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Comparison of Characteristics of Micro-Earthquakes Observed During Hydraulic Stimulation Operations in Ogachi, Hijiori and Cooper Basin HDR Projects

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ABSTRACT

In Hot Dry Rock (HDR) or Hot Fractured Rock (HFR) geothermal energy development, micro-earthquake events were observed to evaluate the location and size of fracture distribution of artificially created reservoirs during hydraulic stimulation operations. Many micro-earthquake events were observed during hydraulic stimulation operations from depths of around 1,000 m to 4,200 m at three different sites: Ogachi and Hijiori in Japan and Cooper Basin in Australia. Comparison of the water injection operations to observed micro-earthquake hypocenter locations and the rate of events led to the observation of some differences and similarities. Seismic activities at the beginning of the water injection phase were low in Ogachi and Hijiori until the injected water volume reached that which was injected in a previous test, but high activity was observed from the onset of injection at the Cooper Basin site. This difference is thought to be caused by the injected water recovery from the fractures.

It was seen in Cooper Basin that the previously activated area was quiet in the successive stimulation operations. This is thought to be caused by stress release from previous water injection.

The water volume injected and the seismically activated area showed linear correlation. However, the inclination of the relationship is different and depends on the site. The seismically activated region at Cooper Basin extended much further than other sites. These differences are thought to be strongly dependent on regional natural joint systems.

1. INTRODUCTION

After the Hot Dry Rock (HDR) geothermal energy development concept was originated by researchers of LANL in the 1970s, many field experiments were conducted around the world. In HDR systems, geothermal reservoirs are artificially created by applying hydraulic stimulation operations, in which large amounts of water are injected into a wellbore at high pressure. Water flowed into joints, which were stimulated by the many elastic (seismic) waves (micro-earthquakes) emitted after the water was injected. These seismic events were used to evaluate the location and size of the reservoirs using a monitoring network set around the injection well.

In this research, the characteristics of micro-earthquakes observed during hydraulic stimulation operations were examined at three different sites having different geological settings and depths. One was the Ogachi project operated by the Central Research Institute of the Electric Power Industry (CRIEPI) from 1989 to 2002 in Japan (Kaieda, et al., 2005). The second was the Hijiori project operated by the New Energy and Industrial Technology Development Organization (NEDO) from 1988 to 2003 in Japan. The third was the Cooper Basin project operated by Geodynamics limited from 2002 to the present in Australia (Wyborn et al., 2005). At these sites, very similar micro-earthquake observation systems were used with seismometers installed as a shallow (near surface) network and a deep-hole network.

2. HYDRAULIC STIMULATION OPERATION

The hydraulic stimulation operations to create HDR reservoirs in the three HDR sites are as described below.

2.1 Ogachi site

The Ogachi site is located in the caldera of northern Japan. The geology of the Ogachi site consists of Cretaceous granodiorite covered with Tertialy lapilli tuff to a depth of 300 m from the surface. A number of pre-existing or natural joints were developed in the granodiorite (the basement rock of the site and also the reservoir rock for hydraulic stimulation) with an average spacing of about 8 cm and a predominant direction in the north-north-east, as observed from geological investigations of oriented cores with a comparably low natural permeability. An injection well called OGC-1 was completed with casings to a depth of 990 m, and the interval of 990 to 1,000 m (bottom) with a diameter of 76 mm was left uncased (open-hole).

For the HDR reservoir creation, water was injected into rock from the open-hole interval between 990 and 1,000 m of OGC-1 in 1991. Hydraulic stimulation operations were conducted as fracture initiation tests by injecting a few tons of water. After the fracture initiation tests, a main stimulation was performed. The history of flow rate, well-head pressure, and the number of micro-earthquake events observed in the main stimulation are shown in Figure 1. A total of 10,140 tons of water was injected for 7 days with a maximum injection pressure of 20 MPa and an average flow rate of 40 tons/hour (Kaieda et al., 2005). The purpose of this stimulation was to show that large reservoirs can be created even at shallow depths by hydraulic stimulation operations.

