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

Role of Differential Stress in Induced Seismicity in Enhanced Geothermal System: a Review of Previous Hydraulic Stimulation Tests

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Keywords: Hydraulic stimulation, differential stress, seismicity onset, large magnitude event (LME)

ABSTRACT

Massive hydraulic stimulation is the key operation to improve the permeability of deep underground heat exchanger in Enhanced Geothermal System (EGS) and numerous stimulation tests have been performed during the past four decades. The induced seismicity (IS) associated with stimulation operation and its impact is a controversial issue for EGS development. This paper attempts to study the role of differential stress in IS with a geomechanical perspective by investigating previous hydraulic stimulation tests in seven EGS projects where massive volume of fluid was injected into the long open well section with interval of tens to hundreds of meters in the granite formation. Specifically, we focus on the role of differential stress in the onset of seismicity which is thought as an indicator of activation of fracture shear slip and the induced large magnitude events (LMEs) with which the public are concerning. Based on the recognition that fracture slip is controlled by the ratio of shear to normal stress acting on its plane, slip tendency analysis is carried out to provide more insight. The analysis and discussion of previous stimulation tests suggests: 1) the injection pressure for activating shear slip and the associated onset of seismicity is mainly controlled by field differential stress and 2) the differential stress condition is one of the necessary factors to raise LMEs and the amount of maximum injection pressure achieved over that at onset of seismicity is another important factor to induce LMEs.

1. INTRODUCTION

Since the first geothermal electricity was generated in Larderello, Italy, people have been making efforts to extract more geothermal energy from not only regions near tectonic plate boundaries such as Ring of Fire but also regions with relatively poor conditions for heat extraction. Especially, for the past four decades, plenty of research and practices have been executed on Enhanced Geothermal System (EGS) concept as part of the efforts to utilize underground heat. EGS is the technology being developed to exploit the vast earth heat resource in the non-volcanic regions where the natural permeability of host rocks is very low (MIT, 2006). It involves artificially enhancing or creating the permeability of hot reservoir mainly by hydraulic stimulation and then circulating the water through injection well and production well to extract heat. Eventually, the high temperature water or vapor is transferred to the power generation facilities. The concept was initially proposed as Hot Dry Rock (HDR) in 1970s by researchers from Los Alamos Laboratory, USA when they initiated Fenton Hill project. Besides, Hot Fractured Rock (HFR) and Hot Wet Rock (HWR) concepts were also reported to highlight the recognition that the deep hot formations are naturally fractured and may contain some fluid. A systematic review of existing EGS projects worldwide was provided by Breede et al. which transpires that EGS is still on a learning curve (Breede et al., 2013). Actually, most of previous EGS were for demonstrating EGS concept with long duration. The emphasis should be given to the fact that much more research efforts are required before the EGS technology can finally become commercially feasible.

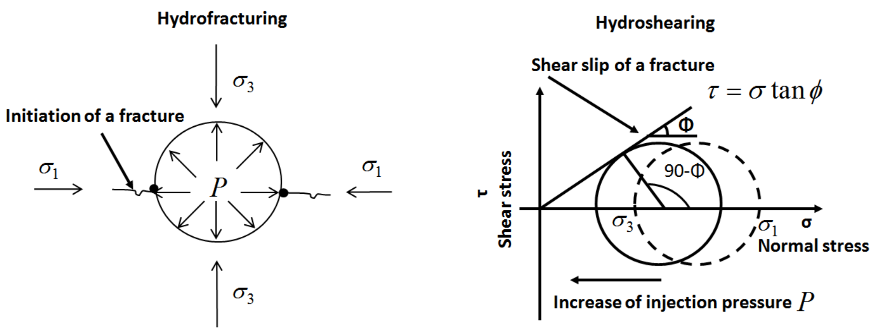

Figure 1: Basic mechanisms of hydraulic stimulation: creating a new fracture (hydrofracturing) and shear slip of an existing fracture (hydroshearing).

