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Microseismic Monitoring of Hydraulic Stimulation at the Australian HDR Project in Cooper Basin

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ABSTRACT

A team of Japanese researchers, who have a considerable experience in the microseismic monitoring of hydraulic stimulation/circulation of HDR/HWR/HFR reservoirs, conducted a microseismic monitoring at the Cooper Basin HDR site, Australia in the last quarter of 2003. A network of seismic instruments with 4 near surface instruments, three downhole instruments and one deep downhole instruments was set up by Geodynamics and CRIEPI. The seismic network detected approximately 32,000 triggers during injection of 20,000 m3 of fresh water into granitic basement over 3 weeks. The authors located the events on a semi-realtime basis using automatic software for picking, and the locations were fed back to the pumping side for determination of further injection plan. The locations of seismic events showed sub-horizontal extension of the reservoir to 1,800 m away from the injection well at a depth of around 4,500 m. The heterogeneous source migration suggests that the fractures in the stimulated zone were close to a critically stressed state.

1. INTRODUCTION

The importance of "green energy" which is environmentally friendly to the earth has been widely understood and accepted in developed countries, and projects for the development of geothermal systems have been started/re-stared in many countries. It has been revealed by data observation from thousands of existing wells that some part of Australia has large volumes of high heat production granites in the depth range of 3 to 5km below the surface (http://hotrock.anu.edu.au/resource.htm). The Cooper Basin, South Australia, has one of the most promising geothermal resources, the temperature in the granitic basement is expected to exceed 270˚C at a depth of around 5km. It is also reported that the horizontal stress is dominant over the vertical in central Australia including in the Cooper Basin (Swenson et al., 2000). These scientific investigations suggest that a horizontal HDR reservoir with a large heat production capacity, which enables generation of electricity with comparable costs to coal, can be realized in the Cooper Basin (http://www.geodynamics.com.au).

A public company Geodynamics Limited started development of a HDR system in early 2003 supported by the Australian national and local governments. In 2003 the company drilled the first injection borehole to a depth of 4421m penetrating into granite approximately 750 m. They confirmed that the bottomhole temperature is around 250 ˚C in this borehole and started the preparation of stimulation to create HDR reservoir.

The Japanese researchers, who have a long experience in the microseismic monitoring of HDR reservoirs, organized a team for the data collection and on-site mapping at the Cooper Basin site. The aim of the contribution of the Japanese team is to cooperate with the Australian side in understanding the reservoir using knowledge accumulated by the Japanese side and to improve mapping techniques using the collected data. The Japanese team started system design, coding software and necessary maintenance of the facilities under collaboration with Geodynamics in 2002, and the subsequent seismic monitoring at the Cooper Basin site is described in this paper.

2. PROJECT DESCRIPTION

A plan view of the Cooper Basin site is shown in Figure-1 as well as its location in the country. 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. The bottom hole temperature was measured by logging at approximately 250˚C, showing considerably good potential for power generation from an HDR reservoir. Several sub horizontal over pressured fractures were found in the granitic section of the well. Geodynamics have changed their concept because of these fractures, and now refer to the project as hot fractured rock or HFR. Some of the existing fractures were plugged to stop lost circulation and only one fracture at a depth of 4,254m in the Habanero-1 remained as the initial dominant entry point into the formation. Because the maximum tectonic stress is horizontal in the central part of Australia, the orientation of the existing fractures are consistent with the global stress field.

The seismic network at the site consists of one deep (depth: 1,794 m) high temperature (150˚C) instruments, three downhole instruments (depth: 200 400 m), and four near surface instruments (depth: 100m). The high temperature downhole seismic detector which has been developed and used in Hijiori HDR Project was deployed as a deep, high-temperature station. Geodynamics and CRIEPI prepared the seismic network with support from JAPEX. The offset to the furthest station was approximately 5 km. Because no data from shooting is available in this case, horizontal (2D) velocity structure was mainly determined by previously collected data from sonic logs and VSP. The Japanese team set up two A/D systems in parallel. Mapping of induced seismic events was carried out at the site on a semi-realtime basis using the computer system and software from Tohoku University and AIST.

The main stimulation 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.

