

Seismic Time-lapse Approach to Monitor Temporal Changes in the Supercritical Water Reservoir

Junzo Kasahara^{1,5}, Yoko Hasada^{1,2}, Haruyasu Kuzume¹, Yoshihiro Fujise^{1,3}, Takashi Yamaguchi¹, Hitoshi Mikada⁴

¹ENAA, Toranomom Marine Building 10th, 3-18-19, Toranomom, Minato-ku, Tokyo 105-0001, Japan

²Daiwa Exploration and Consulting Co. Ltd., 5-10-4 Toyo, Koto-ku, Tokyo 135-0016, Japan

³WELMA Co. Ltd., 2-3-3, Watanabe street, Chuo-ku Fukuoka 810-0004, Japan

⁴Kyoto Univ., Department of Earth Resources Engineering, Katsura, Nishikyo-ku, Kyoto 615-8530, Japan

⁵Shizuoka Univ., Center for Integrated Research and Education of Natural Hazard, 836 Ohya, Shizuoka, Japan

kasahara.junzo@shizuoka.ac.jp

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ABSTRACT

We conducted a feasibility study in November 2018 in the Medipolis geothermal field, Kyushu, Japan. We installed a fiber-optic cable down to 977 m in the borehole. We measured the temperature and acquired seismic data in the borehole by distributed temperature sensor (DTS) and distributed acoustic sensor (DAS) modes, respectively. The measured highest temperature was 264°C at the 914 m depth. The DAS data were acquired at every 1 m-interval. We also installed 20 sets of seismometers on the ground surface in the study field. We obtained 4.5 days of the continuous seismic monitoring via DAS and surface seismometers. The seismic system observed seven natural earthquakes occurring in Kyushu region. One of the earthquakes with M5.2 at 100 km south of the DAS system occurred at 123 km depth and were observed by a whole depth of 977 m to 0 m. It is identified that less or no attenuation of seismic amplitudes at high temperature zone and V_p is approximately 4km/s at this zone. By semblance analysis of all earthquakes, we obtained V_p profile in the borehole. There was tremor like noises observed around the 350 m depth, but the cause is not known. Horizontal components of surface seismometers showed clear P to S converted phase, and it may suggest the presence of deep geothermal reservoirs in the Medipolis area.

1. INTRODUCTION

The geothermal energy is becoming one of the most important energy sources. The supercritical water is drawing the attention of geothermal community as the important future renewable energy source of the world (*e.g.*, Dobson *et al.*, 2017). The critical point of pure water is 373.95°C and 22.064 MPa. In Kakkonda geothermal field, the scientific drilling of WD-1a geothermal well in 1995 revealed that the temperature is higher than 500°C at 3,800 m depth (*e.g.*, Muraoka *et al.*, 1998). In the world, there are many geothermal fields showing the circumstances close to supercritical point of water or above (Reinsch *et al.*, 2017). There are several leading countries including Japan for this supercritical energy source. In Japan, NEDO is promoting supercritical geothermal exploration as an important future energy source. We evaluated the possibility to utilize the supercritical water as a future geothermal energy source (Kasahara *et al.*, 2018a).

The current technologies to know the physical properties of deep geothermal zone are not many. Recently in enhanced geothermal systems (EGS) there have been several efforts to use the fiber optic distributed temperature sensor (DTS) and distributed acoustic sensor (DAS) technologies (*e.g.*, Hartog, 2017) (Patterson, *et al.*, 2018, Mellors *et al.*, 2018, Trainor-Gutton, *et al.*, 2018). The DTS method is sensing the temperature by the Raman or the Brillouin scattering modes of light in the optical fiber. The DAS method is sensing strain (strain rate) by the Rayleigh scattering mode which is the backscattering of input laser light due to seismic wave arrivals (*e.g.*, Hartog, 2017). The sensing interval is quite short as a few meters. Because the temperature at the supercritical point is 373.95°C, ordinal geophones cannot be used in the deeper part of the borehole. The DAS using optical fiber can be used in high temperature circumstances as high as 500°C although it is necessary to coat the fiber by appropriate skin to avoid hydrogen invasion.

