Estimating energy balance for hydraulic fracture stimulations: Lessons Learned from Basel

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Summary

We apply the concepts of hydraulically injected power and radiated seismic energy to data from the hydraulic stimulation program of the 2006 Deep Heat Mining (DHM) project in Basel, Switzerland. After high-pressure injection of 11,500 m^3 of water into a 5-km-deep well, the stimulation program was stopped after 6 days, following the occurrence of a widely felt moment magnitude (Mw) 3.4 event. Suspension of the stimulation program was undertaken in compliance with a pre-defined response procedure ("stop-light system") based on event magnitude, peak ground velocity (PGV) and public response. During the course of the stimulation program, the total injected energy amounted to 726.5 GJ, the approximate energy equivalent of a Mw 4.7 earthquake and about 4.4 times the energy injected during one stage of a large, multi-stage frac treatment in western Canada. After correction for missing data based on measured Gutenberg-Richter *b*-value, the radiated seismic energy from induced and triggered events is 51.9 GJ, or about 7.1% of the injection energy. This represents a much greater fraction of the injection energy than is typically observed for hydraulic fracture treatments for unconventional reservoir development in western Canada, perhaps reflecting release of stored elastic strain energy on fault systems in addition to the energy supplied by injection. Triggered and induced seismicity associated with the Basel DHM project provide useful background data for assessing the potential for seismic activity elsewhere, as well as developing appropriate mitigation procedures.

Introduction

A series of felt earthquakes were triggered in December 2006, after approximately 11,500 m^3 of water were injected at high pressures into a 5-km-deep well in Basel, Switzerland (Häring et al., 2008; Deichmann and Giardini, 2009; Giardini, 2009). As part of the Deep Heat Mining (DHM) Project, this work was undertaken with the objective of developing an Enhanced Geothermal System (EGS) cogeneration plant. As part of this project, a wellbore was drilled through 2.4 km of sedimentary rocks and 2.6 km of granitic basement, and hydraulically stimulated below 4629 m depth in order to enhance the permeability of the basement rocks (Häring et al., 2008). During and after the injection phase, more than 10,500 seismic events were recorded using a 6-station borehole seismometer array installed at depths between 317 and 2,740 meters around the wellbore, as well as by permanent stations of the Swiss national seismograph network (Deichmann and Giardini, 2009). Injections were stopped following increasing seismic activity, the largest having moment magnitude (Mw) 3.4. A pre-defined response procedure ("stop light system") was followed, based on event magnitude, peak ground velocity (PGV) and public response (Figure 1). Triggered and induced seismicity associated with the Basel DHM project provide useful background data for assessing the potential for seismic activity elsewhere, and developing appropriate mitigation procedures.

In this paper, we use hydraulically injected energy (E_I) and radiated seismic energy (E_R) as metrics for assessing energy balance of hydraulic-fracture stimulation programs. Hydraulically injected energy can be determined based on pumping curves, and represents the primary energy input into the system. The radiated seismic energy is calculated from event magnitudes and represents one of the outputs. In the case of hydraulic fracture treatments for unconventional reservoir development, Maxwell et al. (2008) and Boroumand and Eaton (2012) showed that most deformation is aseismic, so that the radiated seismic energy constitutes a very small (<< 1%) component of the overall energy balance. This concept is applied here to data from the Basel DHM project.

Green	• No public response • Event M_L < 2.3 • PGV < 0.5 mm/s	• Regular operations • Continue pumping
Yellow	• Few calls • Event $M_L \geq 2.3$ • PGV ≤ 2.0 mm/s	• Call and inform DSV • Continue pumping • Do not increase flow rate
Orange	• Many calls • Event $M_L \leq 2.9$ • PGV ≤ 5.0 mm/s	• Call and inform DSV • Maintain well head pressure below Stimulation Pressure by pumping at a SPR, stopping pump(s) or bleeding the well
Red	• Generally felt • Event M_L > 2.9 • PGV > 5.0 mm/s	• Call and inform DSV • Stop pumping • Bleed off to minimum wellhead pressure

Figure 1: Stop light system implemented for the 2006 Deep Heat Mining Project, Basel (Häring et al., 2008).

Theory

Often referred to as hydraulic horsepower, the hydraulically injected power is the product of pressure (*P*) and flow rate (*Q*). In units of J, the hydraulically injected energy (E_I) is the time integral of hydraulically injected power, and is given by

$$E_I = \int_{t1}^{t2} P(t)Q(t)\,dt \quad , \qquad (1)$$

where *t*1 and *t*2 are the start and end times of the injection, *P* is given in units of Pa and *Q* is given in units of m^3/s.

For a seismic event of moment magnitude *M*w the radiated seismic energy is given by

$$\log_{10}(E_S) = 1.5M_0 + 4.8 \quad . \qquad (2)$$

This equation is modified from Kanamori (1977), who used the Gutenberg-Richter magnitude-energy relation calibrated for large earthquakes and expressed the result in units of ergs. The cumulative radiated seismic energy can be determined by summing (integrating) all of the events recorded during a microseismic monitoring program.