One major long-standing challenge for EGS development is to improve the hydraulic performance of reservoir, whose natural permeability is very low due to the low porosity of rock matrix and the poor conductivity of natural fracture system. Hydraulic stimulation has been an essential technique, by injecting massive fluid into the target formation with high pressure, to increase the permeability of hot reservoir and thus make artificial hydraulic linkages between two or more boreholes to allow fluid circulation through the stimulated hot rock at rates of commercial interests (Genter et al., 2010). As demonstrated in Fig. 1, basically, two conceptual models about hydraulic stimulation were designed and tested over the previous EGS developing experience: 1) hydrofracturing, creating new fractures or reopening pre-existing fractures like that widely used in hydrocarbon production and 2) hydroshearing, that is the slip of pre-existing fractures associated with shear dilation. In the early stage of Fenton Hill project development, the hydrofracturing concept was adopted and hydraulically created fractures were supposed to provide flow pathways. The accumulated field observations revealed that the deep hot rocks are naturally fractured and thus the idea was shifted to shear and dilate these natural fractures as the hydroshearing concept describes (Jung, 2013). However, the artificially created fractures still can be necessary to connect natural fractures in case that there is no natural fracture to directly cross the pressurized injection interval (Ito & Hayashi, 2003).

It is widely realized that massive fluid injection can induce shear slip on existing fractures and thus leads the induced seismicity (IS). The issue of IS is an unavoidable by-product of hydraulic stimulation in EGS development. Actually, IS is a controversial issue associated with EGS development (Majer et al., 2007; Ghassemi, 2012). On one hand, people have realized the seismicity-based reservoir characterization method is the irreplaceable tool for evaluating the stimulation effects (stimulated volume and fracture network growth); on the other hand, the increasing concern regarding the potential of IS risk has been a big challenge for the EGS development, in particular for the projects near densely populated community. The large magnitude seismic events caused by the stimulation of Basel project in Switzerland finally stopped the project (Haring et al., 2008). Previous studies have found the injection volume controlled characteristics of stimulated region based on the field experience (Jung, 2013; Philllips et al., 2002). The long term stimulation experience in Fenton Hill Phase II revealed that the stimulated region corresponds linearly to the increase of the volume of injected water (Brown, 1995). In situ stress conditions influence the development of stimulated rock regions or migration of IS. It was reported that the seismic clouds appear as vertical or sub-vertical in strike slip stress regions (Resemanowes, Soultz and Basel), moderately dipping in normal faulting stress regime (Fenton Hill and Hijiori) and horizontal or sub-horizontal for reverse faulting stress conditions (Cooper Basin) (Jung, 2013).

It is significantly important to make more efforts to study the mechanisms of IS and to identity the factors that control the event magnitude, and then come up with a more comprehensive but efficient seismic management scheme. In this paper we investigated the previous hydraulic stimulation tests in seven EGS projects where massive volume of fluid was injected into the long open well section with interval of tens to hundreds of meters in the granite formation. We investigate the role of differential stress condition in IS with a geomechanical perspective, including the onset of seismicity which is thought as an indicator of activation of fracture shear slip and the induced large magnitude event (LME) with which the public are increasingly concerned.

2. OBSERVATIONS DURING HYDRAULIC STIMULATION TESTS

For hydraulic stimulation operations in EGS projects, both the hydraulic and induced seismic data is monitored and recorded throughout the treatment, and the monitoring process even continues for a long time after stimulation. A set of recorded data usually includes the time history of injection rate, wellhead pressure (WHP) and occurrence of seismic events. In addition, these induced events are located to show the evolution of injection fluid distribution as well as the development of stimulated region.

An extensive review of the observations and results of stimulation tests in major EGS projects was carried out. In this paper, seven EGS or HDR projects were determined as test data sources based on two criteria: 1) the reservoir host rock is crystalline; and 2) a massive volume of fluid was injected into the open well section with interval of tens to hundreds meters from casing shoe to well toe. Moreover, the key test and performance parameters, which are thought to be able to characterize the test conditions and test performances in terms of hydraulic and seismic responses, were defined as follows and listed in Tab. 1.