2.2 Hijiori site

The Hijiori site is located on the southern edge of the Hijiori caldera in northern Japan, which is 10,000 years old and has a diameter of 2 km. The predominant fracture orientation in the area is East-West, with a high dip angle to the north (Tenma et. al., 2008). An injection well called HDR-1 was drilled to a depth of 2,205 m. HDR-1 was cased from the surface to a depth of 2,151 m, the hole was left uncased from this depth to the bottom with a diameter of 8 1/2 inches. The temperature at a 2,300 m depth was measured to be 270°C.

After some fracture initiation tests with a few tons of water injection, a main stimulation operation was conducted. The main hydraulic stimulation was carried out in HDR-1 with a total of 2,115 tons of water being injected for 12 hours at three stages of flow rate: 1, 2, and 4 tons/min (Sasaki and Kaieda, 2000). The history of the injection flow rate and well-head pressure is shown in Figure 2. In this stimulation, the intent was not to create large fractures, because there were already many natural open joints in the reservoir rock. If larger fractures are created, water recovery would be low during successive water circulation tests. Therefore, a large flow rate was applied in this stimulation on the short term to stimulate the area just around the HDR-1 well.

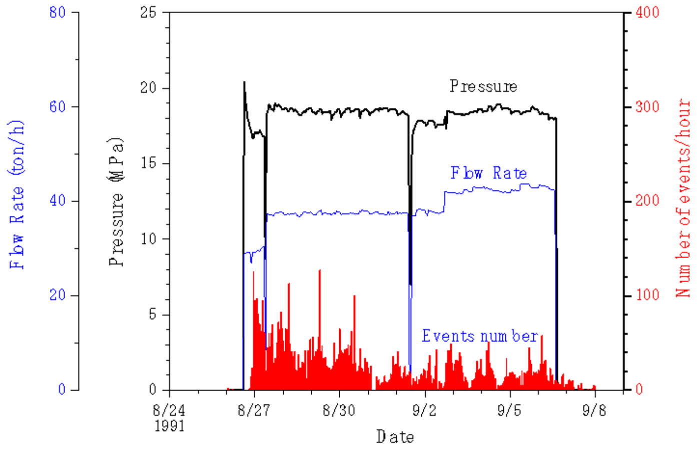

Figure 1: Water injection flow rate, well-head pressure and observed event rate during hydraulic stimulation at Ogachi in 1991.

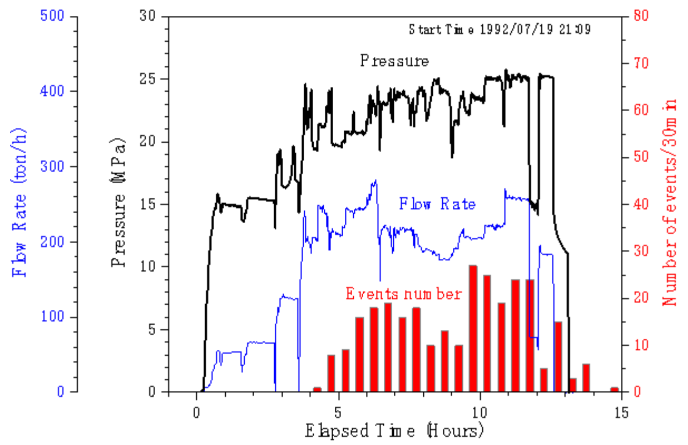

Figure 2: Water injection flow rate, well-head pressure and observed events rate during the 1992 hydraulic stimulation at Hijiori.

