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Identification of faults activated during the stimulation of the Basel geothermal project from cluster analysis and focal mechanisms of the larger magnitude events

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ABSTRACT

High-precision relative location procedures of the stronger seismic events ($0.7 \leq M_L \leq 3.4$), based on cross-correlations of signals recorded by a six-sensor borehole network and numerous surface stations in the immediate epicentral area, show that clustering of hypocenters on different spatial scales is a dominant feature of the microseismicity induced by the stimulation of enhanced geothermal reservoir in Basel. In line with the fact that many of the observed earthquakes form clusters of similar events, several focal mechanisms are also nearly identical to each other. A comparison between the high-precision relative locations of the events within each cluster and the focal mechanisms often shows a good coincidence of the hypocentral distribution with one of the nodal planes of the focal mechanism. In some cases, the spatial extent of the individual clusters is limited to a few meters, which suggests that the corresponding events represent repeated slip with partial stress drop as pore pressures increase with time. In other cases, that include some of the stronger events ($M_L > 2$), the dimension of the individual clusters can amount to several 100 m, and the activity within these clusters can extend over several days. Given that the orientation of many fault segments identified in this way deviates significantly from the overall orientation of the seismic cloud, these results reveal a complex internal structure of the flow paths in the rock volume stimulated by the water injection.

1. Introduction

To stimulate the reservoir for an Enhanced Geothermal System (EGS) initiated by a private/public consortium in the city of Basel, Switzerland, approximately 11,500 m^3 of water were injected at high pressures between December 2nd and December 8th 2006 into a 5-km-deep well below Kleinhüningen (Häring et al., 2008). Seismicity induced by the injections was monitored by regional networks of surface stations operated by national and state agencies, and by a dedicated six-sensor borehole network, installed by the operators. More than 10,500 seismic events were recorded during the injection and immediate post-injection phase. Hypocentral locations could be calculated for more than 3000 of these events. The gradual increase in flow rate and wellhead pressure was accompanied by a steady increase in seismicity, both in terms of event rates and magnitudes. In the early hours of December 8th, after water had been injected at progressively higher flow rates up to 55 l/s and at wellhead pressures up to 29.6 MPa over a 16 h period (Häring et al., 2008), a magnitude M_L 2.6 event occurred within the reservoir (Fig. 1). This exceeded the safety threshold for continued stimulation, so that injection was stopped prematurely, and the well shut-in. In the afternoon and evening of the same day, two additional events of magnitude M_L 2.7 and 3.4 occurred within the same source volume. As a consequence, the well was opened and in the following days about one third of the injected water volume flowed back out of the well (Häring et al., 2008). Though the seismic activity declined rapidly thereafter, three more events with $M_L > 3$ occurred in January and February 2007, and sporadic lower-magnitude earthquakes are still being recorded in 2013.

This article presents the results of an ongoing analysis based mainly on the larger magnitude events that were induced by the stimulation of the reservoir. In this context, by "larger magnitude events" we mean all events that were recorded not only by the local borehole network installed by the project operators, but also by the regional seismometer and local surface accelerometer networks of the Swiss Seismological Service (SED) and the Landeserdbebendienst of Baden-Württemberg (LED). The goal is to examine the role

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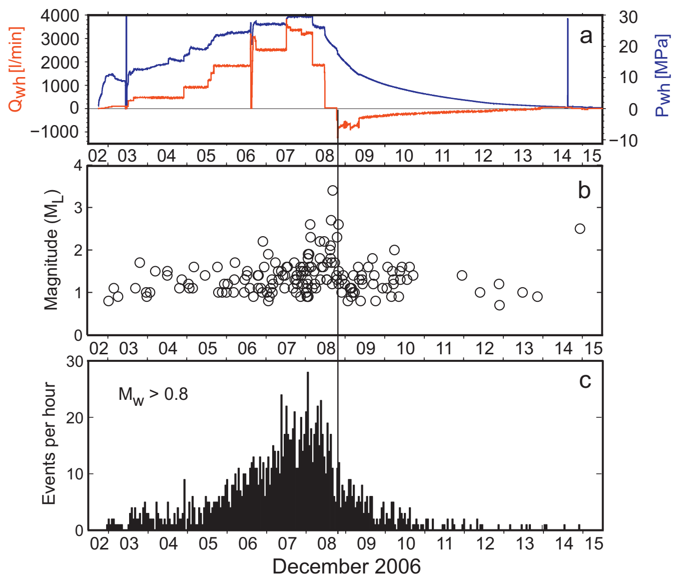

