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Characteristics of large-magnitude microseismic events recorded during and after stimulation of a geothermal reservoir at Basel, Switzerland

Yusuke Mukuhira[a,*], Hiroshi Asanuma[a], Hiroaki Niitsuma[a], Markus O. Häring[b]

[a] Graduate School of Environmental Studies, Tohoku University, 6-6-20, Aramaki-Aza-Aoba, Aoba-ku, Sendai 980-8579, Japan
[b] Geo Explorers Ltd., Wasserturmplatz 1, CH-4410 Liestal, Switzerland

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ABSTRACT

Induced seismicity with large events occurred during and after a hydraulic stimulation at Basel, Switzerland, in 2006. This paper describes a study of the characteristics of the large events (those of moment magnitude greater than 2.0) to understand their origin. The large events during the stimulation and just after bleeding off had hypocenters within the seismic cloud while the large events that occurred several weeks after shut-in were located outside of the seismic cloud. We found no evidence that either local stress concentration or increased pore pressure caused the increase of event magnitudes as no shear slip with extremely high stress drop, or a significant correlation between pore pressure and large event magnitude were identified. Our integrated analysis of the fault plane solution and rock failure mechanism showed unbalanced seismic activity and seismic energy release in the pre-existing fracture system. From these observations we conclude that the large events did not originate from the rupture of rigid asperities triggered by increased pore pressure. Our observations suggest instead that critical changes of the stress state or coefficient of friction on fracture planes during stimulation triggered the unstable shear slip of large events. We also conclude that the characteristics of the large events are dependent on their occurrence times and hypocentral locations.

1. Introduction

1.1. Background and objective of this study

Hydraulic stimulation is an essential component in the development of engineered geothermal systems (EGS) and hot dry rock (HDR) projects as it is used to increase well injectivity and system productivity. It is widely accepted that fluid injected into crystalline or consolidated sedimentary rocks can induce shear slip on existing fractures, thus inducing microseismic events. The magnitude of shear slip so induced has a strong impact on the enhanced permeability, so the hypocenters of induced events have been used to identify zones of improved permeability (Katagiri et al., 1980; Evans et al., 2005). It is commonly expected by EGS/HDR developers that for hydraulic stimulation at depths of around 3000–5000 m, induced microseismic events cannot be felt at the surface because the moment magnitude (M_w) of such events is less than 1.5.

However, induced microseismic events that have been felt at the surface (hereafter referred to as "large events") have been reported at commercial-scale EGS/HDR sites at Soultz (France) (Baria et al., 1999), in the Cooper Basin (Australia) (Asanuma et al., 2005), and at Landau (Germany) and Basel (Switzerland) (Majer et al., 2007). Up to nine induced events of $M_w > 2.0$ occurred during and after hydraulic stimulation at Basel in 2006, causing considerable damage to buildings (Kraft et al., 2009). The Basel project was then suspended pending the results of risk analysis and was finally discontinued in 2009 (Baisch et al., 2009). Damage claims amounted to more than US$9.0 million (Giardini, 2009).

Large events have also been reported in and around conventional hydrothermal reservoirs where no hydraulic stimulation has been conducted (Roger and Charles, 1982), and in various other subsurface development projects, including EOR from oil and gas reservoirs (Suckale, 2009, 2010), CCS (Evans et al., 2012), dam construction (Chen and Talvani, 1998), and mine development (Yabe et al., 2009). Large events such as these present a serious problem for subsurface development projects (Majer et al., 2007; Suckale, 2010).

The effectiveness of the large events in the creation or extension of reservoirs is an issue of interest. It is generally believed by seismologists that the magnitude of large events is closely related to the size of the rupture area (Lay and Wallece, 1995). Spatiotemporal analyses of the hypocenters and source parameters of large events induced in the Cooper Basin have shown improved permeability and extension of reservoirs (Asanuma et al., 2005). However, for the Basel EGS and other subsurface projects, the relationship between

* Corresponding author. Tel.: +81 22 795 7401; fax: +81 22 795 7401.
E-mail address: mukuhira@geoth.kankyo.tohoku.ac.jp (Y. Mukuhira).

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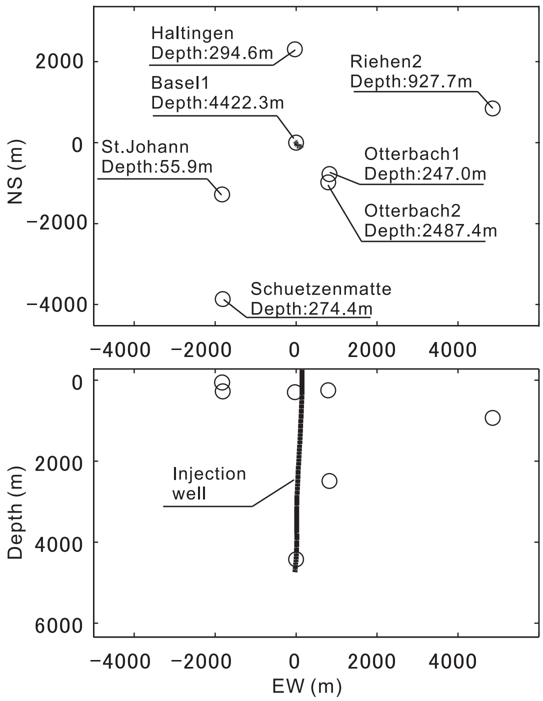

Fig. 1. Microseismic monitoring network at Basel in 2006.