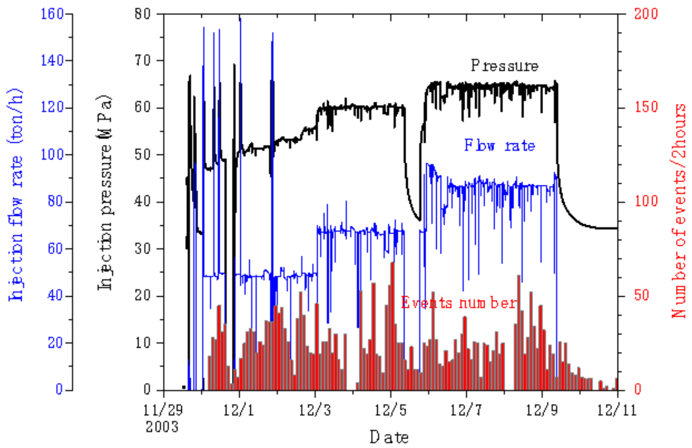

Figure 3: Water injection flow rate, well-head pressure and observed event rate during the 2003 hydraulic stimulation at Cooper Basin.

2.3 Cooper Basin site

The Cooper Basin site is located in the northeast of South Australia. The site is characterized by a granite basement overlain by 3.6 km of sedimentary cover. The granite is intersected by many dykes and veins of white aplite or alaskite. Local stress conditions indicate an overthrust stress regime. An injection well called Habanero 1 was drilled to a depth of 4,421 m, cased from the surface to a depth of 4,139 m, and left uncased below 4,139 m with a diameter of 6 inches. The bottom-hole temperature is expected to exceed 250°C (Wyborn et. al., 2005).

Water was injected into the open-hole interval of Habanero 1 to create a Hot Fractured Rock (HFR) reservoir, but below a depth of 4,254 m, the bottom was filled with salt. After a total of 1,600 tons of water was injected for fracture initiation, the main stimulation was commenced on 30 November, 2003. A flow rate of 48 tons/hour was pumped for the first two days. It was then increased in steps to 67 tons/hour and 86 tons/hour in 7 day intervals until a cumulative volume of 16,350 ton had been injected by 9 December, 2003 (Wyborn et al., 2005). The history of the water injection flow rate and well-head pressure during the main stimulation period is shown Figure 3. The purpose of this stimulation was to create a large reservoir for the extraction of a large amount of heat for many years. Therefore, large amounts of water were injected at high injection pressure for the long term.

The concepts of hydraulic stimulation operations at these three different sites, including depths and temperatures, are summarized in Figure 4.

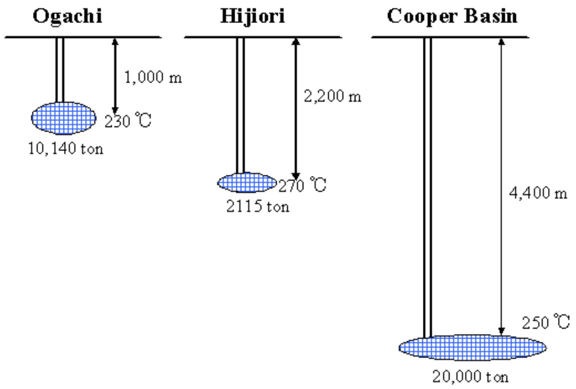

Figure 4: Concept of the hydraulic stimulation operations at three different sites, Ogachi, Hijiori and Cooper Basin.

3. MICRO-EARTHQUAKE OBSERVATION

Very similar micro-earthquake observation systems were deployed at the three different sites. Some geophones were set in shallow (10s m to 150 m) boreholes and a few geophones were set in deep (1000 m to nearly 2,000 m) boreholes. Analog signals from geophones were transmitted through six-conductor cables from the stations to the measurement house, band-pass filtered, and digitized at a sampling rate of 1 kHz or 2 kHz.

The seismic magnitudes (Ml) of observed micro-earthquakes were determined with waveform amplitude (Av) in cm/s, distance from the hypocenter to the sensor (r) in km. These parameters were used in the formula modified from Watanabe (1971) with a comparison to natural earthquakes observed near the sites, as shown below.

$$Ml = \frac{(\log Av + 1.731 \log r)}{0.85 + 2.50} \quad (1)$$

$$Ml = \frac{(\log Av + 1.731 \log r)}{0.85 + 2.94} \quad (2)$$

The magnitudes of micro-earthquakes observed at Ogachi and Hijiori were determined using Equation (1), but that at Cooper Basin was calculated using Equation (2). For the magnitude of larger events, Equations (1) and (2) could not be applied because of amplitude saturation in the waveform. These magnitudes were determined by local seismic networks operated by the Japanese (Japan Meteorological Agency) and Australian (Geoscience Australia) governments.