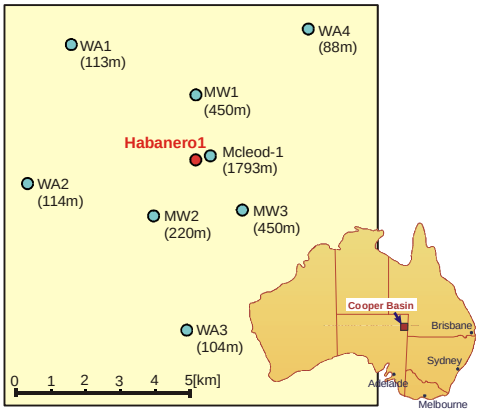

Figure 1: The Australian HDR site in Cooper Basin.

3. SEISMIC ACTIVITY

A typical seismic trace collected during the stimulation is shown in Figure-2. The seismic events were detected by the network from the initial stage of the FIT where the pumping rate is around 8 l/s. Most of the seismic signals were detected by the near-surface stations with clear onsets of P and S waves. We recorded 32,000 triggers and 11,724 of these were located in 3D space and time on site until the end of the stimulations (on 23 December 2003). Some of the seismic events had large energy and people on the site could feel them. Roughly estimated magnitude of the largest event was M3.7.

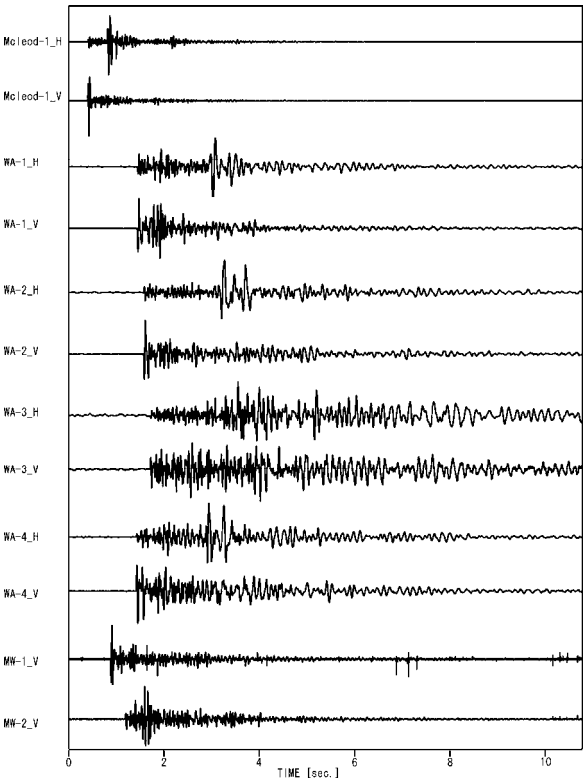

Figure 2: Typical microseismic signal detected during the stimulation.

4. SEISMIC LOCATION

In this study, we used a 2D (horizontal) velocity model for overburden which is determined by the data from VSP and logging, and a homogeneous velocity in granite. Because no data was available to precisely estimate the velocity of P wave in the granite, we decided to optimize the velocity in granite by fitting the initial events to the existing fracture at 4,254m in Habanero-1 by changing the velocity in the granite. There was no data on velocity for S wave both in basement and overburden, the picks for S wave was not used for on-site mapping. The onsets were detected by manual observations and software for automatic picking (Soma et al., 2003) depending on the event rate. The highest average event rate was 1,000 per day.

The 3D distribution of the seismic locations for all the tests and stimulations is shown in Figure-3. The locations were estimated by a single event determination method. It is clearly seen that a sub horizontal seismic cloud with thickness of around 500m and horizontal extension of 1,800m from Habanero-1 was created. The typical residual (error) in the location of the events was 13m, where vertical error is dominant because of shallow network configurations. Location of events with larger energy is shown in Figure-4. The location of the large events has a trend where they are distributed near the injection well and on the south and NW edge of the seismic cloud.

The horizontal source migration (change in horizontal distance from Habanero-1) is shown in Figure-5 along with the pumping rate, wellhead pressure and total amount of injected fluid. It is seen that (a) the number of located events is correlated to the total amount of injected fluid and (b) the seismic cloud grew heterogeneously in the horizontal direction.