Boroumand and Eaton (2012) observed that since seismicity catalogs are always incomplete, a correction should be applied for missing data. They proposed to correct for missing data by computing the expected number of events based on extrapolation of the Gutenberg-Richter curve to a minimum magnitude of Mw –3.0.

Results

Figure 2 summarizes pumping curves and induced/triggered seismicity for the Basel DHM project (from Häring et al., 2008). Starting on December 2, 2006, the flow rate and wellhead pressure were gradually increased. This was accompanied by an increase in seismicity recorded by the local and national seismograph networks, both in terms of event rates and magnitudes. A local magnitude (ML) 2.6 event occurred early in the day on December 8. Although this did not exceed the "orange" threshold for stop-light system, the event was widely felt and injection was stopped prematurely (Deichmann and Giardini, 2009). While preparations were being made to reduce the downhole pressure to hydrostatic conditions, two additional events of magnitude ML 2.7 and 3.4 occurred later that day.

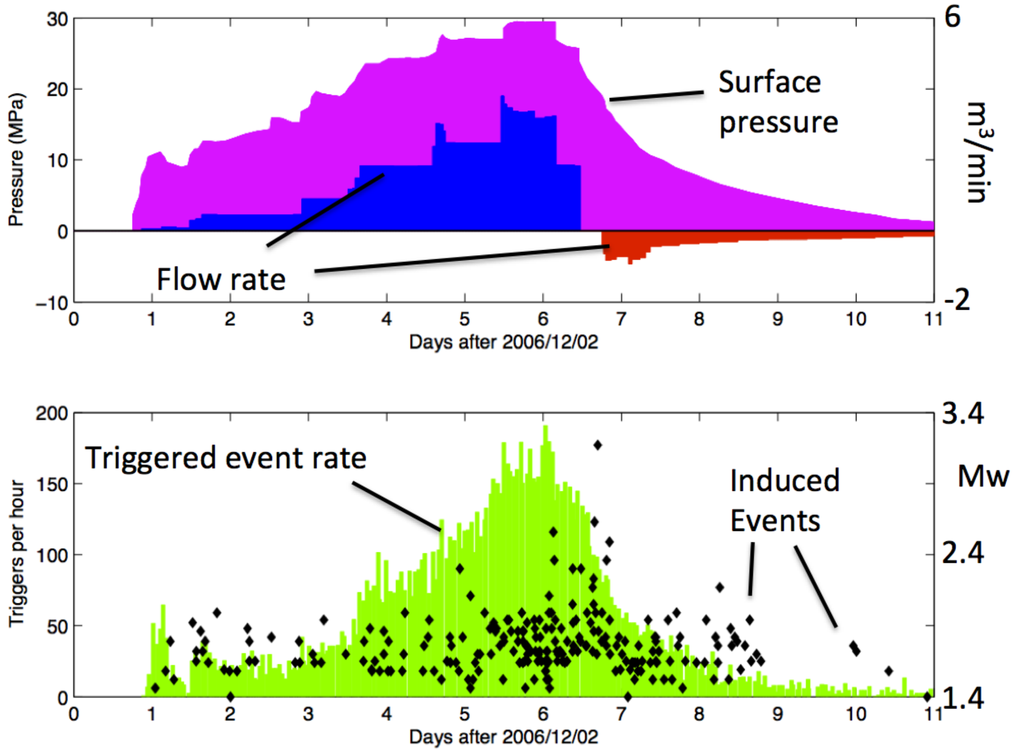

Figure 2: Top panel: treatment curves showing surface pressure and flow rate for the December 2006 Basel project. Bleed-off period is shown as negative flow rate. Lower panel: Triggered event rate from the local seismograph network (bar graph) and events reported by the Swiss Seismological Service (symbols). Modified from Häring et al. (2008).

Figure 3 shows the calculated curves for injected power and hydraulically injected energy for the Basel DHM project. The curves were calculated using equation (1), based on the data presented in Figure 2. The total hydraulically injected energy is 726.5 GJ; for comparison, this is equivalent (in energy) to a Mw 4.7 earthquake. Compared with similar calculations performed for a large multi-stage hydraulic fracture treatment in western Canada, it is worth noting that the total injected energy for Basel is ~ 4.4 times the injected energy for an average injection stage (Boroumand and Eaton, 2012).

Figure 4 shows a Gutenberg-Richter graph of Basel induced seismicity. The data used to compute this curve were taken from the Swiss national earthquake catalog (ECOS 2009). We obtained a *b*-value of 1.26±0.1. This represents the slope of the magnitude-recurrence curve, found here by simple linear regression. Extrapolated to Mw –3.0, we obtain a corrected radiated seismic energy of 51.9 GJ, or 7.1% of the total injected energy. Relative to the total injection energy, we remark that this ratio is several orders of magnitude greater than that found by Boroumand and Eaton (2012). We suggest that the enhanced radiated seismic energy at Basel may reflect the release of stored elastic strain energy.