3.1 Ogachi site

Micro-earthquakes were monitored with a 10-station network of three-component geophones (natural frequency of 5 Hz, sensitivity of 1.6 V/cm/s) installed in 30 to 50 m deep boreholes (Kaieda et al., 2005) and by a three-component geophone (overall sensitivity of 316 V/(cm/s)^2) set at a depth of 380 m in a 946 m deep observation well (Nagano et. al., 1994). Signals detected by these geophones were transferred to a measurement house by six-conductor cables, band-pass filtered between 10 Hz (or 30 Hz) and 1 kHz, and digitized by 2 kHz sampling.

According to the seismic refraction survey and detonation shot tests, the P-wave velocity structure was determined as a three-layer model: 2.6 km/sec from the surface to 224 m depth, 3.7 km/sec from 224 m to 465 m, and 5.0 km/sec below 465 m. An S-wave velocity model was constructed by assuming the Poisson's ratio to be 0.25. Using these velocity models, the locations of observed micro-earthquake events were determined. Absolute location was estimated within about 10 m in horizontal and about 20 m in vertical relative to the detonation shot points around a 1,000 m depth (Kaieda et. al., 2000).

3.2 Hijiori site

A seismic network consisting of 10 stations deployed in a circle with a radius of 1.5 to 3 km was constructed. At these stations, three-component geophones (natural frequency of 5 Hz) were installed at depths of 50 to 150 m in boreholes. At one station, a three-component geophone was set at a depth of around 2,000 m.

According to the seismic logging results of HDR-1 and detonation shot tests, the P-wave velocity structure was determined as an eight-layer model: 2.1 km/sec from the surface to 110 m depth, 2.5 km/sec from 110 m to 250 m, 3.1 km/sec from 250 m to 450 m, 3.6 km/sec from 450 m to 650 m, 4.0 km/sec from 650 m to 850 m, 4.7 km/sec from 850 m to 1,460 m, 5.2 km/sec from 1,460 m to 2,000 m, and 5.4 km/sec below 2,000 m. S-wave velocities of these layers were calculated assuming a Poisson's ratio of 0.25. Using this velocity model, locations of micro-earthquake events were determined.

3.3 Cooper Basin site

The microseismic network consisted of 8 wells: four 100 m deep with each set approximately 5 km from Habanero 1 (WA-1 – WA-4), three 850 m deep and 2 km from Habanero 1 (MW-1 – MW-3), and one 1,791 m deep and 450 m from Habanero 1 (ML-1). The WA sensors contain a 3-axis geophone array, with each geophone having a sensitivity of 1.6 Volts/cm/sec and a natural frequency of 5 Hz. The MW sensors contain a tri-axial array of six geophone elements, each with a sensitivity of 0.692 volts/cm/sec.

According to the seismic logging results of a well located about 500 m from Habanero 1, McLeod-1 (ML-1), the P-wave velocity structure was determined as a six-layer model: 2.134 km/sec from the surface to 472 m depth, 2.591 km/sec from 472 m to 792 m, 2.896 km/sec from 792 m to 1,557 m, 3.962 km/sec from 1,557 m to 2,022 m, 4.572 km/sec from 2,022 m to 3,673 m, and 5.525 km/sec below 3,673 m. S-wave velocities of these layers were calculated using the Wadati diagram (Wadati, 1933) to be 0.961 km/sec from the surface to 472 m depth, 1.167 km/sec from 472 m to 792 m, 1.305 km/sec from 792 m to 1,557 m, 1.785 km/sec from 1,557 m to 2,022 m, 2.738 km/sec from 2,022 m to 3,673 m, and 3.011 km/sec below 3,673 m. Using this velocity model, locations of micro-earthquake events were determined.

4. MICRO-EARTHQUAKE OBSERVATION RESULTS

Micro-earthquake observation results during hydraulic stimulation operations to create HDR reservoirs in the three projects are summarized below.