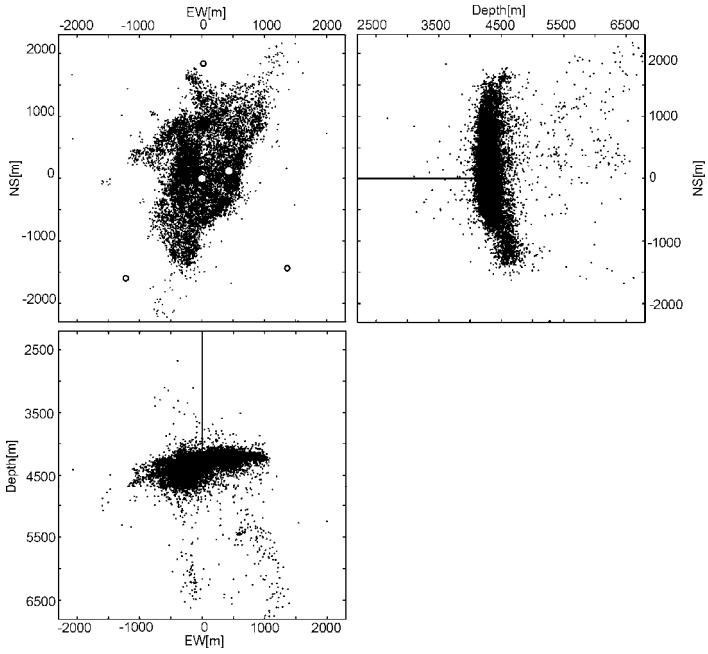

Figure 3: Location of the all the picked events.

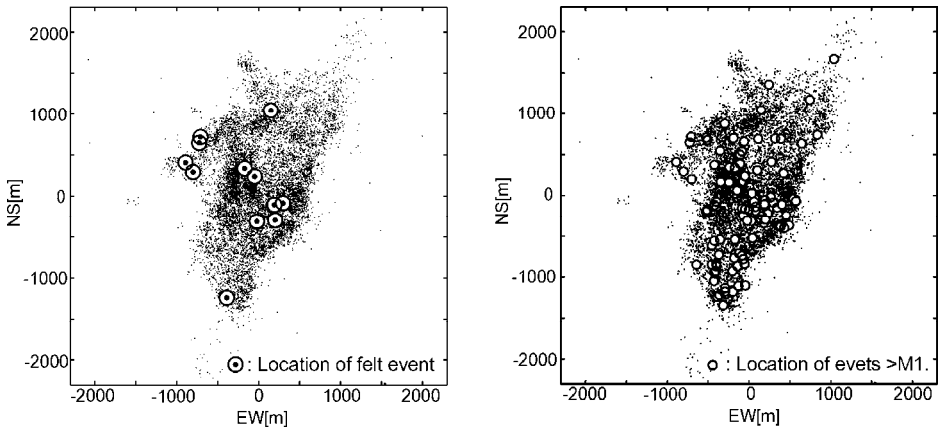

Figure 4: Location of the events with larger energy.

The seismic events were re-located by a collapsing method, which is a statistical optimization of the whole cloud (Jones and Stewart, 1997). The vertical distribution of the seismic location by the collapsing is shown in Figure-6. The thickness of the seismic cloud remains approximately 100m after collapsing, suggesting that the surrounding zone of the existing fracture at 4,254m was seismically active. It is probable that the collapsing method has reduced the locations to a volume more condensed than the true volume.

The seismic locations in the FIT and LFT are compared with that of the main stimulations in Figure-7. It is clearly seen that during the main stimulations, an aseismic zone occurred around injection well, Habanero 1. This aseismic zone is spatially correlated with the locations of events produced in the earlier FIT and LFT.

