Big Boom in Basel: is Oz next?

Malin P.E.[1], Shalev, E.[1], and Kahn, D.[2]
[1] *Institute of Earth Science and Engineering, University of Auckland, 58 Symonds St, Auckland 1142, New Zealand*
[2] *Earth and Ocean Sciences, Duke University, Box 90227, Durham, NC. USA 27708*
Email: p.malin@auckland.ac.nz; shalev@duke.edu; N.A.

ABSTRACT

We deployed a 6 station borehole microearthquake network around an Engineered Geothermal System stimulation-site beneath the city of Basel Switzerland. The borehole stations ranged in depth between 400 m to 2,700 m. During the stimulation several thousand accurately-locatable microearthquakes were generated, culminating in an M~3.4 event late in this man-made tremor sequence. This event exceeded the license limits for the stimulation, shutting down the associated Hot/Dry Rock power venture. Using standard source parameter analysis procedures and theory we have plotted the radiated energy versus seismic moment of the EGS sequence. The results suggest that the bulk of the stimulated events do not follow standard source scaling relations, with only a small fraction of small events and event larger than about M~1, falling along a constant stress drop line. Among the possible explanations for this break down are continued near source attenuation and scattering effects, which could be hiding the critical high frequency portions of the borehole seismic data. It could also be that the stimulation events actually follow different source physics than standard double couple events, owing to their origin in hydraulic fracturing. If so, then it might be possible to use this type of analysis to forecast the likely distribution of induced event magnitudes prior to licence exceeding induced earthquakes.

INTRODUCTION

We present a case history of a (somewhat) unexpected outcome of a geothermal investment of many millions of Euros by the city of Basel, Switzerland. The objective of the investment was to obtain clean geothermal power from hot rocks beneath this medieval-age city. The reason for the investment was the growing conflict between an electricity starved city and heavy air pollution from fossil fuel power plants. The idea was to “crack” the hot, but dry rocks under a very small portion of the city (under its main power distribution station) and pull heat up by circulating water into the cracks – i.e. create an Engineered Geothermal System in downtown Basel.

The main stimulation commenced on December 2, 2006. To monitor the anticipated seismic activity a small network of borehole seismographs were deployed in the vicinity of the injection well, but all within the city. Despite heavy cultural noise, the net could detect and locate M<0 microearthquakes from the drill site. On December 8, 2006 a magnitude 3.4 was induced, raising a civil alarm. The entire EGS effort was shut down shortly thereafter and is still being debated in Swiss court.

Could this same scenario take place in Australia?

To avoid a repeat of this very costly and embarrassing situation we have been studying the sequence and source parameters of the microearthquakes induced by the Basel stimulation. Even before the main stimulation, at the time of cementing of the well casing, it was possible to observe and locate the induction of very small events with the borehole seismic array. Standard source parameter analysis of the borehole seismic data after the sequence of events was more-or-less over shows that there was a breakdown in source scaling. This observed change in scaling related to the difference between very much fewer, but unfortunately larger, events and the bulk of the induced seismicity. Larger events appear to lie along curves of constant apparent stress, while the much more numerous small events fall along a significantly different curve. Perhaps careful real time monitoring of the induced seismicity could thus have been used to avoid this transition ahead of time by adjusting the stimulation factors that control it?

Observing the Big Boom with borehole seismology

Switzerland is powered by hydroelectric and nuclear power. Additional power could be supplied by geothermal sources. Basel sits at the southeast end of the Rhine Graben and at the northern front of the Jura Mountains, a young section of the Alps; the combination of the two leads to mild seismic activity. In fact, Basel has experienced several major quakes, the worst in 1356 has been analyzed to have been of magnitude 6.5 to 7.0 (Weidmann, 2002). Most quakes are rather shallow, some occurring within 5 km of the surface. The heat flow in the region is between 100 and 130 mW/m^2 (Medici and Rybach, 1995) compared to a globally averaged value of about 50 mW/m^2. This suggests that the region near Basel would have a strong potential to be a source of geothermal energy that could be efficiently mined. (see: Kahn, 2008, PhD Dissertation, Duke University.)

The main stimulation of the Basel Switzerland Hot Dry Rock geothermal experiment commenced on December 2, 2006. The primary purpose of the stimulation was to create a hydro-fractured reservoir, using an injection well bored to 5,000 m that could be used for heat exchange in the Basel Deep-Heat Mining Project.

