Interpretation of Microseismic Events with Larger Magnitude Collected at Cooper Basin, Australia

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ABSTRACT

The authors analyzed the spatial and temporal distribution of the microseismic events with larger moment magnitude observed during a hydraulic stimulation at the Australian HFR site in the Cooper Basin. The seismic traces of the large events were saturated and we could not directly estimate the moment magnitude from the trace. Accordingly we estimated the moment magnitude from a combination of the duration time and the local magnitude of smaller unsaturated events. There was no clear relationship between the magnitude of the events so determined and the hydraulic records. Indeed some of the big events occurred even after shut-in. We have found that some of the big events brought very clear extension of the seismic cloud into previously seismically silent zones suggesting that some kind of hydraulic barrier was broken by the big events. The authors currently consider that the microseismic events at this site mainly originate from a slip of asperities in existing fractures. Control and prediction of the big events at this site requires further study.

Introduction

It has been widely known that microseismic events are observed at many geothermal sites (Niitsuma et al., 1988, Parker 1989, Baria et al., 2005). Microseismic events in conventional hydrothermal systems are mainly related to production and injection activities, and less commonly seismic events are associated with build-up operations and with lost circulation while drilling. The microseismic events from hot dry rock, hot fractured rock, and enhanced geothermal systems (HDR/HFR/EGS) reservoirs on the other hand are mainly induced by hydraulic stimulation and the activity, location, magnitude and source mechanism of these microseismic events has been effectively used as one of the few methods for the 3D location and characterization of the reservoir with high resolution.

The typical moment magnitude of microseismic events from a geothermal reservoir is less than 0. It is widely accepted that people can hardly feel them on surface, and only downhole seismic detectors or highly-sensitive surface seismometers can detect them. However, some of the microseismic events have higher magnitude and can be felt on the surface. These large events can be hazardous from an environmental point of view, while at the same time resulting in an improvement of permeability in the reservoir. Clearly a management technology that both prevents large events and improves production is required, especially in the development of HDR/HFR/EGS systems. Previous studies suggest that the magnitude of the microseismic events is dependent on the site, the operation of the reservoir and sometimes on the depth of development. This in turn suggests that the mechanism causing the large events is complex and that the controlling factors require further study (Fehler, 1989). The Environmental Annex of the IEA Geothermal Implementing Agreement includes “better understanding of the factors that affect the intensity and distribution of induced earthquakes in developed geothermal fields”, and research on the large events is currently underway (Bromley, 2005).

In the Australian HDR/HFR project, which is conducted by Geodynamics Co. Ltd. in the Cooper Basin, South Australia, some of the microseismic events had larger magnitude (M3.0 max.) and several events were felt on surface. We have investigated the spatial-temporal distribution and source mechanism of these events to interpret the physics of these large events as described in this paper.

Outline of the Data

The location of the Australian HDR/HFR site in Cooper Basin is shown in Figure 1. Geodynamics Limited drilled the first injection well (Habanero-1) into a granitic basement to a depth of 4,421 m (754 m into granite) in 2003. Several sub-horizontal over-pressured fractures were found in the granitic section of the well. The orientation of these existing fractures is consistent with the maximum tectonic stress being horizontal in the central part of Australia as indicated in the global stress field (Zoback, 1992).

The main stimulation of Habanero-1 took place after several tests to initiate fractures (fracture initiation tests: FIT) and evaluate their hydraulic characteristics (long term flow test: LFT). The total amount of liquid injected was 20,000 m^3 with a highest pumping rate of 48 *l*/s. All the open-hole section was pressurized in the first and main stimulation. A second stimulation was performed through perforated casing above the open-hole section, but this stimulation was dominated by fluid flow back into the main stimulated zone below.

The seismic network at the site consists of one deep (depth: 1,794 m) high temperature (150˚C) instrument and four near surface instruments (depth: 88-114m). The horizontal distance from Habanero-1 to the deep borehole detector was 440m and that for the near-surface stations were in the range of 4880-4990m. The seismic events were detected by the network from the initial stage of the FIT where the pumping rate was around 8 *l*/s. Seismic signals were recorded by the deep detector and in most cases also by the near-surface stations with clear onsets of P and S waves. The authors recorded 32,000 triggers with 11,724 of these located in 3D space and time on site during the stimulations (Asanuma *et. al.,* 2005).