Stimulation interval. It is the uncased open section where the potential fluid flow paths intersect the well and the fluid pressure diffuses. A longer open section intuitively indicates more chances to have natural fractures available to accept injected fluid.

Injected fluid volume. Generally, a massive volume of fluid (up to tens of thousands of cubic meters) is injected accounting for the long stimulation interval and a large stimulated reservoir volume which is expected for economic issue.

Maximum injection rate and maximum injection pressure. They are often thought to be closely related to the IS, especially to the LME, and they are regularly listed as main controlling parameters with respect to the seismic risk management.

Fluid pressure at onset of seismicity. The onset of seismicity can be treated as a strong indicator of the beginning of shear slip and thus the fluid pressure at onset of seismicity would be meaningful to understand the stress state and fracture nature. We admit that the observation of onset of seismicity heavily depends on many factors such as seismic monitoring network configuration, seismic sensor resolution and the pre-defined threshold of recording events. Because of very limited accessible data, we could not define a universal criterion of onset of seismicity. Instead, we either adopted the stated fluid pressure directly from the specified references or picked up the one from pressure history data when the seismic event was firstly recorded. In this way we simply stick to the determination of onset of seismicity the same as the references.

Mean depth of induced seismic cloud. The massive volume injection into a long open section usually induces a big seismic cloud and, intuitively, the mean depth of seismic cloud can be more representative to feature the overall seismic event distribution in depth. For efficiency, the stress state at mean depth of seismic cloud is adopted when characterizing and discussing the roles of field stress condition in induced seismicity.

Maximum seismic event magnitude. The injection induced seismicity is a controversial issue and the potential of inducing LME is a challenge for project development. The investigation of LME not only helps to study the mechanisms of IS but also contributes to the seismic risk management which could benefit the project and the site vicinity community. The site stimulation tests find that LME can occur during injection or after shut-in.

These test parameters and results summarized in Tab. 1 form the data base for the following correlation analysis and discussion. Due to the difficulty and cost of field data measurement or the limited access to the full set of data, some of the key parameters listed above for some stimulation tests may not be available in Tab.1.

3. TEST OBSERVATION ANALYSIS AND DISCUSSION

These projects are sparsely distributed on earth and the reservoir conditions can be quite variable. We highlight that 1) the number of hydraulic stimulation tests in EGS or HDR projects is relatively limited, 2) within these limited samples, the reliable data was sparse and 3) the test conditions were variable except that they were involved with massive volume injection into a long bottom hole open section in granite host rock. In this regard, it is very difficult for us to draw firm conclusions. So what we attempt is to discuss the role of field stress with respect to injection induced seismicity based on the analysis of collected test observations and test conditions.

3.1 Reservoir stress state

Reservoir state of stress is a fundamental geomechanical parameter that plays a critical role in the reservoir response to hydraulic stimulation and one of the determinant components in permeability evolution as well as the migration of IS. In the basic conceptual models of stimulation, in situ stress is an important input (Fig. 1).