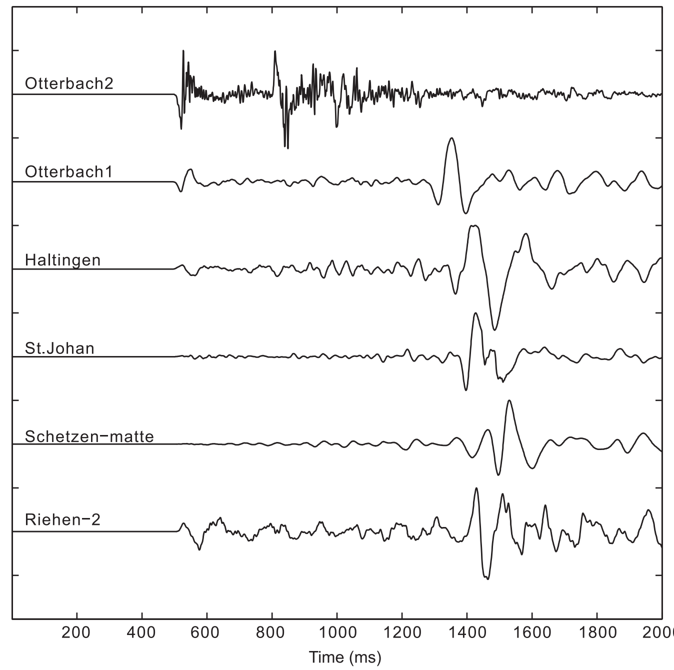

Fig. 2. Velocity waveform at the onset of the P wave of the largest event as detected at six monitoring stations. Time of arrival of P wave is around 500 ms. Amplitude of waveforms has been normalized by the maximum individual amplitude.

event magnitude and improvement of permeability and productivity remains unclear. There is a need to understand the mechanism of induced microseismic events and to identify the factors that control their magnitude so that technologies can be developed to increase permeability without inducing large events (Majer et al., 2007). Methods of risk analysis and development of stimulation techniques that do not cause large events are the subject of ongoing research. Shapiro and Dinske (2009) and Shapiro et al. (2010) developed a technique, based on the b value concept from natural earthquake statistics, to assess the probability of inducing large events on the basis of the volume of fluid injected during hydraulic stimulation.

Progress in the development of understanding of the physics depends on collection of broadband seismic data of high dynamic range and signal to noise ratio, as well as access to other complementary engineering and geophysical data (Suckale, 2010). To date, most of the seismic data associated with induced large events has been recorded by systems that were not designed to capture the unexpectedly large events induced by hydraulic injection. These systems have either provided saturated waveforms or have failed to detect the large event waveforms at all because they were not operating during periods of post injection. However, at Basel in 2006, the waveforms of large events were clearly recorded by broadband, high dynamic range downhole systems in six boreholes in consolidated sedimentary rock (Figs. 1 and 2). The corner frequency showed clear correlation to the magnitude of events in the data shown in (Fig. 3), as previously noted by Asanuma et al. (2007). Thus, we concluded that the data set from Basel stimulation has sufficient quality for precise and reliable investigation of the fundamental characteristics of large events.

1.2. Hydraulic stimulation and monitoring network

Basel is at the southern end of the Rhine Graben, an area with the high potential for geothermal resources in Europe (Hurtig et al., 1992). In 2006, Geopower Basel AG and Geothermal Explorers Ltd. (GEL) commenced joint development of a geothermal cogeneration system capable of delivering 3 MW of electric power and 20 MW of thermal power. GEL drilled a deep borehole (Basel-1) in urban Basel for its first hydraulic stimulation that penetrated granitic basement and reached a true vertical depth (TVD) of 5000 m. Hydraulic stimulation was conducted for six days from 2 December 2006. The open-hole section from 4603 to 5000 m (TVD) included pre-existing permeable fractures and was pressurized by injection of a total of 10,000 m^3 of fresh water. Maximum wellhead pressure reached 30 MPa and maximum flow rate was around 4000 L/min (Asanuma et al., 2007; Ulrich et al., 2007).

A seismic monitoring network had been deployed, being designed to avoid errors in hypocenter determination related to network geometry (Hölker, 2005; Hölker and Graf, 2005; Hölker et al., 2005). The network comprised six permanent downhole seismometers and one temporary downhole seismometer (Fig. 1), all of which employed multi-component sensors. A temporary monitoring station was deployed in the injection well Basel-1 at 4400 m depth, which was thought to be the approximate depth of the dominant feed point; the signals recorded at this station during the initial stage of stimulation were used to improve the subsurface velocity model and to determine station corrections for hypocenter location. The signals were digitized at the wellhead of each observation well with a sampling frequency of 1 kHz by using a 24-bit analog to digital converter and then transmitted to a main server via a virtual private network.

1.3. Occurrence of microseismic events

The seismic network detected about 13,000 events during and after stimulation. By February 2008, GEL had made approximately 2700 real-time hypocenter determinations by using conventional mapping techniques (Asanuma et al., 2007). After manual picking, Asanuma et al. (2007) also determined their hypocenters with Single Event Location (SEL) and Joint Hypocenter Determination (JHD) methods. The hypocenter location showed a sub-vertical planar seismic structure oriented approximately NNW–SSE, consistent with the stress state in the Basel region estimated by Reinecker