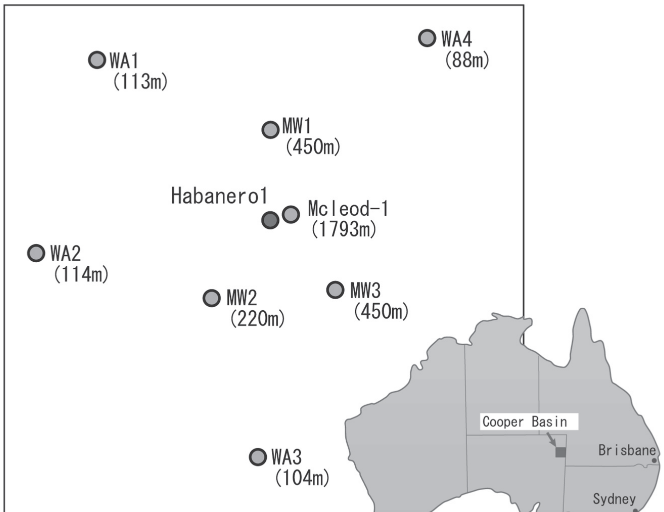

Figure 1. Example of a big event with a magnitude 3.0.

Analysis of the Microseismic Events with Higher Magnitude

Estimation of the Moment Magnitude

During the FIT, LFT and the main injection, we observed several events with higher magnitude. The largest event occurred at 00:03 on 14 Nov., 2003. This event was detected by the Australian national earthquake monitoring network of Geoscience Australia (GA) and had a moment magnitude of M 3.0. Because of the unexpectedly large seismic vibration, the trace is saturated just after the P wave onset and we lost most of the information on the trace after the saturation. This prevented us calculating the seismic moment and the corner frequency directly from the trace for the saturated events. However, for smaller, non-saturated events, we were able to calculate an uncalibrated relative magnitude which we call here the local magnitude. We estimated the moment magnitude of the saturated events and local magnitudes to the moment magnitude by using two reference events. One is the largest event, of moment magnitude M 3.0 estimated by GA with a duration time of 180 [s]. The other reference was an event that had a critical amplitude for saturation with a duration time of 63 [s]. From experience with the same detectors at Japanese HDR sites, where the configuration of seismic source and the detector is similar to the Cooper Basin site, it is known that such critically-saturated events have a moment magnitude of M 1.0, although the attenuation in the Australian site may differ from the Japanese one. We used these results to estimate the moment magnitude of all the events and we plot the frequency distribution of the moment magnitude (Figure 2). Following the Gutenberg-Richter law, the accumulated histogram of event magnitudes plotted on a logarithmic scale should define a linear relationship. However in this case there is an apparent inflection point at around M 1.0, suggesting that the seismic origin or mechanism may be different for events with higher magnitude than M 1.0. We refer to such events as “big-events” and analyzed 30 big-events in the FIT and LFT where rapid and heterogeneous reservoir extension was clearly observed.

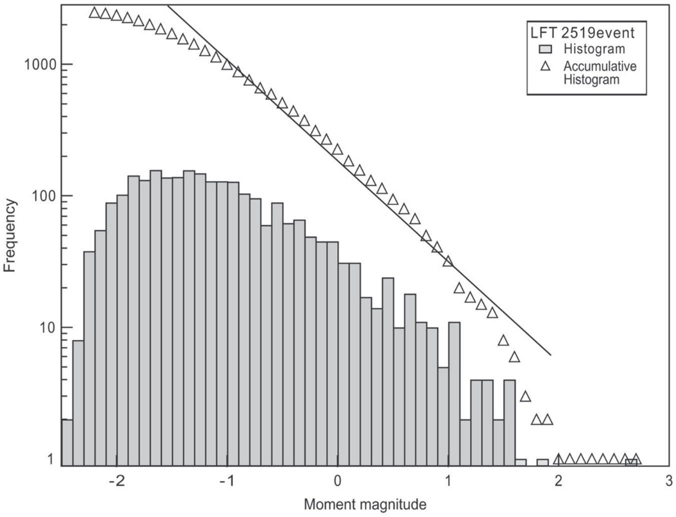

Figure 2. Histogram of the estimated moment magnitude.