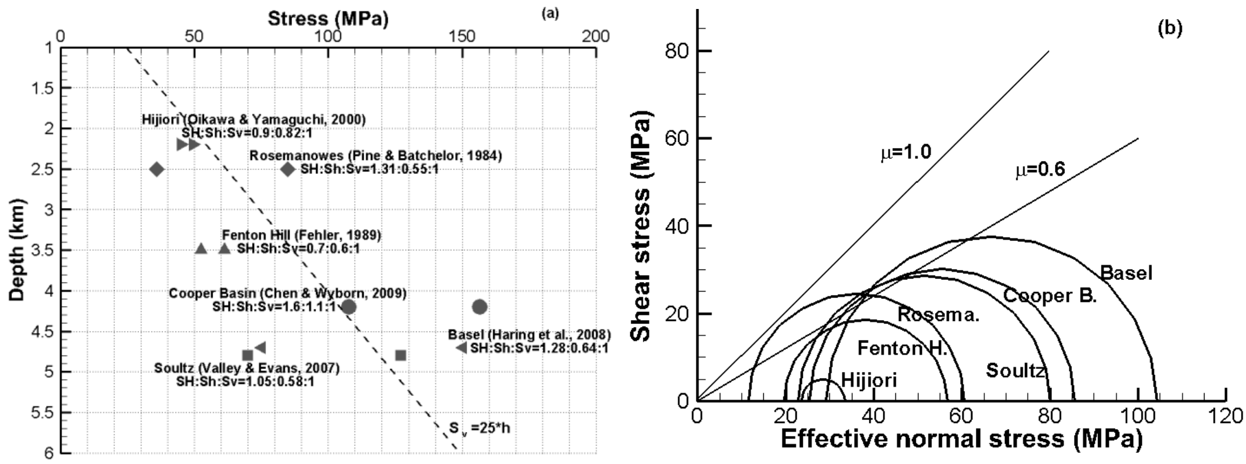

Figure 2: Stress state at mean depth of seismic cloud. (a) stress magnitude plot where SH and Sh are solid symbols and Sv, represented by dashed line, is treated as the overburden load with formation mass density of 2,500kg/m^3; (b) Mohr stress circles in terms of effective normal stress. Solid straight lines are the Coulomb failure envelopes when coefficient of friction is 1.0 and 0.6 without accounting for cohesion.

Fig.2 plots the stress state of reservoir at mean depth of seismic cloud for these projects, expressed by both stress magnitude plot and Mohr circle. We have no intention to discuss the in situ stress estimation methods used and the associated differences of evaluated stress information from different methods, thus the stress information in the plots represent a general estimation from the given references. In Fig. 2a, both the maximum horizontal principal stress and minimum one are normalized with respect to the vertical principal stress. Such a treatment is helpful to compare the relative stress magnitude and makes it easy to determine the stress regime according to the Anderson's faulting theory. In general, these projects cover all stress regimes from normal faulting to reverse faulting stress state. The projects in West European countries (Soultz, Basel and Rosemanowes) are consistently in a relatively extreme strike slip stress condition and the Cooper Basin project is intermediately reverse faulting stressed. No arguments related to the optimal stress regime for the success of stimulation were found; however, it is definite that in situ stress conditions influence the development of stimulated rock regions, the forming of fluid plow pathways and the migration of IS (Jung, 2013; Ito and Hayashi, 2003).

It is shown that the stress component difference can be very significant. For example, the SH is more than twice of Sh for the case of Rosemanowes. In order to demonstrate the role of this stress difference in the potential of fracture slip and the associated seismicity, the tool of Mohr diagram was adopted. Fig. 2b shows the Mohr stress circles at depth of induced seismicity center for each project before stimulation, where the effective normal stress is treated as the total stress (shown in Fig. 2a) minus the hydrostatic water column pressure. For Cooper Basin project, it is found very high in situ overpressure, 35 MPa, exists in the reservoir and thus it should be deducted from total stress when calculating the effective normal stress. The solid straight lines are the Coulomb failure envelopes when the coefficient of friction is 1.0 and 0.6 respectively without accounting for the cohesion. The region between them covers all possibilities with frictional coefficient value ranging from 0.6 and 1.0. It is obvious that the cases with large differential stress are close to critical stress conditions for fracture slip or require less additional fluid pressure to activate the slip of fractures.