To monitor the seismic activity we deployed 6 sondes each with 3 velocity sensors (5 also having 3 accelerometers) in the vicinity of the injection well at depths ranging from 317 to 2,740 meters below the ground surface. On December 8, 2006 a magnitude 3.4 was induced. This main event occurred after the injection flow had been "shut-off", in response to increased seismic activity. During the surrounding period, data from over 13,000 events were recorded with approximately

Figure 1. Air photo showing location of induced earthquake beneath the Basel HDR site.

3,300 of those events being locatable and nearly one hundred of them of magnitude one or greater (Figure 1).

Source scaling: a key to avoiding limit exceeding HDR earthquakes?

An important topic in seismology is the question of scaling relations of earthquakes. Are small quakes (magnitude ~< 2) simply large quakes scaled down? If so, then perhaps there exists a simple relationship to "forecast" what might happen during a stimulation by simply monitoring the size of the fracture being created and stopping short of the local "large" scale size. Numerous studies have examined this question with mixed results (see for example: Ide et al. (2003)). There are several reasons that might explain the disagreement (see: https://eed.llnl.gov/scaling-workshop/overview.php); these include 1) large uncertainties in the seismic energy; 2) large energy variability for different earthquakes with the same moments within the same study; 3) lack of common events between studies, making comparisons of the different scaling difficult; and 4) few studies using a single consistent technique covering a wide range of sizes (e.g. M~-1 - M~3).

Other than energy, one of the variables that we examined is the standard description of stress drop, the change in stress before and after the quake. The stress drop, which is a ratio of seismic moment and source dimension cubed is hypothesised to be constant over many magnitudes (0 to 7). However, because of the difficulty in separating the effects of source, path, and site, it is difficult to verify the scaling relationships below magnitude 3. Below this magnitude, using standard data collection and analysis techniques, the source dimension appears to have a constant value of about 100m; therefore, the stress drop decreases with decreasing moment.

While there are arguments that support this dimension (typical width of a fault zone), it has also been suggested that the attenuation seen in surface stations is responsible for the breakdown. This attenuation is particularly important for high frequencies (>50 Hz), because the absence of short wavelength observations could severely restrict the resolution of small source sizes. As a result studies are using relatively deep (~3 km) sites to eliminate near-surface attenuation and determine whether the scaling relations hold. In our Basel study, we used the borehole seismic data acquired during the hydro-fracture stimulation to examine the source scaling parameters for the ~3000 events that were recorded in one week, the borehole data significantly reducing attenuation.

We find that the standard plot of radiated energy versus seismic moment differs significantly from the standard scaled models (e.g. Ide and Beroza, 2001; Figure 2). The nearly linear plot of data is significantly different from the expected values. Rather than being proportional to M, which is the commonly stated relation for events of constant apparent stress, the radiated energy appears to go as ER ~ M*1.74. Using the standard model results, apparent stress for smaller Basel stimulation events increases with increasing moment, up to a point. However, larger events, and a small fraction of smaller ones, do seem to track along the constant τA=0.2MPa line. In particular, the results could be taken as suggesting that scaling is valid for events of moment greater than approximately M~1 or so.

SUMMARY AND CONCLUSIONS

The result of the Basel HDR stimulation was that the operators working on behalf of the city exceeded the allowable limit of ground shaking and the project was shut down pending a public hearing on what happened. Given the several hundred thousand Euro cost of the drilling operation each day, several millions were lost in the confusion resulting from the M~3.4 event. The whole sequence of subsequent "political events" illustrates how a very good idea can go badly wrong without a great deal of care by both private investors and public officials. While geothermal conditions in Australia are significantly different than in Switzerland, there is much to be learned