Spatial and Temporal Distribution of the Big Events

The locations of the big events plotted in Figure 3 were determined by the joint hypocenter determination (JHD) method using manually picked P wave onsets. A distribution of all the microseismic events in the LFT (1st to 5th day) and LFT (after 5th day) are also plotted in Figure 3 as small dots. The relationship of the origin time and the moment magnitude of all the events are plotted along with the hydraulic record in Figure 4. An example of the change in the well head pressure of Habanero-1 around the origin time of a big event is shown in Figure 5.

We have clustered the microseismic events in the FIT and LFT by their location and the origin time, because the extension of the seismic cloud at the Cooper Basin site was heterogeneous. Two examples of the location of the events before and after the big events, where extension of the seismic cloud was clearly seen after the big event, are shown in Figures-6 and 7. The size of the circle at the location of the microseismic events shows the source radius of the event estimated from the moment magnitude.

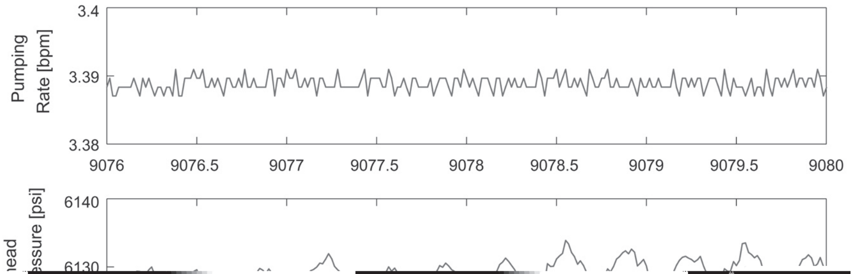

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Figure 5. Change in the pumping rate and the wellhead pressure at the occurrence of a big event.

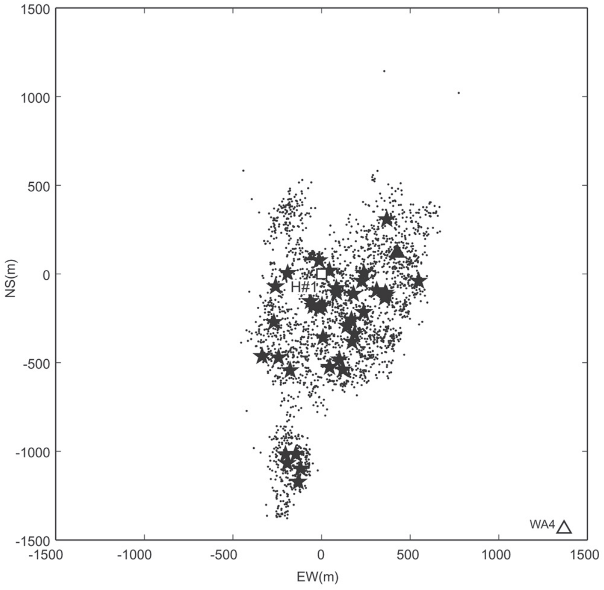

Figure 3. Distribution of the microseismic events in the FIT and LFT. Star: big events (>M1.0), solid circles: smaller events.