4.1 Ogachi site

Seismic activity was very low for about 5 hours from the beginning of stimulation, and almost no events were observed, as shown in Figure 1. The total volume of injected water during these 5 hours was almost the same as the volume of the previously injected water volume for fracture initiation tests. It is suggested that this was caused by the Kaizer effect of event occurrence, which means that seismic events will not occur until the water volume injected exceeds the previous water volume injected. The maximum magnitude of the events was determined to be 2.0. Except for this one event, the magnitude of all events were smaller than -1.0.

1,553 micro-earthquake events were located in total. The epicenters of these events are shown in Figure 5. The event hypocenter was distributed in the southern area of OGC-1 at first, but the extension to the south stopped at about 250 m from OGC-1, and then the hypocenter distribution extended to the north-north-east. The hypocenter extension direction was in the predominant direction of the natural joint strike. Finally, the distribution moved about 250 m south and 700 m north from OGC-1. The hypocenter distribution also extended about 500 m in depth, so the dimensions of the hypocenter distribution region were estimated to be 1,000 m * 400 m (horizontal) * 500 m (depth) (Kaieda et al., 2005).

4.2 Hijiori site

The seismic activity was very low for about 4 hours after the beginning of the stimulation, as seen in Figure 2. No micro-earthquake events were observed in this interval. This phenomenon was almost the same as that seen at Ogachi. The maximum magnitude of the observed events was determined to be 0.3, and the magnitudes of other events were smaller than -1.0.

A total of 107 micro-earthquake events were located. The epicenters of these events are shown in Figure 6. The event hypocenter was distributed in the southern area within 100 m of HDR-1. Then, the hypocenter distribution extended to the east. Finally the distribution moved about 150 m south and 500 m east from HDR-1. This hypocenter extension direction was in the predominant direction of the natural joint strike. The hypocenter distribution also extended about 400 m in depth, so the dimensions of the hypocenter distribution region were estimated to be 700 m * 150 m (horizontal) * 400 m (depth) (Sasaki and Kaieda et al., 2000).

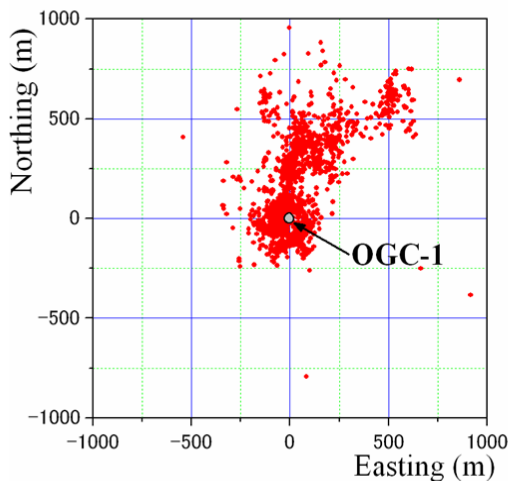

Figure 5: Micro-earthquake epicenter distribution observed in the 1991 hydraulic stimulation at Ogachi.

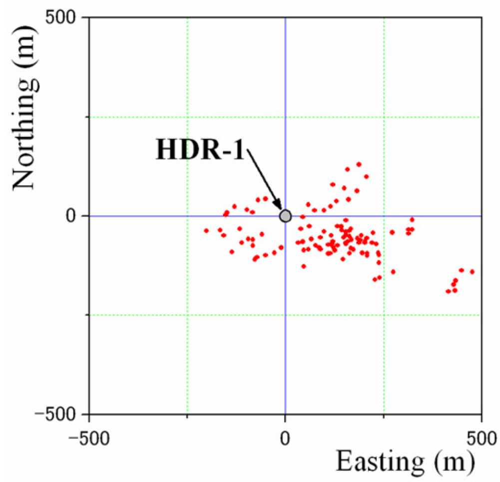

Figure 6: Micro-earthquake epicenter distribution observed in the 1992 hydraulic stimulation at Hijiori.

