Geothermics 52 (2014) 74–83

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Evidence for tensile faulting deduced from full waveform moment tensor inversion during the stimulation of the Basel enhanced geothermal system

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ARTICLE INFO

Article history:
Received 23 August 2012
Received in revised form
12 November 2013
Accepted 8 January 2014
Available online 2 March 2014

Keywords:
Induced seismicity
Hydraulic fracture
Crack opening and closure
Source mechanism
F-test

ABSTRACT

Our study presents the results of a moment tensor inversion of 19 microseismic events with M_L between 2.0 and 3.4, associated with the stimulation operation of an enhanced geothermal reservoir in Basel, Switzerland, in 2006. We adopt a three-step procedure to retrieve point source solution parameters based on full waveform inversion. The inversion is performed by fitting displacement amplitude spectra and displacement seismograms in the first and second step, respectively, assuming a double couple source model and thus obtaining focal solutions for all 19 events. Our results are in agreement with focal mechanisms from a previous study, which employed P wave first-motion polarities from more than 40 stations, whereas our solutions are achieved using full waveform data recorded by less than 10 surface stations. In the last step, a full moment tensor inversion is performed. The results from the moment tensor inversion show an improvement on the waveform fitting compared to the double couple models, which is verified by an F-test. We investigate the stability of the moment tensor solutions by employing different velocity models. The isotropic components of the moment tensor solutions of some events are not negligible, suggesting source volume changes due to fluid injection. Events with significant isotropic components occurred mainly during the stimulation phase and close to the injection well. On the other hand, events that occurred in the post-stimulation phase are predominantly pure shear failure and located further away from the well bore. These spatio-temporal patterns can be explained by the influence of pore pressure variations during and after the hydraulic stimulation at the geothermal site.

1. Introduction

To develop an efficient geothermal reservoir, a technique called hydraulic stimulation or hydraulic fracturing is required. During the stimulation, large amounts of fluid are injected at depth with high pressure to re-open and create new fracture networks in order to increase the permeability of the subsurface reservoir. In most cases pore pressure changes due to hydraulic stimulation result in sudden stress releases and the associated microearthquakes radiate seismic energy that can be detected, e.g., by sensitive downhole geophones (Maxwell et al., 2010). In a few cases, however, minor earthquakes have occurred that were strong enough to be felt by local population, for example during stimulation in Basel, Switzerland, Soultz-sous-Forêts, France, and Landau, Germany (for an overview see Evans et al., 2012). The stimulation process should therefore be optimized to generate a high number of microearthquakes, and at the same time avoid any larger magnitude earthquake that, due to its shallow depth, might cause considerable damage to the enhanced geothermal system (EGS) and the local infrastructure. Understanding the general mechanisms of hydraulically induced fractures is therefore critical to efficiently generate fracture networks, and to estimate their potential seismic hazard at the surface.

Among the few existing EGS projects in the world, the Deep Heat Mining (DHM) Project in the city of Basel provides an excellent site for studying the source mechanisms of hydraulically induced fractures. The project was initiated to construct a local geothermal power plant (Häring et al., 2008). Between 2nd and 8th of December 2006, approximately 11,600 m^3 of river water were injected in a five-km-deep well (Häring et al., 2008; Deichmann and Giardini, 2009). Right from the start, the injection was accompanied by seismic activity in the reservoir. After six days of continuous injection, the well was first shut in, due to an unacceptably high level of

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http://dx.doi.org/10.1016/j.geothermics.2014.01.003

seismicity (M_L 2.6). During that shut-in phase an even larger event of M_L 3.4 occurred, which led to a full bleed-off, only about seven hours after the shut-in (Häring et al., 2008). The ML 3.4 event was also the largest magnitude earthquake associated with this stimulation and after the wellhead was opened (bleed-off), the level of seismicity declined (see Fig. 5 of Häring et al., 2008). However, even after five years, sporadic seismicity is still detected close to the injection well (N. Deichmann, pers. comm., May 2012).

The entire project was suspended due to the negative public response caused by the largest event and eventually abandoned after an independently conducted risk assessment. Nevertheless, the large amount of data collected from this project provides a great opportunity to study different aspects of hydraulic fracturing, such as rock response to high pressure and fluid rate injection, seismic hazard and ground shaking from the strongest induced event. Results of microearthquake locations, focal solutions and stress analysis can be found in Häring et al. (2008), Dyer et al. (2008), Deichmann and Giardini (2009), Goertz-Allmann et al. (2011), Bachmann et al. (2011), Kummerow et al. (2012), Terakawa et al. (2012), and Catalli et al. (2013).

With more than 10,500 induced seismic events detected during and after the injection, the analysis and interpretation of microearthquakes may help to improve the understanding of the physical processes related to the fluid injection. High resolution images of the seismic cloud may delineate parts of the fracture network and thus provide information on the fluid flow (e.g., Phillips et al., 2002). Microearthquake source parameters often contain information about the stress distribution and the role of fluid in source regions (Goertz-Allmann et al., 2011; Bachmann et al., 2011). Deichmann and Ernst (2009) documented focal mechanisms of the 28 strongest induced seismic events until May 2007 by fitting first onset polarities of P-waves. Their results show that the majority of the events can be interpreted as pure shear failure. For three co-located events, though, they discovered a case of inconsistent polarities at two close-by stations, which may suggest the existence of non-double-couple components indicating simultaneous volume changes (Deichmann and Ernst, 2009).