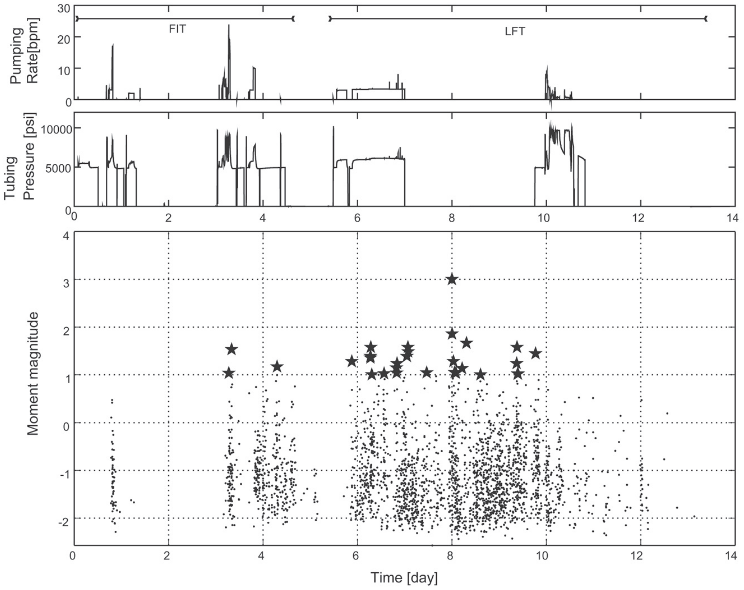

Figure 4. Temporal distribution of the moment magnitude.

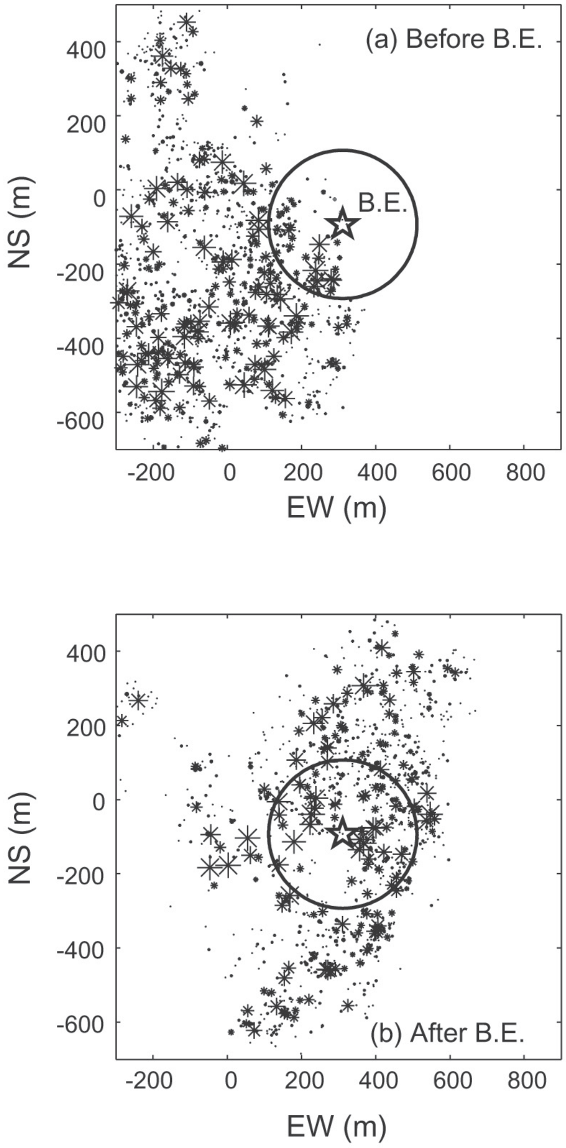

Figure 6. Distribution of the events before (top) and after (bottom) a big event (B.E.).

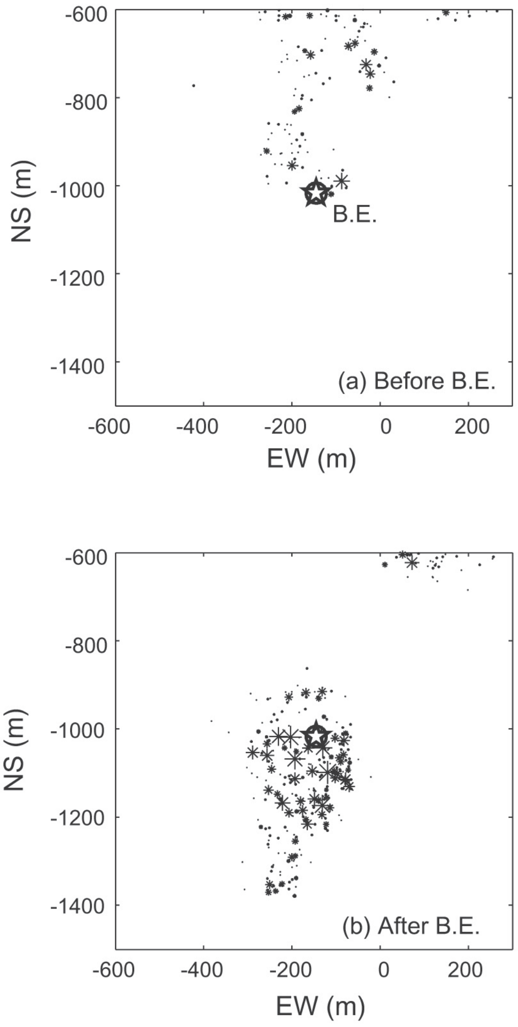

Figure 7. Distribution of the events before (top) and after (bottom) a big event (B.E.).