For comparison, we present the results of slip tendency analysis for project Rosemanowes with the highest differential stress condition and project Hijiori with the smallest differential stress condition (Fig. 3). Correspondingly, the additional pressure required for slip of a fracture is also provided with a frictional coefficient of 1.0. The stereo plot is used to cover all the possible fracture orientations. Actually, the slip tendency analysis is a tool widely used for assessing the potential of fault reactivation and fracture slip, e.g., Moeck et al. (2003). It is defined as the ratio of resolved shear stress to resolved normal stress on a fracture surface (Morries et al., 1996).

$$T_S = \tau / \sigma_{neff} \tag{1}$$

where τ and σ_{neff} are the shear and normal effective stress on a given plane. When the value of T_S is equal to or greater than the given fracture frictional coefficient, shear slip occurs.

From Fig. 3, it is clear to find that the slip tendency of Hijiori is much lower than that of Rosemanowes due to its rather even stress condition, even though it is least stressed. Correspondingly, it requires more injection pressure to trigger shear slip of optimally oriented fractures in Hijiori project and to move its Mohr stress circle to meet the failure envelope in Fig. 2b. This feature of less pressure for activating slip of optimally oriented fractures for large differential stress condition will be discussed more in the next section.

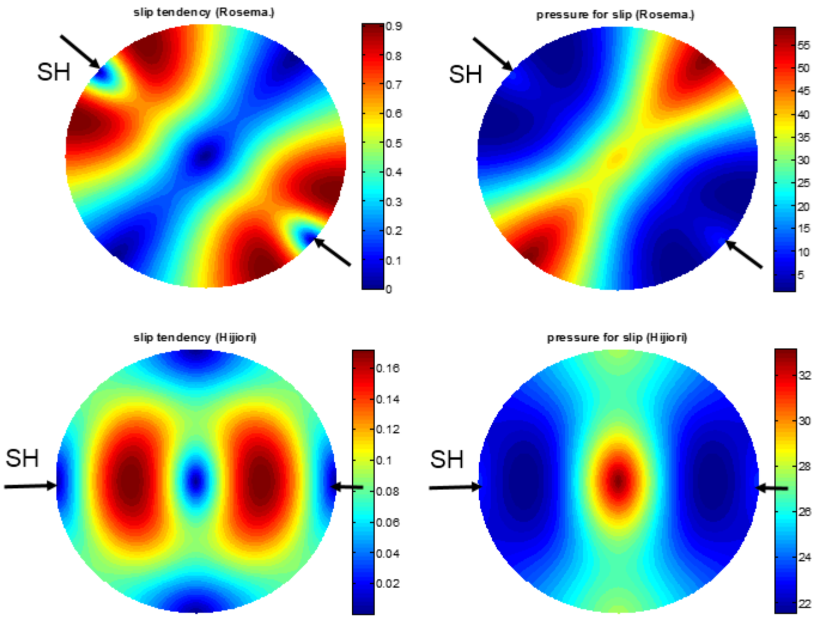

Figure 3: Stereo projection plot of slip tendency and pressure for shearing: project Rosemanowes (most differential stress) and project Hijiori (least differential stress). Pressure for shearing is estimated with a given frictional coefficient of 1.0, arrows represent the direction of maximum horizontal principal stress.

3.2 Onset of seismicity

The solid black bars in Fig. 4 demonstrate the observed wellhead pressure at onset of seismicity during the stimulation tests which implies the beginning of shear slip on the fracture plane. The grey bars are the additional pressure estimated to trigger slip of optimally oriented fractures according to Eq. (2) when adopting the fracture frictional angle of 45 degree. Actually, the pressure estimated using Eq. (2) represents the minimum value to move the stress circle to meet a specific failure envelope as depicted in the hydroshearing concept plot of Fig. 1.

$$P = \frac{k_c - k}{k_c - 1}\sigma_3$$
$$k = \frac{\sigma_1}{\sigma_3}, k_c = \frac{1+\sin\phi}{1-\sin\phi} \qquad (2)$$

where σ_1 and σ_3 are the effective maximum and minimum far field principal stresses, respectively, ϕ the fracture fictional angle.