4.3 Cooper Basin site

Seismic activity during hydraulic stimulation at the Cooper Basin site was very high and quickly occurred just after water injection started, as shown in Figure 3. The magnitudes of events were much larger than those of the other sites, with a maximum magnitude of 3.7.

A total of 5,029 micro-earthquake events were located. The epicenters of these events are shown in Figure 7. The early event hypocenters were distributed in the southern area of Habanero 1 during the fracture initiation operation conducted previously. The extension moved to the north-north-east during the main stimulation. The hypocenter distribution extended to a depth of 350 m. Finally, the distribution spread about 1,000 m south and 2,000 m north from Habanero 1. Thus, the dimensions of the hypocenter distribution region were estimated to be 1,000 m * 3,000 m (horizontal) * 350 m (in depth) (Wyborn et al., 2005).

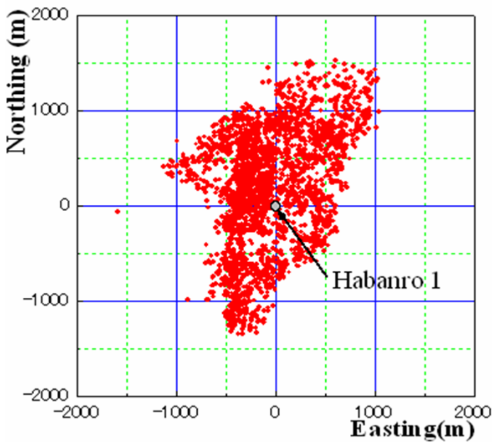

Figure 7: Micro-earthquake epicenter distribution observed in the 2003 main hydraulic stimulation at Cooper Basin.

5. COMPARIZON OF MICRO-EARTHQUAKES OBSERVATION RESULTS

Both differences and similarities between seismic activities and hypocenter distributions at the three sites were observed during the hydraulic stimulation operations.

5.1 Seismic activity

From the beginning of water injection during the stimulation operation, seismic activity was low at the Ogachi and Hijiori sites. In these two sites, much of the water injected in the fracture initiation or permeability tests was recovered to the surface by venting the injection well. When the reservoir pressure was released, fractures which may have been newly created and/or reopened by the test injections may have closed. Therefore, they were seismically quiet at the beginning of stimulation until the injected water volume reached to the previously injected volume at these sites. However, the injected water was not allowed to flow back to the surface in the Cooper Basin site, and the reservoir pressure was maintained until the main stimulation, so the seismic activity was very high even at the beginning of the main stimulation operation.

5.2 Hypocenter distribution

At the Cooper Basin site, seismic activity during the main stimulation was low in the area where event hypocenters were distributed in the earlier fracture initiation tests, as pointed out by Baisch et al. (2006). Seismic activity during the second stimulation was also low in the area where event hypocenters were distributed in the previous initial and main stimulations. These hypocenter distribution differences are shown in Figure 8. This is thought to be due to stress release caused by previous water injection.

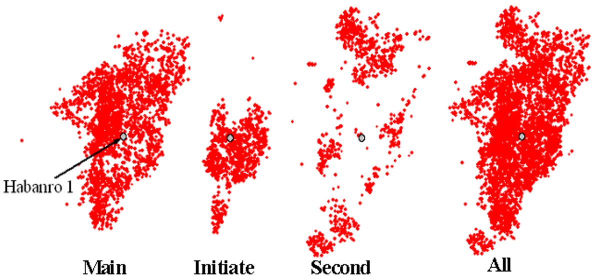

Figure 8: Micro-earthquake epicenter distribution during the 2003 stimulation at Cooper Basin.

This phenomenon was not clear in the Hijiori and Ogachi sites, because not enough events were located for discussion of the hypocenter distribution change in these fracture initiation stimulations.