Interpretation

It has been previously reported by the authors that the seismic signals collected at the Cooper Basin site during the stimulation had the following characteristics (Asanuma *et. al.,* 2005);

(a) The seismic cloud had a thickness around 50m.

(b) Almost all the microseismic events had the same polarity at the onset of the P wave.

(c) The percentage of multiplets, which is a group of events with high mutual similarity, was 96%. This was much higher than in other data sets collected worldwide in HDR/HWR/EGS projects.

(d) Assuming that the orientation of the seismic cloud is consistent with the fracture orientation, the fracture is in a critical or over-critical stress state of shear slip.

As seen in the figures in this paper, the following characteristics of the big events are obtained throughout this study;

(1) The histogram of the moment magnitude apparently shows a different trend for events with magnitudes exceeding 1.0, although the number of samples is clearly not satisfactory from a statistical point of view.

(2) The locations of the big events are widely distributed in the seismic cloud. There is no clear seismic structure of the big events that could correlate to existing geological structure.

(3) The origin time of the big events are also widely distributed in the FIT and LFT and little correlation was observed between the seismic magnitude and wellhead pressure. In fact, 11 of 30 big events occurred after shut-in.

(4) There was no clear breakdown in the wellhead pressure of Habanero-1 at the occurrence of a big event.

(5) The source radius of the big events had a variation of 10-150 m, which is in the same order of typical joint size in granite.

(6) In some cases, the seismic cloud subsequently extended beyond the big events which occurred at the edge of the seismic cloud.

(7) In most cases, a number of seismic events with small magnitude occurred after the big events within the source radius of the big events.

(8) There was no difference in the polarity at the P wave onset between big events and the rest of the microseismic data-set.

In view of the above, we currently conclude that the physical processes responsible for the big events at the Cooper Basin site are similar to that of the smaller events, namely;

- The induced slip of the existing sub-horizontal fracture at this site can be modeled by slip on a plane containing heterogeneously distributed asperities. It has been revealed that the size of asperity is correlated to the moment magnitude of the earthquake in the case of repeating earthquakes at a plate boundary (Nadeau R.M. and Johnson, 1998). In the same manner, the magnitude of the events may be correlated to the size of the asperity, and the “after-shock” events within the source radius of the big events may be correlated to the non-geometrical shape of the asperity or remaining asperities present after the big events.
- It is reasonable to assume that prior to the big events water can not easily flow beyond the asperity, and that the subsequent extension of the seismic cloud beyond the big events shows improvement of the permeability.
- The fact that big events occurred after shut-in supports the idea that the initial stress state of the fractures is critical/over critical.
- We could not see any clear change in the well head pressure associated with the big events. This may indicate that the capacity of the reservoir at this site is very large compared to the improvement of permeability caused by a big event.

From the current data set at the Cooper Basin site, we could not find any obvious precursor of the big events. For example, there was no seismically silent zone before the big events, and correlation of the seismic magnitude to the flow/pressure was not found. There was also no unexpected increase of the wellhead pressure before the big events. In this case of the Cooper Basin site, we may say that the factors that control seismic magnitude do not have a simple explanation.

Conclusion

In this paper, we described the analysis of the larger magnitude events collected during a hydraulic stimulation of a HFR reservoir at Cooper Basin, Australia. Some of the features of these big events including the spatial and temporal distribution of the big/small events, correlation to the hydraulic history, and source mechanism have been described. Although further study is required, we currently understand that the big events at the Cooper Basin had the same origin as the more common smaller events. Because the existing fractures at this site are apparently in a critical or over-critical stress state for slip, the prediction/control of big events is a complex issue.

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