Basically, the observed test data is consistent with the previous finding from Mohr circle and the tests with larger differential stress conditions required less additional pressures to activate fracture slip and the associated seismicity. It is also found that these estimated pressures (grey bars) from Eq. (2) with a common frictional coefficient of 1.0 and the prescribed stress data at mean depth of seismic cloud are close to the real site observations (black bars).

It is recognized that the joint orientation with respect to the field stress is critical to the determination of pressure required to trigger shear slip of joints. Considering that usually the uncased open well section which is subject to high injection pressure is very long (tens to several hundred meters), there can be many natural fractures crossing this open section. Their orientation can range widely or even a simple assumption may be made such that natural fractures are randomly oriented along the long open well section. In this scenario, the optimally oriented fractures exist and Eq. (2) is applicable to estimate the required injection pressure for activating shear slip or onset of seismicity. Indeed, the fine match between the analytically computed, simply using Eq. (2), and the real site observations supports the pre-made statements related to the orientation distribution of natural fractures. Furthermore, Xie et al. (2014), performed slip tendency analysis for Basel and Soultz cases, and then observed an overlap between the optimal slip zones and highly dense fracture zones in the associated stereo plot, which indicates the existence of optimally oriented fractures for slip in reservoir rock mass. Above discussion demonstrates the usefulness of Eq. (2) based on the concept of hydroshearing although it is very simple. Eventually it is concluded that the injection pressure for activating fracture shear slip and the associated seismic onset are mainly controlled by field stress condition recognizing that optimally oriented fractures for slip can be naturally available. Besides this stress-controlled pressure for activating fracture slip, the research by Ito and Hayashi (2003) suggests a feature of stress-controlled flow pathways in HDR geothermal reservoir.

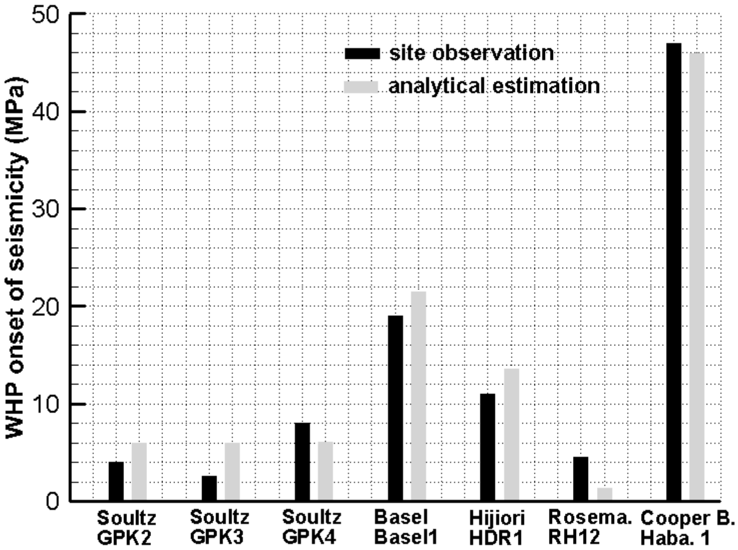

Figure 4: Well head pressure at onset of seismicity. Solid dark bars represent the real site observations while solid grey bars are the estimated ones from Eq. (2) with frictional coefficient of 1.0. For Cooper Basin project, the insitu overpressure of 35 MPa is considered.