5.3 Relationship between injected water volume and hypocenter distribution region

The relationship between the injected water volume and the seismically activated region (volume) during the hydraulic stimulation operations was studied. The seismically activated region was calculated by dividing the area around the injection well by cubes with 50 m sides. If more than one seismic event is located within a cube, the cube is considered to be activated. The relationship between the injected water volume and the seismically activated volume is illustrated in Figure 9. It can be seen in this figure that the seismically activated volume increases linearly with the injected water volume. The inclination of the relationship is different at each site. The inclination of the Cooper Basin is very high (4 times larger than Hijiori and 2 times larger than Ogachi). This means that water injection in the Cooper Basin site seismically activated a larger area than in other sites. A likely explanation for this is that a small number of natural joints were stimulated concentrically.

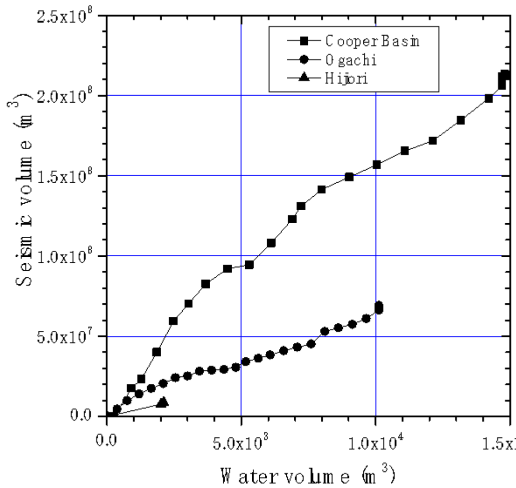

Figure 9: Relationship between injected water volume and event hypocenter distribution region in the Ogachi, Hijiori, and Cooper Basin hydraulic stimulations.

5.4 Relationship between injected water energy and seismic energy

Seismic energy (E_{AE}) was measured using the seismic magnitude (Ml) of events, as shown below (Gutenberg and Richter, 1956).

$$E_{AE} = 10^{(1.5 \cdot Ml + 11.8)} \quad (3)$$

The cumulative seismic energy in the stimulations was calculated to be 2.5×10^{12}erg at Ogachi, 9.8×10^{10}erg at Hijiori, and 2.3×10^{17}erg at Cooper Basin.

The cumulative energy of water injection (E_P) was also calculated with injection pressure (P), flow rate (F) and time interval (T) according to Equation 4:

$$E_P = P \cdot F \cdot T \quad (4)$$

The pumping energy in the stimulations were calculated to be 1.8×10^{16}erg at Ogachi, 4.8×10^{15}erg at Hijiori, and 4.0×10^{18}erg at Cooper Basin.

The ratio of the seismic energy to the pumping energy was 4×10^{-5} at Ogachi, 2×10^{-7} at Hijiori, and 6×10^{-2} (6%) at Cooper Basin.

Much more seismic energy was emitted in the Cooper Basin stimulation compared to the Ogachi and Hijiori stimulations. This was considered to be caused by a small number of natural joints that were stimulated concentrically at the Cooper Basin site.

6. CONCLUSIONS

When comparing the water injection operations with observed micro-earthquake hypocenter locations and the rate of events at three different fields (Ogachi, Hijiori and Cooper Basin), some differences and similarities were found. Seismic activities at the beginning of the water injection were low in the Ogachi and Hijiori sites until the injected water volume reached that of the previously injected volume, but the activity was high from the beginning of the injection in the Cooper Basin. This difference is thought to be caused by the injected water recovery from the fractures. It was seen in Cooper Basin that the area activated by a previous test was quiet in the successive stimulation operations. This is thought to be due to stress release caused by previous water injection.

The water volume injected and the seismically activated area showed linear correlation, but the inclination of this relationship is different depending on the site. The seismically active region at Cooper Basin extended much further than at the other sites. The amount of seismic energy released was also much larger in the Cooper Basin. These differences are thought to be strongly dependent on the regional joint system and stress conditions. There are many natural joints and a relatively low stress condition in the Ogachi and Hijiori sites, and therefore, small magnitude events occurred. However, few natural joints and high stress conditions were observed in the Cooper Basin, so a small number of natural joints were stimulated concentrically. This is considered to be the cause of the large magnitude seismic events that occurred and the large area that was seismically activated by the water injection.

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