For the imaging of the oil and gas, we use backpropagation method like time-reversal method (Kasahara and Hasada, 2016), where a receiver array behaves as pseudo seismic sources, and the DAS provides dense seismic sources in the imaging of supercritical water reservoirs. In our approach, we contrive the method by active and/or passive seismic sources, DAS and full-waveform inversion method (Kasahara *et al.*, 2018b, c, 2019) (Figure 1). We could image the temporal change of supercritical water caused by migration of geothermal reservoir, hydrofracturing to create new geothermal reservoirs and production of geothermal heat. Therefore, we propose the seismic time-lapse technology to know the physical properties of the supercritical water reservoir.

As the first step, we evaluated the quality of DAS data in the field (Kasahara *et al.*, 2018c, d). We used three 100 m long fiber-optic cable buried at 20 cm beneath the ground surface. We also used one hundred 4.5 Hz vertical geophones placed at every 1 m. In addition, 1-5 sec 3C seismometers were used. The hammer hits and a mini-Vib seismic source were used as active sources. Waveforms taken by seismometer and DAS were compared quantitatively (Kasahara *et al.*, 2018c, d). Figure 2 shows the results of waveform comparison of horizontal seismometers and DAS. We calculated strain waveform using seismometer records and two waveforms showed extremely

well resemble each other (Figure 2). This suggests that the DAS could measure comparable physical quantity to the ordinal seismometer. We recognize that the current DAS sensitivity is a bit less sensitive than that of seismometer. Even though we know this weakness, DAS could provide very dense data, namely a few meters interval.

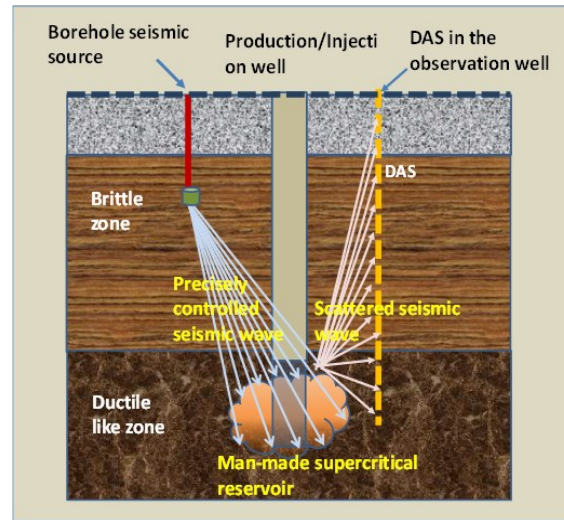


Figure 1: Seismic monitoring method to image natural and/or man-made supercritical reservoir(s) using borehole seismic source, DAS array in the borehole and surface seismic array.