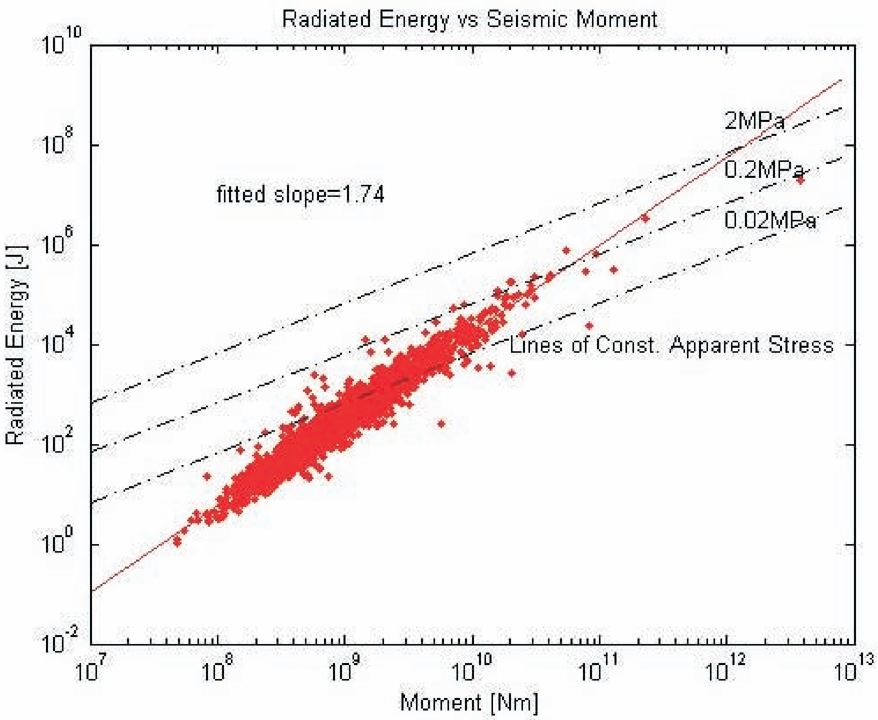

*Figure 2. Radiated energy versus seismic moment for the P-wave in the full cluster. Lines of constant apparent stress are given by the -.-. curves. The red line is the least squares fit of log(E_R)=a*log(M)+b, with a=1.74. While the overall fit is not consistent with constant apparent stress, those events with larger moment seem to lie along a constant apparent stress of =0.2 MPa (Kahn, 2008, PhD Dissertation, Duke University). It may be that, in the case of Basel, beyond the intersection of this line with the observed curve one can expect larger events to occur.*

from the Big Boom in Basel even here. Given Australia's thrust forward in geothermal development, this case should give pause for both sectors, private and public, and spur significant efforts in both research and human relations so as to avoid similar losses in time and resources.

We have used the very high quality borehole seismic data from Basel to test to see if the standard energy-stress-scaling relationships of these events might yield a way to forecast the potential occurrence of a "license-exceeding" earthquake during HDR stimulation (Kahn, 2008, PhD Dissertation, Duke University). Using standard analysis and scaling relations we conclude from this study that:

- Scaling does not appear to be valid for stimulated events over the full range of moments.
- Scaling is approximately obeyed for the larger events and a small fraction of smaller events.
- It maybe possible to track the energy – moment relations of fracture stimulation to a point beyond which larger events can be expected. These events appear to follow a more standard scaling relation.

Thus we suggest it may be possible to develop an empirical method for monitoring the progress of a HDR stimulation and forecast the potential for a licence exceeding event. It is also possible that this relationship holds only for a given configuration of observation stations and induced events, with near source attenuation and other propagation effects such as scattering still obscuring the true scaling. However, given that the induced microearthquakes could include mechanisms fundamentally different from natural, double couple events, our results do not preclude the development of such a monitoring system. So there is still hope that Australia can be saved from the embarrassment and expense of a Basel while trying to develop alternatives to fossil fuel energy.

REFERENCES

Ide, S. and Beroza, G.C. 2001. Does apparent stress vary with earthquake size?, *Geophys. Res. Lett.*, **28**, 3349-3352.

Ide, S., Beroza, G.C., Prejean, S.G. and Ellsworth, W. L. 2003. Apparent break in earthquake scaling due to path and site effects in deep borehole recordings. *J. Geophys. Res.*,**108(B5)**, 2271.

Kahn, D., PhD Dissertation, Duke University, 2008.

Medici F., And Rybach, L., 1995. Geothermal map of Switzerland 1:500'000 (Heat Flow Density). *Beitr. Geol. Schweiz, Ser. Geophys.* Nr. **30**, 36 pp.

Weidmann, M., 2002. Erdbeben in der Schweiz, Verlag Desertina, Chur.