PROCEEDINGS, Thirty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30-February 1, 2006
SGP-TR-179

SPATIAL AND TEMPORAL DISTRBUTION OF LARGER SEISMIC EVENTS AT EUROPEAN AND AUSTRALIAN HDR SITES

H. Asanuma*, H. Nozaki*, T. Uhara*, H. Niitsuma*, R. Baria**, and D. Wyborn***

*: Graduate School of Environmental Studies, Tohoku University
6-6-20 Aramaki Aza Aoba, Aoba-ku
Sendai, 980-8579, Japan
**: MIL-TECH, UK
***: Geodynamics, Australia
e-mail: asanuma@ni2.kankyo.tohoku.ac.jp

ABSTRACT

The authors analyzed the spatial and temporal distribution of the microseismic events with larger magnitude (big events) observed during hydraulic stimulations at the Australian HFR site in the Cooper Basin and European HDR site in Soultz, France. A comparison between the origin time of the big events and the hydraulic record showed that many of the big events occurred after the shut-in at both the sites. We have also found that some of the big events at the Australian site 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. Although further investigation is needed, the authors currently consider that the microseismic events at Australian site mainly originate from a slip of asperities in existing fractures although some of the characteristics of the big events are different from natural earthquakes at the plate boundary.

INTRODUCTION

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

Typically, the moment magnitude of microseismic events from a geothermal reservoir is less than 0, and most of them are detectable only by downhole sensors with high sensitivity. However, it has been known that 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. It has been also noted that the large events may correlated to unexpected reservoir extension which brings shorter lifetime of the reservoir or reduction of heat capacity. Clearly a management technology that both prevents large events and improves production is required, especially in the development of HDR/HFR/EGS systems. Previous reports from the worldwide HDR/HFR/EGS projects show that the magnitude of the microseismic events is dependent on the site, the operation to the reservoir and sometimes on the depth of development. This 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. In the European HDR project at Soultz France, several events are felt at villages around the site, and people are getting nervous for the further stimulation/pumping because of possible felt events. 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 DATA

A plan view showing location of the major wells in Soultz site is shown in Figure 1. The 5,005 m deep well GPK-3 was drilled in 2002 to intersect the southern edge of the seismic cloud induced in 2000. The openhole section of GPK-3 starts from MD of 4,437m. The whole section of GPK 2 and 3 was stimulated by injection from the well head. The induced microseisimicity was detected by a seismic network consisting of 4 component accelerometers in wells 4550, 4601 and OPS 4. Two three-component geophones were also deployed in the wells EPS 1 and GPK 1.

The data from each seismic station was digitized by a system of the Japanese team. Around 86,985 events were triggered in the AD system during the stimulation and shut-in, and approximately 12,000 of them were picked/located on-site.

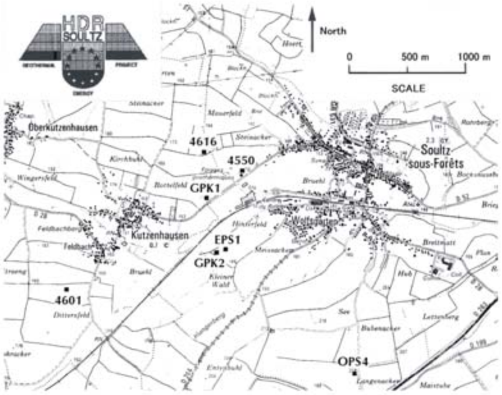

Figure 1. Plan view of the Soultz HDR site.

The location of the Australian HDR/HFR site in Cooper Basin is shown in Figure 2. 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 m3 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 this 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).

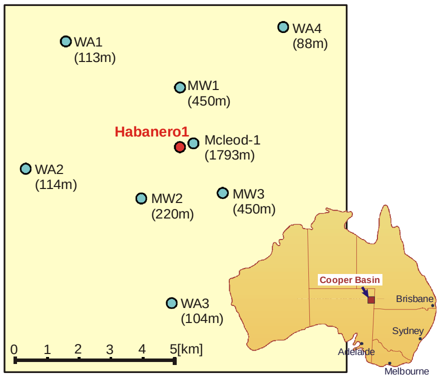

Figure 2. Plan view of the Australian HFR site in Cooper Basin.