3.3 Large magnitude events (LMEs)

Fig. 5 plots the recorded maximum event magnitude during the hydraulic stimulation tests and its correlation with (a) the difference between maximum field principal stress and minimum one which is normalized against the vertical principal stress, and (b) the pressure difference of maximum WHP and WHP at onset of seismicity. A seismic event of magnitude larger than 2.0 can be felt at surface and this is referred as 'large magnitude event (LME)' (Evans et al., 2012). As analyzed in section 3.1, the significant differential stress condition is preferable for fractures to be critically stressed to slip and a similar trend is spotted in terms of the existence of LME. It is found that LMEs occurred in the projects which are subject to large differential stress conditions whether it is strike slip stress regime or reverse faulting stress regime (Soultz, Basel and Cooper Basin). But no LME was detected for the projects with relatively even stress condition (Fenton Hill and Hijiori). Obviously, the differential stress condition is a necessary factor to raise LMEs and a strong correlation between them is found (Fig. 5a). Moreover, as found in Fig. 5b, achieved maximum pressure over that at onset of seismicity (Max. WHP – Sei. WHP) is a very important additional condition to induce LMEs and a strong correlation between them is observed. This feature becomes more evident if we compare the observations of Ogachi and Hijiori. For the case of Ogachi, a maximum magnitude of 2.0 was ever detected even though it holds a very large differential stress condition because a small additional injection pressure was applied. But for Hijiori case, only very small magnitude events were monitored even under a relatively high injection pressure because of the small stress difference. In this regard, there would be little potential of inducing LMEs even with increased the injection pressure in Hijiori Site.

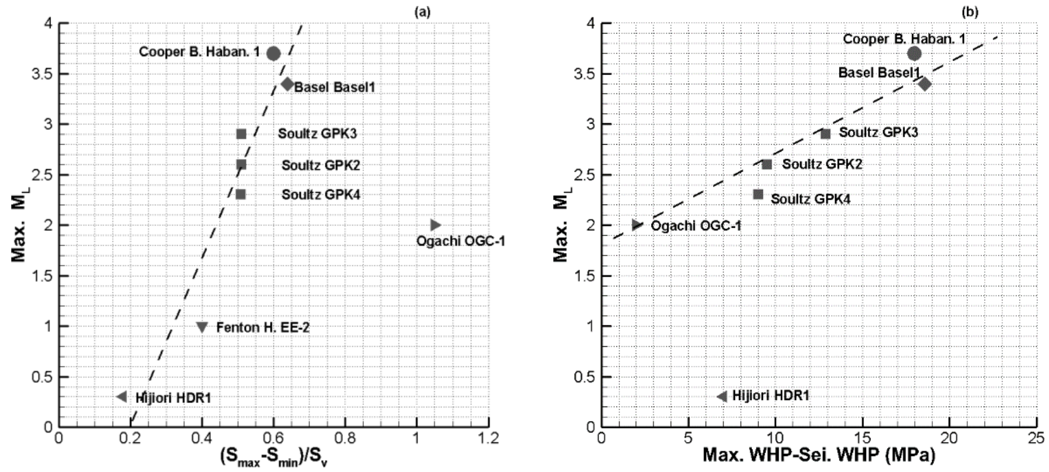

Figure 5: Maximum event magnitude observed and its correlation with (a) the normalized difference between maximum field principal stress and minimum one, (b) the pressure difference of maximum WHP and WHP at onset of seismicity

The above analysis and discussion, which highlights that the differential stress condition is one of the necessary factors to raise LMEs while the difference of maximum injection pressure achieved over that at onset of seismicity is another important factor to induce LMEs, is very meaningful in practice. The field stress condition is natural and almost impossible to change, however, we may control the maximum pressure to decrease seismic magnitude. Of course, many other factors contribute to the triggering of LMEs. Some researchers discussed the effects of the existence of fault zones in the well vicinity on the induced big events and found a close relationship between them (Evans et al., 2012; Mcclure & Horne, 2012). The correlation between the maximum injection pressure and LME was also investigated and no evidence was found to support their correlation (Evans et al., 2012; Mukuhira et al., 2013). More work is needed to study the mechanisms of inducing LMEs and to identify the factors controlling the event magnitude since the evaluation of the potential of LMEs induced by fluid injection is one of the main issues in EGS project.

