electricity production in Larderello, Italy, the humans have the experience of harnessing the earth heat to generate electricity for more than one century. It is increasingly accepted that power generation from earth heat has become an attractive option to serve as a CO_2-free, base-load renewable energy source [1]. However, geothermal power accounts for only 0.3% of the global electricity supply due to the limited geologically viable locations where the natural heat, water and rock permeability is sufficient for economical heat resource extraction [2]. It is known that most hydrothermal resources are within the volcanic regions near tectonic plate boundaries that form the Ring of Fire [3] and those used for geothermal power generation are just pinpoints on a map of global scale [4]. The huge amounts of geothermal resources within the drillable depth are stored in the formations that are deficient in water or permeability. For example in the US, only 2% of the total thermal energy stored between 3 km and 10 km reservoir, which is considered to be conservative recoverable Enhanced Geothermal System (EGS) resource, is sufficient to provide the US primary energy for 2800 years [5]. EGS or previously named Hot Dry Rock (HDR) are the technologies being developed to exploit the vast earth heat resource in the non-volcanic regions where the natural permeability of host rocks is very low [5]. It involves artificially enhancing or creating the permeability of the reservoir mainly by hydraulic stimulation, then circulating the water through injection and production wells to extract heat. Eventually, the high temperature water or vapor is transferred to the power generation facilities. In this study, we chose a narrower definition of EGS which excluded the case with hydraulic stimulation applied to existing hydrothermal reservoir for additional permeability increase.

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Dating back to early 1970s, the HDR concept was innovatively proposed by the Los Alamos Laboratory, USA. So far almost ten EGS/HDR projects were or are being developed and tested in the world (Table 1). These projects are successful in accessing fine geothermal resources within the drillable depth (usually less than 5 km) as depicted in Fig. 1 where the temperature gradients are all larger than the average one, 25 °C/km. Most of these are R&D projects for testing and developing the EGS concept with long duration. Indeed, a sustainable commercial MW scale power generation has not been achieved yet by EGS systems. In this regard, much more effort are required before the EGS technology can finally become commercially feasible.

Apart from the high cost related to the deep drilling, one major long-standing technical challenge for EGS development is to improve hydraulic performance of the reservoir, whose natural permeability is very low due to the low porosity of rock matrix and the poor connectivity of natural fracture systems. For this issue, the key technique is hydraulic stimulation, by injecting massive volumes of fluid into the target formation with high pressure, to increase the permeability of hot reservoirs and thus make artificial hydraulic linkages between two or more boreholes to allow fluid circulation through the stimulated hot rock at rates of commercial interest [6]. As demonstrated in Fig. 2, basically, two concept models of hydraulic stimulation were designed and tested over the previous EGS development experience: 1) hydrofracturing, creating new fractures or reopening the pre-existing fractures which has been widely used in hydrocarbon production and 2) hydroshearing, that is the slip of pre-existing fractures associated with shear dilation. The required pressure, P to initiate hydraulic fractures under impermeable reservoir which is referred to as the breakdown pressure is expressed as

$$P = (3-k)\sigma_3 + T_0$$
$$k = \frac{\sigma_1}{\sigma_3} \tag{1}$$

Where σ_1 is the applied maximum far field principal stress, σ_3 the minimum one, k the ratio of σ_1 to σ_3 and T_0 the host rock tensile strength. The injection pressure necessary for activating shear slip of most optimally oriented fracture is

$$P = \frac{k_c - k}{k_c - 1}\sigma_3$$
$$k_c = \frac{1+\sin\phi}{1-\sin\phi} \tag{2}$$

where ϕ is the frictional angle of natural fractures. Eqs. (1) and (2) provide a simple first order estimation of injection pressure required for activating stimulation.

In reality, however, stimulation behaviors are far more complex than those shown in Fig. 2 due to difficulties related to 1) the determination of in-situ stress condition, 2) the characterization of pre-existing natural fracture system and host rock properties and 3) the stimulation operation itself. They are often not well understood even after the site stimulation operations have been performed, let alone the prediction of stimulation performance before operation. McClure concluded four possible mechanisms of hydraulic stimulations in EGS system and shale gas production to reflect its complexity: pure opening mode (POM), pure shear stimulation (PSS), primary fracture with shear stimulation leakoff (PFSSL) and mixed mechanism stimulation (MMS) [7]. Recently the research by Jung suggested that a multi-fracture concept with wing-crack model could provide a plausible explanation for the intensive and strong induced seismicity as well as for the strong after-shocks observed at various site tests [4].

For the last three decades, hydraulic stimulation has been an essential procedure for EGS or HDR projects where many deep wells were finished and stimulated. These stimulations achieved the enhancement of reservoir permeability to various degrees and only two (Soultz and Cooper Basin) pilot power plants using EGS technique were reported being run. But our knowledge on hydraulic stimulation, both stimulation performance and mechanism, unfortunately could not completely meet the requirements raised by the challenging issues with respect to EGS project development. In this paper we collected the key hydraulic stimulation test and performance parameters based on critical reviews of the results and observations of existing EGS or HDR projects. Furthermore, the correlation analysis, among performance parameters, test parameters and reservoir fundamental conditions, and the general discussion were addressed to provide more insight into hydraulic stimulations during EGS development.

2. Observations during hydraulic stimulation tests

For hydraulic stimulation operations in EGS projects, both the hydraulic and induced seismic (IS) data are monitored and recorded throughout the treatment, and the monitoring process even continues for a long time after stimulation. These monitoring works play an important role in stimulation process management and the associated reservoir behavior interpretation.

Real time recordings of injection rate and fluid pressure are fundamental for evaluating the entire system hydraulic performance as well as the deep reservoir hydraulic properties. Both wellhead pressure (WHP) and bottom hole pressure (BHP) are of interest for engineers and researchers, but the complete reliable high quality BHP measurement is seldom available due to high cost and poor performance of measurement devices subject to high temperature and pressure conditions. Thus many stimulation tests could provide only WHP data, and the BHP can usually be estimated as the summation of measured WHP and the corresponding hydrostatic fluid column pressure as Eq. (3).

$$\mathrm{BHP} = \mathrm{WHP} + \rho_w g h \tag{3}$$

where ρ_w is the density of injection fluid.

Table 1
Overview of EGS (HDR) projects.

Project	Country	Duration	Type	Depth	Rock	Temp.	Developer	Status
				Km		°C		
Fenton Hill	USA	1974–1995	R&D	3.5	Granite	240	LANL	Closed
Resemanowes	UK	1977–1991	R&D	2.6	Granite	95	CSM	Closed
Soultz	FR	1987–now	R&D	5	Granite	200	GEIE EMC	Operating
Ogachi	JP	1989–2002	R&D	1	Granite	230	CRIEPI	Closed
Hijiori	JP	1985–2002	R&D	2.3	Granite	270	NEDO	Closed
Cooper Basin	AUS	2002–now	Comm.	4.3	Granite	243	Geodynamics	Developing
Gross Schonebeck	GE	2000–now	R&D	4.3	Volcanic & sandstone	150	GFZ, Potsdam	Developing
Basel	CH	2005–2009	Comm.	5	Granite	190	Geothemal Explorers	Closed