SPATIAL AND TEMPORAL DISTRIBUTION OF BIG EVENTS

European HDR site at Soultz

Because no calibration data to calculate the moment magnitude was available for the data collected at Soultz, we used energy of the trace (integration of squared amplitude) as a measure of the magnitude. A three dimensional distribution of the microseismic events collected in 2000 and 2003 is shown in Figure 3 where bigger events are plotted by red stars. Migration of the hypocenters of the events is plotted with a hydraulic record in Figure 4.

The following characteristics of the big events at Soultz are found from this study.

(s1) Many of the big events occurred after shut-in, and their hypocenter are within the existing seismic cloud.

(s2) At the occurrence of the big events, no clear correlation to the hydraulic record (breakdown at the big event or increase of the wellhead pressure before the big event) was seen.

(s3) Big events are widely distributed within the seismic cloud and seismic structure of the big events was not observed.

(s4) Extension of the seismic cloud around a big event was not found.

(s5) Roughly estimated source radius of the bigger events (in the order of several hundred meters) is much larger than the size of joins at this site estimated by seismic analysis (Evans et al., 2005).

(s6) "Silent zone" and aftershocks around the hypocenter of a big event were not found.

(s7) There is no evidence to show that the big events have different source mechanism to the smaller events.

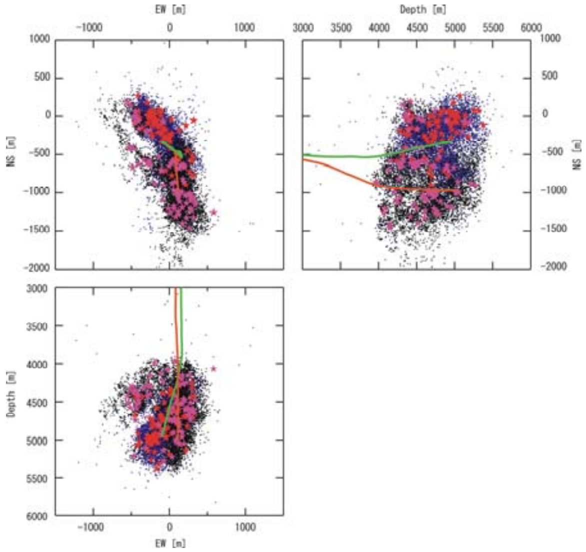

Figure 3. Three dimensional location of hypocenters of microseismic events collected at Soultz in 2000 and 2003.

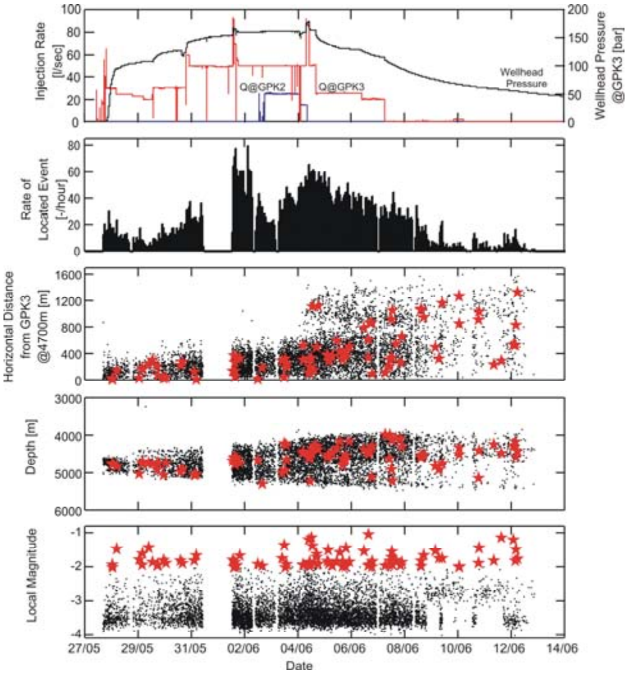

Figure 4. Migration of hypocenters of the events and hydraulic record at a stimulation at Soultz in 2003.