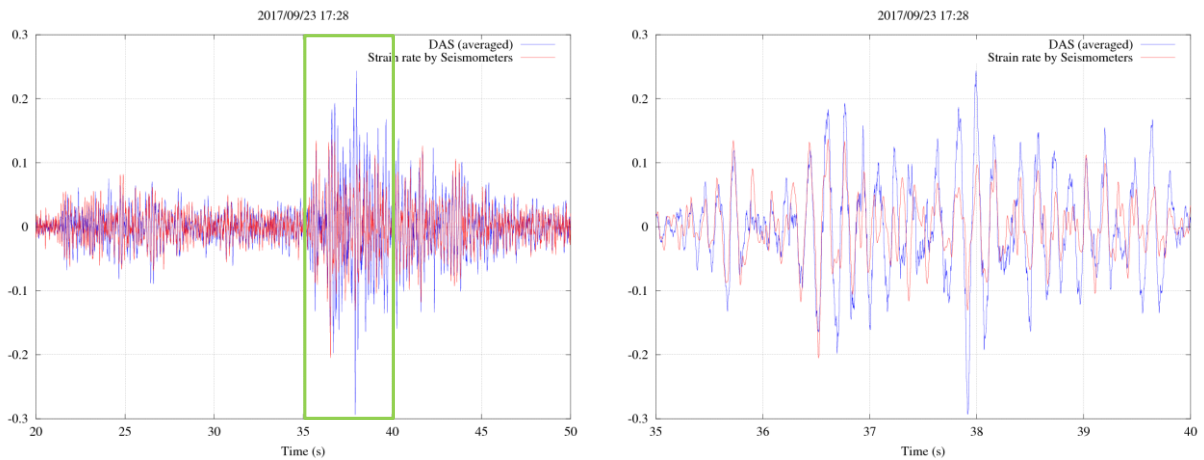


Figure 2: An earthquake record of M3.1, off Ibaraki, Japan, observed by horizontal seismometer and DAS (Kasahara *et al.*, 2018c, d). The waveforms of average strain rates calculated by seismometer records and DAS were compared for the M3.1 Ibaraki earthquake which occurred at 08:28 GMT on September 23, 2017. (Right) P- and S-waves during 17:28:20–17:28:50. (Left) Enlarged waveforms after 35 seconds. Blue lines: DAS; red lines: calculated strain rate using seismometers. Amplitudes are normalized.

As the 2nd step, we carried out simulations using full-waveform inversion method assuming active seismic sources and natural earthquakes (Kasahara *et al.*, 2018b, 2019). It was found that physical properties such as V_p , V_s and density in the reservoir were clearly retrieved if active seismic source is at the 2 km depth and the 3 km distance from the DAS array. We also studied natural earthquakes as seismic sources to image deep-seated igneous intrusion at the 4 km depth. We showed the image of the intrusion clearly, but the assumed quantities of V_p , V_s and density ρ are not fully retrieved due to no earthquakes in the Medipolis area (Kasahara *et al.*, 2018c). To evaluate usefulness of our approach in the real geothermal field, in 2018 we carried out a feasibility study in the Medipolis geothermal field located on Kyushu Island, Japan (Figure 3). In this study, we did not use active seismic source, but we used natural earthquakes occurring near the geothermal field.

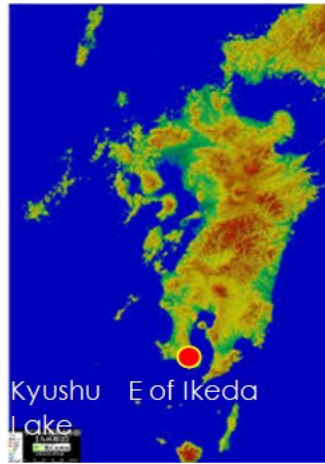


Figure 3: Medipolis geothermal field located in Kyushu Island, Japan (red circle).

2. FEASIBILITY STUDY AT THE MEDIPOLIS GEOGOTHERMA FIELD

The Medipolis geothermal field was studied by NEDO (NEDO, 2008, 2009, 2010). There are three wells; IK-1 well for the production, IK-3 well for the reduction and IK-4 well for the observation. We used the IK-4 well for DTS and DAS measurements. The Medipolis geothermal power plant generates 1.4 Mw by the binary system. Depths of three wells are 1,500m. The wellhead of IK-1 and IK-4 is just a few ten meters apart. Even the bottoms of two wells are only 200 m apart. The steam production is continuously operated during the DAS study. The production of steam is taken from the 1200 m depth of the IK-1 well. The IK-4 well is vertical down to the 500 m depth and slightly inclined from 500 m depth to 1500 m depth. An optical fiber was deployed down to the 977 m depth in the IK-4 borehole. The upper 240 m of the borehole was filled with air and the rest was filled with water. The gauge length of the DAS processing was 4 m and seismic data at every 1 m was continuously obtained for 4.5 days with 1 kHz sampling. We also installed 20 sets of 3C short period seismometers on the ground surface in the study field. The length of surface seismic array is 2 km with 100 m-interval.

3. RESULTS OF FEASIBILITY STUDY

3.1 Results of temperature measurement

Before the DAS data acquisition, we measured the temperature by DTS mode from 0 m to 977 m depth in the borehole by the same fiber-optic cable as DAS. As shown in Figure 4, the maximum temperature was 264°C at 914 m. The temperature at the depth of 350 m was 120°C and around this depth tremor like noises were dominated (described later).