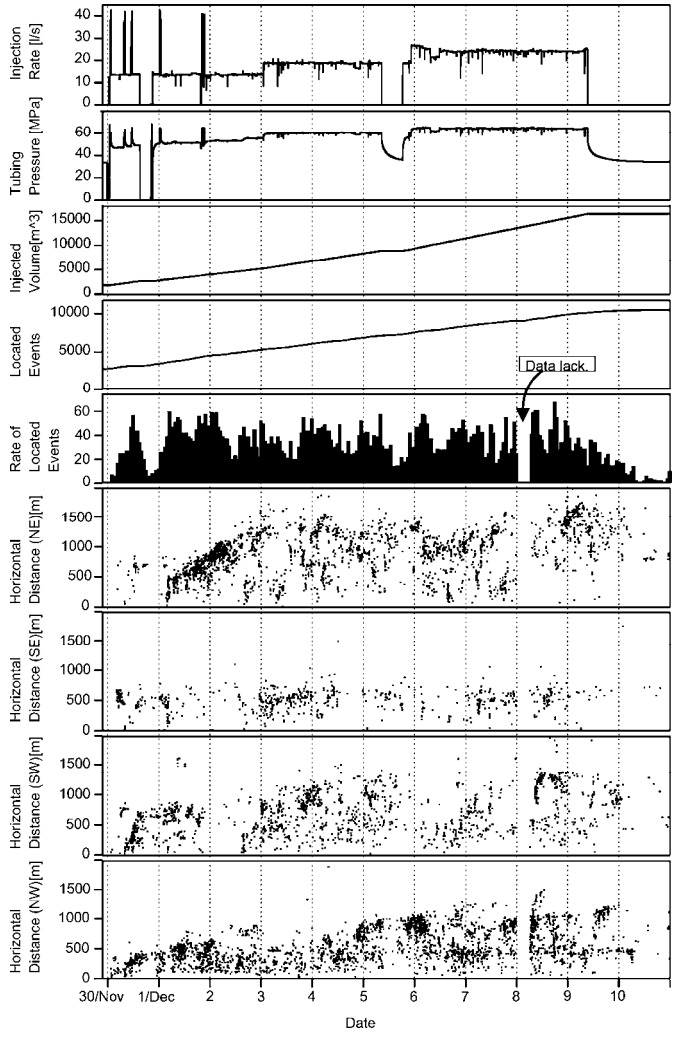

Figure 5: Horizontal source migration.

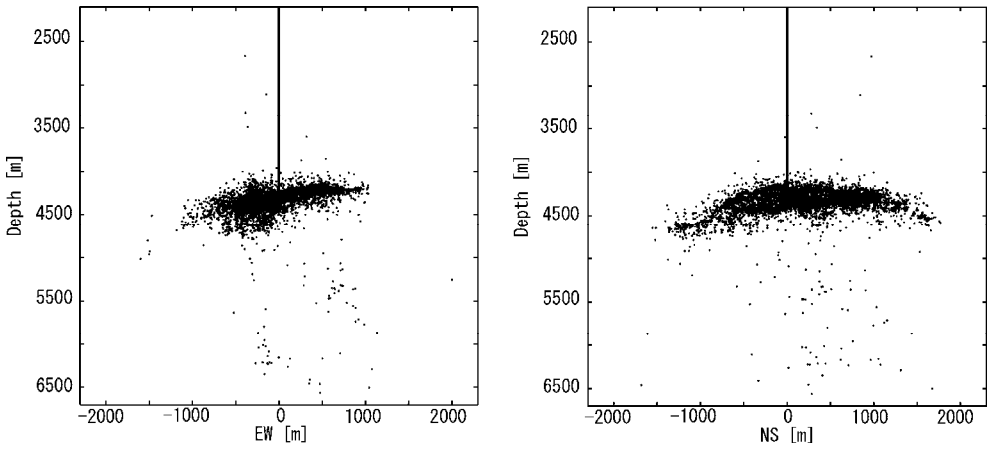

Figure 6: Collapsed location of seismic events.