Australian HFR site at Cooper Basin

We have estimated the moment magnitude of the events using the duration time of events with a reference event with M3.0 (by Geoscience Australia). A horizontal distribution of all the microseismic events in the LFT (1st to 5th day) and LFT (after 5th day) are plotted in Figure 5 where the big events are plotted by red stars. The relationship of the origin time and the moment magnitude of all the events are plotted along with the hydraulic record in Figure 6.

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 Figure 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. The following characteristics of the big events at Cooper Basin are seen from this study.

(c1) The histogram of the moment magnitude 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.

(c2) The locations of the big events are widely distributed in the seismic cloud. There is no clear seismic structure of the big events.

(c3) 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.

(c4) There was no clear breakdown in the wellhead pressure of the injection well at the occurrence of a big event.

(c5) 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 at this site.

(c6) In some cases, the seismic cloud subsequently extended beyond the big events which occurred at the edge of the seismic cloud.

(c7) In most cases, a number of seismic events with small magnitude occurred after the big events within the source radius of the big events.

(c8) There was no difference in the polarity at the P wave onset between big events and the rest of the microseismic dataset at all the seismic stations, suggesting that almost all the events have the same source mechanism. One of the possible source mechanisms is a slip of a reverse fault which has the same orientation to the existing fracture intersecting the injection well.

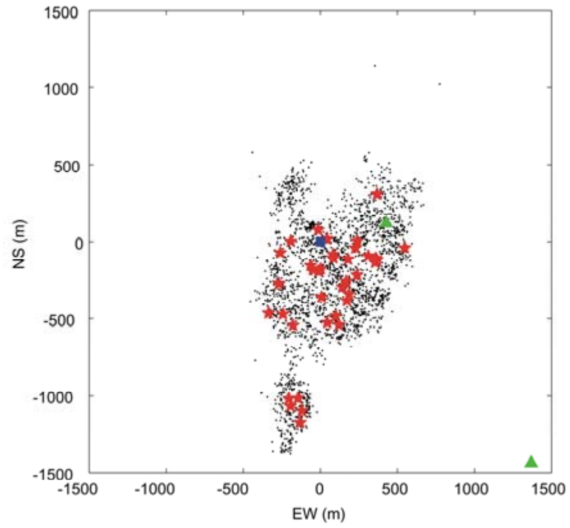

Figure 5. Horizontal distribution of hypocenters of microseismic events collected at Cooper Basin site in 2003.

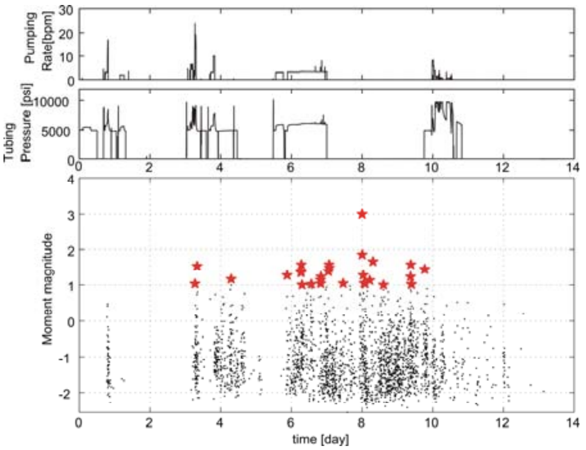

Figure 6. Distribution of the moment magnitude and a hydraulic record at a stimulation at Cooper Basin site in 2003.

DISCUSSION

It is very likely that the origin of the big events at Soultz and Cooper Basin is different. For the Soultz case, we have not derived a best model to interpret the big events, because no significant difference of the big events to the smaller events has been found from our study. However, the Australian big events can be interpreted by a "asperity model". This concept has been used by the global seismologists and 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.