In this study, we invert for the full moment tensors of seismic events enabling us to resolve non-double-couple components. We here present the source parameters of the 19 strongest induced seismic events in Basel that occurred between 2nd December 2006 and 6th of May 2007 for both double-couple (DC) and moment tensor (MT) source models. We then correlate the temporal and spatial patterns of isotropic components of MT solutions with injection parameters. To check the improvement of MT solutions compared with DC models, we apply an F-test. We also investigate the stability of our inversion results employing various velocity models to compute Green's functions. In the next two sections, we briefly introduce the dataset and explain the methodology of the moment tensor inversion in detail.

2. Tectonic setting and seismic data

The city of Basel is located at the Southeastern margin of the Upper Rhine Graben (Häring et al., 2008), intersecting with the Jura Mountains to the South. Roughly speaking, the five-km-deep injection well penetrates 2.4 km of sedimentary layers on the top and 2.6 km of granitic basement (Häring et al., 2008). The region is characterized by a strike-slip regime with a Northwest orientation of maximum horizontal stress S_{hmax} (Deichmann et al., 2000; Kastrup et al., 2004; Häring et al., 2008). The orientation of principal stresses measured within the borehole Basel 1 within the granite section (2600–5000 m) is about 144° for S_{hmax} and 54° for S_{hmin}, respectively (Häring et al., 2008) and is consistent with focal mechanisms derived from natural seismicity in this region. Since the start of the stimulation, more than 10,500 events have been observed near the injection well within the granitic basement (Deichmann and Giardini, 2009), forming a lens-shaped seismicity cloud elongated in SSE direction. For our study, we choose the strongest events from the catalog of Deichmann and Giardini (2009) with $M_L \geq 2$ (Table 1).

The seismic networks in this area are operated by three different organizations: a Swiss regional network by the Schweizerischer Erdbebendienst (SED), a German regional network by the Landeserdbebendienst Baden-Württemberg (LED), and six borehole sensors installed by Geothermal Explorers Ltd. (GEL). The networks are composed of different instruments, including both broadband seismometers and accelerometers with various sampling rates (from 62.5 Hz up to 1000 Hz). More detailed information about seismic stations near the site can be found in Deichmann and Giardini (2009). We only select seismic stations within 15 km distance to the injection well in order to reduce the impact of lateral heterogeneity of the geological layers. A total of 40 seismic stations are located within this range (Fig. 1), among them the borehole monitoring sensors installed by GEL providing great detail about source locations of the induced seismicity (Häring et al., 2008; Dyer et al., 2008; Deichmann and Ernst, 2009; Goertz-Allmann et al., 2011). Unfortunately, the current version of the applied moment

Table 1
Catalog of 19 events analyzed in this study and their corresponding percentages of ISO, DC, and CLVD components using the velocity model N2. The event ID is the same as in Deichmann and Ernst (2009).

ID	Time	Longitude	Latitude	Depth (km)	Mag	ISO (%)	DC (%)	CLVD (%)
39	2006.12.06 22:27	7.593	47.587	4.2	2.2	23.8	73.6	2.6
86	2006.12.08 03:06	7.596	47.585	4.1	2.6	−9.4	89.7	0.9
87	2006.12.08 03:24	7.595	47.584	4.8	2.3	−5.8	85.6	8.7
94	2006.12.08 09:04	7.593	47.584	4.8	2.2	18.2	62.0	19.9
98	2006.12.08 11:36	7.596	47.584	4.6	2.2	17.9	63.1	19.0
102	2006.12.08 15:13	7.595	47.583	4.7	2	17.1	63.7	19.2
104	2006.12.08 15:31	7.595	47.585	4	2.1	−8.7	89.6	−1.7
105	2006.12.08 15:47	7.593	47.588	4.1	2.7	8.9	47.9	43.3
108	2006.12.08 16:49	7.593	47.584	4.7	3.4	14.9	72.0	13.1
112	2006.12.08 19:27	7.596	47.582	4.7	2.3	3.4	81.3	15.3
113	2006.12.08 20:20	7.593	47.583	4.9	2.6	35.3	52.0	12.7
147	2006.12.10 06:11	7.595	47.584	4	2	−11.7	84.7	3.6
159	2006.12.14 22:39	7.596	47.584	4	2.5	−13.5	84.5	2.0
168	2007.01.06 07:20	7.596	47.582	4.2	3.1	−2.0	76.8	21.3
170	2007.01.12 03:35	7.597	47.581	4.2	2.2	1.0	81.0	18.0
174	2007.01.16 00:09	7.596	47.582	4.1	3.2	−4.6	85.0	10.5
176	2007.02.02 03:54	7.596	47.582	4	3.2	−2.2	88.1	9.7
184	2007.03.21 16:45	7.596	47.581	4	2.8	4.6	74.2	21.2
185	2007.05.06 00:34	7.597	47.581	4	2.3	−1.7	94.7	3.6