4. CONCLUDING REMARKS

Massive hydraulic stimulation is an essential component in the development of EGS projects and the associated seismicity, which draws an increasing public concern, is an unavoidable by-product of stimulation operation. We reviewed the hydraulic stimulation tests carried out on seven EGS or HDR projects where the massive volume of fluid was injected into the open well section with interval of tens to hundreds meters in the granite formation. Attempts were made to study the role of differential stress with respect to IS with a geomechanical view. The analysis and discussion of previous test observations demonstrate that 1) the injection pressure for activating shear slip and the associated onset of seismicity is mainly field stress controlled and a larger differential stress allows more possibility for the fractures to be critically stressed for slip; and 2) the differential stress condition is one of the necessary factors to raise LME and the difference of maximum injection pressure achieved over that at onset of seismicity is an important additional factor to induce LME.

5. ACKNOLEDGEMENTS

This work was supported by the New and Renewable Energy Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) through a grant funded by the Korean government's Ministry of Knowledge Economy (No. 20123010110010-11-2-200).

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Table 1 Hydraulic stimulation test and performance parameters of major EGS (HDR) projects

Project	Str.	Well	Date Sti.	Sti. Int.	V_{in}	Max. Q_{in}	Max. WHP	$D_{sei.}$	Sei.WHP	M_L	Ref.
			[year]	[km]	[m^3]	[L/sec]	[Mpa]	[km]	[MPa]		
Soutlz	SS	GPK2	2000	4.4-5.09	23400	50	13.5	4.8	4	2.6	Weidler et al., 2002
Soutlz	SS	GPK3	2003	4.56-5	34000	50	15.5	4.8	2.6	2.9	Baria et al., 2005; Tischner et al., 2007
Soutlz	SS	GPK4	2004	4.49-4.98	9134	30	17	4.9	8	2	Tischner et al., 2007; Baria et al., 2006; Charlety et al., 2007; Schindler et al., 2010; Valley & Evans, 2007
Soutlz	SS	GPK4	2005	4.49-4.98	13000	45	18.3	4.9	13	2.6	
Ogachi	RF.	OGC-1	1991	0.99-1.0	10140	11	19		17	2	Kaieda et al., 2010; Shin et al., 2000
Hijiori	NF	HDR1	1992	2.15-2.2	2115	67	26	2.2	19	0.3	Kaieda et al., 2010; Oikawa & Yamaguchi, 2000
Basel	SS	Basel 1	2006	4.63-5	11570	55	29.6	4.7	11	3.4[a]	Haring et al., 2008
Rosema.	SS	RH12	1982	1.7-2.06	18500	90	14.2	2.5	4.5		Jung, 2013; Pine & Batchelor, 1984; Batchelor et al., 1983
Rosema.	SS	RH15	1986	-2.6	5700	200	15				Parker, 1999
Cooper B.	RF	Hab. 1	2003	4.14-4.42	16350	24	65	4.3	47	3.7	Kaieda et al., 2010
Cooper B.	RF	Hab. 1	2005	4.14-4.43	22500	32	62	4.3	56	3	Kaieda et al., 2010; Baisch et al., 2009
Cooper B.	RF.	Hab. 2	2005	3.92-4.36	7000	7	63	4.3			Parker, 1999; Baisch et al., 2009 ; Chen & Wyborn, 2009
Cooper B.	RF	Hab. 3	2008	4.05-4.2	2200	55	62	4.2			
Cooper B.	RF	Hab.4	2012	4.05-4.2	34200	48	49	4.1		3	Baisch & McMahon, 2014
Fenton H.	NF	EE-2[b]	1983	3.45-3.47	21000	108	38	3.5		1.0[c]	Dreesen & Nicholson, 1985; Brown et al., 2013; Fehler, 1989

Sti. Int.: well open section interval, V_{in}: injected volume, Max. Q_{in}: maximum injection rate, Max. WHP: maximum well head pressure, D_{sei}: mean depth of seismic cloud, Sei. WHP: well head pressure at onset of seismicity, M_L.: maximum event magnitude.

a: it is the maximum magnitude recorded after shut in. b:it is the massive hydraulic fracturing test (MHF): Expt. 2032 in 1983. c: it is the magnitude of the biggest induced seismic event ever observed throughout the Fenton Hill project duration (Brown et al., 2013).