Fig. 1. (a) Well-head pressure (upper blue curve with scale on the right) and injection rate (lower red curve with scale on the left) from the start of the stimulation until mid December 2006 (modified from Häring et al., 2008); (b) local magnitudes (M_L) of the induced events recorded by the surface network of the Swiss Seismological Service; (c) events per hour with moment magnitudes (M_w) greater than 0.8 recorded by the borehole network of Geothermal Explorers. The M_w of 0.8 is the estimated average magnitude of completeness over the given time period (Bachmann et al., 2011) and corresponds to an M_L of about 0 (Bethmann et al., 2011). The vertical line identifies the time when the well was opened and the water was allowed to flow back out of the well (the beginning of bleed-off). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

that these larger events play in the stimulation process by mapping the faults on which they occurred. The temporal evolution of the seismic activity induced by the Basel geothermal project can be subdivided into three periods. The first from December 2nd to December 8th corresponds to the period of active stimulation and ends when the well was vented; 108 larger magnitude events, according to the definition given above, occurred in this first period. The second period, which lasted until the end of December 2006, is characterized by a steady decrease of activity, both in terms of magnitude and of number of events, as wellhead pressure declined due to the venting (Fig. 1). Another 57 events occurred during this second period. The third began in January 2007 with a renewed increase in seismic activity that was followed by a gradual decline in spring and summer. By the end of November 2007, the regional networks had recorded a total of 195 seismic events with magnitudes between M_L 0.7 and 3.4 (Deichmann and Giardini, 2009). An additional M_L 0.6 event was recorded in 2010. Activity picked up again, with five events with M_L between 0.9 and 1.2 in 2012 and two events in 2013 with M_L 1.8 and 1.0.

As already noted by several different authors (e.g. Asanuma et al., 2007, 2008; Dyer et al., 2010; Häring et al., 2008; Mukuhira et al., 2013), a substantial part of the seismicity induced by the stimulation of the Basel reservoir occurred in clusters of events with similar waveforms, or so-called families of similar events (also termed multiplets). This implies that the hypocenters of the events in each cluster must be located very close to each other and that their focal mechanisms must be nearly identical. Very commonly, the hypocenters of events in such clusters are located on a plane that coincides with one of the nodal planes of their focal mechanism. In the present analysis, we take advantage of the high waveform similarity and apply a cross-correlation procedure between the signals of the different events to obtain precise relative arrival times. These arrival times serve as input for a master-event location technique to compute high-precision relative hypocenter locations that serve to resolve the structures such as planes on which the events are occurring. Planes identified in this way can be compared to the focal mechanisms of the events, which are based on first-motion polarities observed at both the local borehole seismometers and the regional surface networks. In a companion article (Kraft and Deichmann, 2014) a similar procedure has been applied to the larger data set recorded only by the local borehole network and using different selection criteria to identify the clusters of similar events. As discussed in more detail in Section 4.3 of the present article, the different selection criteria reveal special and temporal clustering at different scales, so that the two articles together give a complementary picture of the seismicity induced by the Basel geothermal project.

2. Tectonic setting

Basel is located at the southern end of the Rhine Graben, where it intersects the fold and thrust belt of the Jura Mountains of Switzerland (Fig. 2 and Fig. 1 of Valley and Evans, 2009). As such, it is an area that, in the geologic past, has seen both extension (rifting phase of the Rhine Graben) and thrusting (folding of the Jura Mountains). A recent comprehensive summary of the evolution of the Upper Rhine Graben and Jura Mountains through geologic time, together with an exhaustive reference list, can be found in Ustaszewski and Schmid (2007). The borehole itself is situated at the southern end of the Rhine Graben and reaches a depth of 5 km below the Earth's surface. As shown in the lithological section reproduced in Häring et al. (2008) and in Valley and Evans (2009), it penetrates a 2426 m thick sedimentary sequence before entering the crystalline basement.

Focal mechanisms in the Southern Rhinegraben, the Black Forest and northern Switzerland south of Basel, are dominated by strike-slip and normal faulting mechanisms (e.g. Kastrup et al., 2004; Plenefisch and Bonjer, 1997). The average value for the direction of the regional maximum compressive horizontal stress, S_{Hmax}, calculated by Kastrup et al. (2004) from the focal mechanisms in the southern Rhinegraben region and in the central part of northern Switzerland, using two different inversion methods, is about 144°. This value is identical to the average local S_{Hmax} in the crystalline basement derived from measurements in the 5 km deep Basel borehole by Valley and Evans (2009). Terakawa et al. (2012) obtain a strike-slip stress field from an analysis of 118 focal mechanisms of the seismicity induced by the Basel EGS with directions of the principle axes that match the borehole observations of Valley and Evans (2009) to within a few degrees.

3. Seismic networks

The seismic data available for the Basel geothermal project and analyzed in this article were recorded by several different seismometer and accelerometer networks operated by three separate institutions: the Swiss Seismological Service (SED), Landeserdbebendienst Baden-Württemberg (LED) and Geothermal Explorers Ltd. (GEL). The locations of stations are shown in Fig. 2. The network included a six-sensor borehole network installed by GEL around the project site at depths between 317 and 2740 m. Detailed documentation of the instruments and digital data acquisition systems can be found in the articles by Deichmann and Ernst (2009) and Deichmann and Giardini (2009). It should be noted that accelerometers at epicentral distances of a few kilometers installed at the Earth's surface in the middle of a noisy city such as Basel can provide good-quality data, even for events with magnitudes M_L < 1.