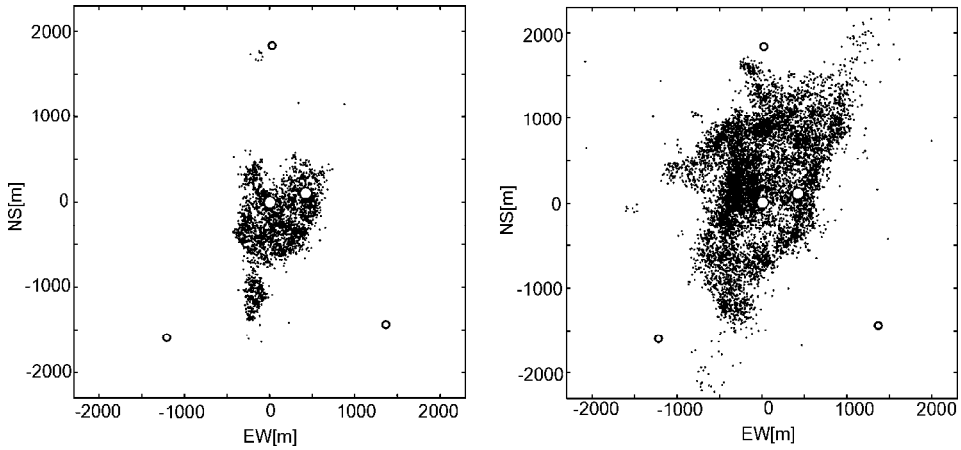

Figure 7: Comparison of seismic location in FIT/LFT and the main stimulations.

5. INTERPRETATION

The seismic activities and locations while the FIT, LFT and the main stimulations suggest the following characteristics of the HDR reservoir at Cooper Basin.

(1) Both the higher seismic activity from the initial stage of the FIT and heterogeneous extension of the seismic cloud suggest that the fractures near the existing fracture are under critical or overcritical stress state. The seismic cloud did not initially spread across all the openhole section as their locations were limited to the depth around the existing fracture at 4,254m. The plugging of the other fractures strongly avoided water penetration inside these other fractures. The seismic cloud after perforation of casing pipe also did not extended horizontally very much because the flow impedance of the existing main fracture may be much lower than the others and the dominant flow path was created to the existing main fracture in near field.

(2) The seismic density (number of events/volume of the seismic cloud) of the Cooper Basin site is 4,800/km3 which is much lower than that at Soultz (11,800/ km3). In general, seismic density is considered to be correlated to the improvement of permeability after stimulation, and, hence, there is a possibility that the flow impedance around the existing fracture has not increased as much as at Soultz. We need results from circulation tests for further interpretation. However, the naturally high overpressures discovered in the main fractures point to existing high permeability and probable natural stimulation of the fractures as these overpressures developed.

(3) The thickness of the seismic cloud is much larger than the error in mapping. The collapsed seismic cloud showed planer structure with thickness of 100-150m. It is reasonable to interpret this observation as though the stimulated rock mass with seismic activity extended 100-150m away from the existing fracture. Considering the stress state and orientation of existing joints in the granite, we can assume that a system of sub-parallel horizontal fractures was stimulated.

(4) The seismic cloud did not extend into the sedimentary basin overburden even if there is some possible variation in the depth of the granitic basement.

(5) The seismically activated zone in the FIT and LFT became aseismic in the main stimulations, especially in the south-east side of Habanero-1. Presumably the FIT and LFT experiments resulted in both increased permeability in the aseismic zone and the release of differential stress within the affected rock volume.

(6) Some of the larger events seem as though they broke some geological “barrier”, showing breakthrough beyond the barrier after the large event. Most of the large events in the stimulations appeared within the existing seismic cloud. Although the detail has not been fully investigated there may be some difference in the reservoir extension in the FIT/LFT and main stimulations.

6. CONCLUSIONS

The Japanese team for microseismic monitoring at the Cooper Basin HDR/HFR project successfully detected and located approximately 12,000 events during the injection of 20,000m3 of liquid. The seismic cloud showed sub-horizontal shape with thickness of 500m and horizontal extension of 3.2km. It is consistent with the initial design based on existing geological information.

The sub-horizontal distribution of the seismic cloud/reservoir can be effectively used to develop a HFR system with lower risk in targeting of the following wells. Also of benefit is the existence of the overpressured fractures containing 250˚C water. This overpressured state should bring better production rates with larger amounts of energy extracted from the granite although further investigation is required through pumping/circulation tests after drilling of a second borehole.

ACKNOWLEDGMENTS

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