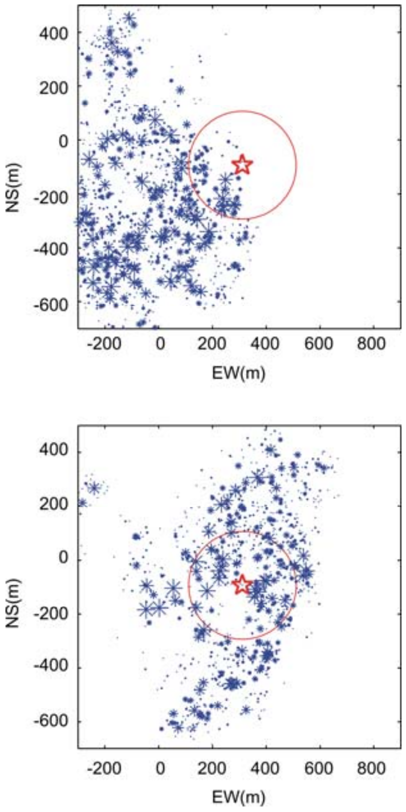

Figure 7. Distribution of the microseismic events around a big event at Cooper Basin.

CONCLUSIONS

The authors analyzed induced microseismic events while simulation at European and Australian HDR/HFR sites. The temporal spatial distribution of the big events had different characteristics for European and Australian data. Because some of the characteristics of the big events from the Australian site had similarity to that of natural earthquake at a plate boundary, the big events at the Australian site may be interpreted by "asperity model". Further study is needed for the interpretation of the big events from European site at Soultz because significant difference of the big events has not been found out.

ACKNOWLEDGMENTS

The work presented here was done as a part of the MTC Project. We would also like to thank EEIG Heat Mining for its cooperation in data acquisition and for offering hydraulical/geological data from the European HDR site at Soultz which is supported mainly by the European Community, BMWI

(Germany) and ADEME (France). The authors wish to acknowledge other members of the MTC/MURPHY Project, Dr J Baumgaertner (BESTEC) who made the cooperation possible and Dr. Ben Dyer, Semore Seismic, for their discussion, advice and encouragement. The authors also wish to acknowledge Geodynamics especially for Dr. B. de Graaf for their provision of the hydraulic data during stimulation and the permission to publish this result.

REFERENCES

Asanuma, H., Soma, N., Kaieda, H., Kumano, Y., Izumi, T., Tezuka, K., Niitsuma, H., and Wyborn, D., 2005, “Microseismic monitoring of hydraulic stimulation at the Australian HDR project in Cooper Basin,” *Proc. WGC 2005* (CDROM)

Baria, R., Michelet, S., Baumgaertner, J., Dyer, B., Gerard, A., Hettkamp, T., Teza, D., Soma, N., Asanuma, H., Garnish, J., 2005, “Creation and Mapping of 5000 m deep HDR/HFR Reservoir to Produce Electricity,” *Proc. WGC 2005* (CDROM)

Bromley, C., 2005, “Advances in environmental management of geothermal developments,” *Proc. WGC 2005* (CDROM)

Evans, K., Moriya, H., Niitsuma, H., Jones, R. H., Phillips, W. S., Genter, A., Sausse, J., Baria, R., 2005, “Microseismicity and permeability enhancement of hydro-geologic structures during massive fluid injection into granite at 3km depth at the Soultz HDR site,” *JGI*, 160, 388-412.

Fehler, M., 1989, “Stress control of seismicity patterns observed during hydraulic fracturing experiments at the Fenton Hill Hot Dry Rock geothermal energy site, New Mexico,” *Int. J. Rock Mech. Mining Sciences and Geomech Abstr.* 26, 211-219.

Nadeau R.M., Johnson L.R., 1998, “Seismological studies at Parkfield VI: moment release rates and estimates of source parameters for small repeating earthquakes,” *BSSA*, 88, 3, 790-814.

Niitsuma, H., Chubachi, N., Takanohashi, M., and Doi, N., 1988, “AE evaluation of geothermal reservoir created by natural and artificial stimulations in Kakkonda field, Japan,” *Acoustic Emission*, 283-290.

Parker P., 1989, “Hot dry rock geothermal energy, Phase 2B - final report of the Camborne School of Mines Project,” *Pergamon Press.*

Zoback, M.L., 1992, First- and second-order patterns of stress in the lithosphere: The World Stress Map Project, *JGR*, 97, 11703 - 11728.