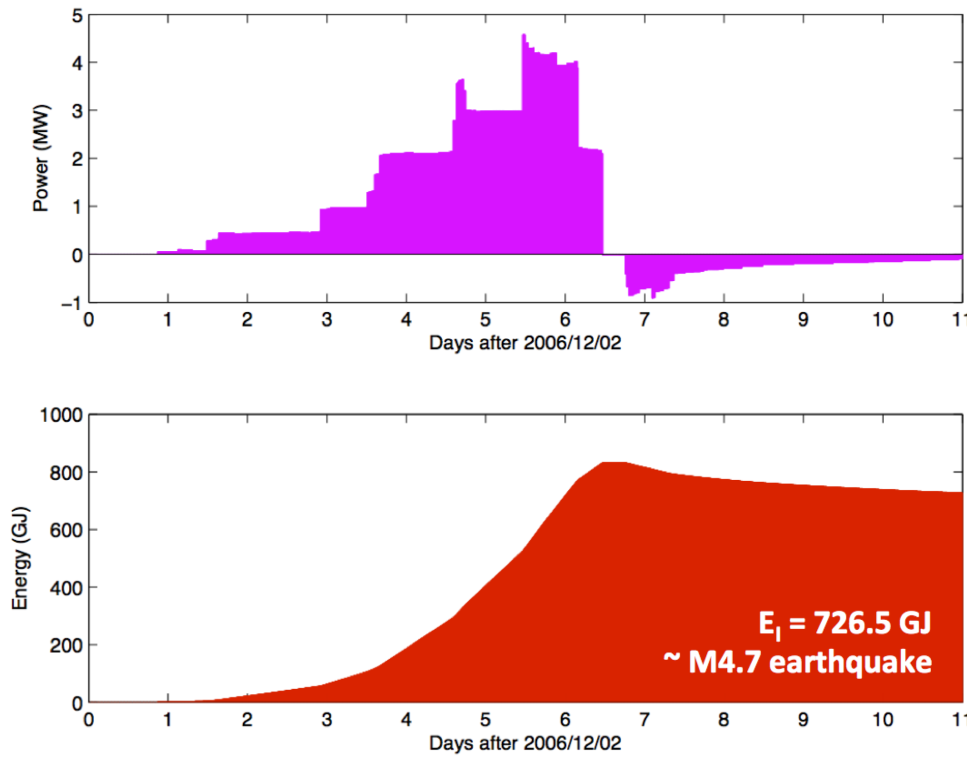

Figure 3: Top panel: Hydraulic power during the Basel injection, computed using the curves in Figure 2. Lower panel: Cumulative injected energy (E_I), obtained by integrating the power curve. The net injected energy is approximately equivalent to a Mw 4.7 earthquake.

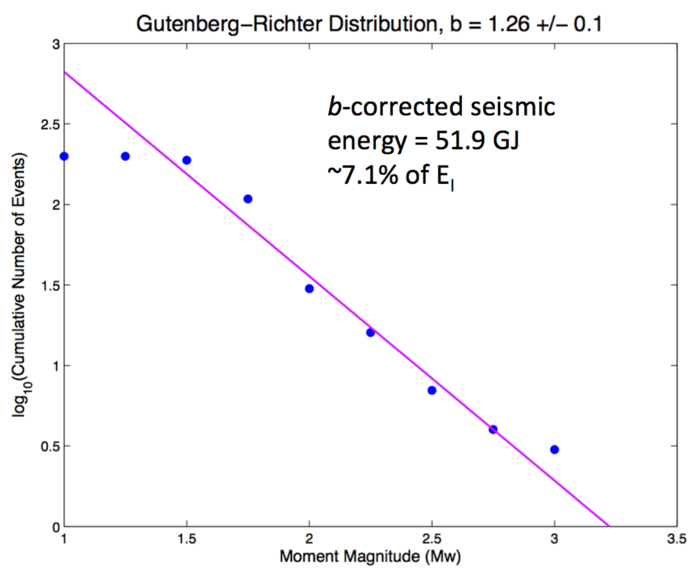

Figure 4: Gutenberg-Richter plot for Basel-area induced seismicity reported by the Swiss Seismological Service (ECOS 2009) for the period 2006/12/03 to 2006/12/12. After *b*-value correction for missing data to Mw –3.0, the radiated seismic energy is computed to be 51.9 GJ, or about 7.1% of E_I.

Conclusions

The Basel DHM project provides important background information for analysis of induced and triggered seismicity at other locations. Although injection occurred at a lower rate, the total injected energy is slightly less than would be expected for a large multistage hydraulic fracture treatment for unconventional resource development in western Canada (Boroumand and Eaton, 2012); however, the radiated seismic energy is orders of magnitude larger than previously documented examples (Maxwell et al., 2008). We suggest that the comparatively large radiated seismic energy following the Basel injection may be due to the additional release of stored elastic strain energy on subsurface fault systems.

Acknowledgements

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