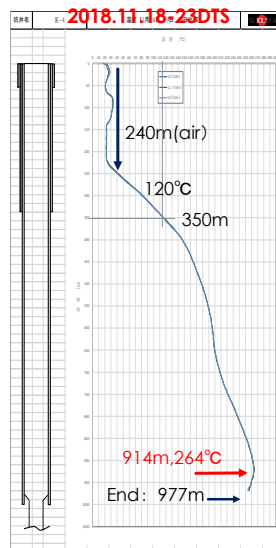


Figure 4: Temperature profile observed by DTS in the observation borehole. The temeprrure at the 914 m depth in the borehole was 264°C. DAS system used the same optical fiber with 1m-interval data acquisition. Casing plan is shown at the left.

3.2. Results of seismic measurements

We conducted the seismic measurement by DAS and ground surface seismometers. Two of surface seismometers near the production wellhead show very large artificial noise of 30 Hz and 57 Hz, but no such noise was observed by DAS in the borehole.

For 4.5 days of continuous monitoring by DAS, we observed seven natural earthquakes from $M=0.8$ to $M=5.2$ (Figure 5). One of the observed $M5.2$ earthquake records is shown in Figure 6. The P first arrivals were observed at a whole depth of 977 m to 0 m for every 1m-interval. Although the temperature at the 914 m depth was 264°C , any distinct attenuation of observed seismic waves was not observed. We recognize surface reflected arrivals. The S arrivals observed by surface seismometers are 17 seconds after the P first arrivals, but we do not identify S arrivals on the DAS records. An aftershock of this $M5.2$ was $M3.5$ and shows similar waveforms. The $M=0.8$ and 1.4 earthquakes which occurred at 15 km focal distances (Figure 5 in the left) did not show any P first arrivals. The tremor like noise was observed around the 350 m depth and it disturbs the earthquake arrivals.

To estimate vertical V_p profile, we made semblance analysis (Figure 7) and obtained V_p for every 100 m depth-interval along the borehole (Figure 8). The V_p is approximately 4km/s and 3.3 km/s between 800m-977m and between 500 m and 800 m, respectively (Figure 8). V_p around the 350 m depth is not well determined due to large tremor noises.

In some earthquake records, some surface seismometers show a large arrival on EW and NS components at 0.8 seconds after P arrivals on vertical component. The large amplitudes on the horizontal components are considered as P-to-S conversion phases.

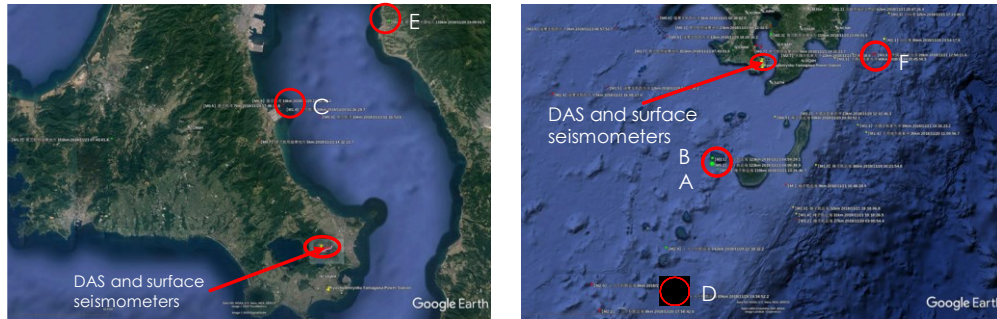


Figure 5: Seven observed natural earthquakes in 2018 and DAS and surface seismometers in the geothermal field (Right and left. Scales are not the same) A: Near Tanegashima $M5.2$ (2018/11/21); B: Near Tanegashima $M3.1$ (2018/11/21); C: Kagoshima Bay $M1.4$ and $M0.8$ (2018/11/20); D: Near Tokara islands $M4.0$ (2018/11/10); E: Ohsumi Peninsula $M1.8$ (2018/11/21); F: East of Ohsumi Peninsula $M1.8$ (2018/11/21). Geothermal field is located in the southern end of Kyushu Island.

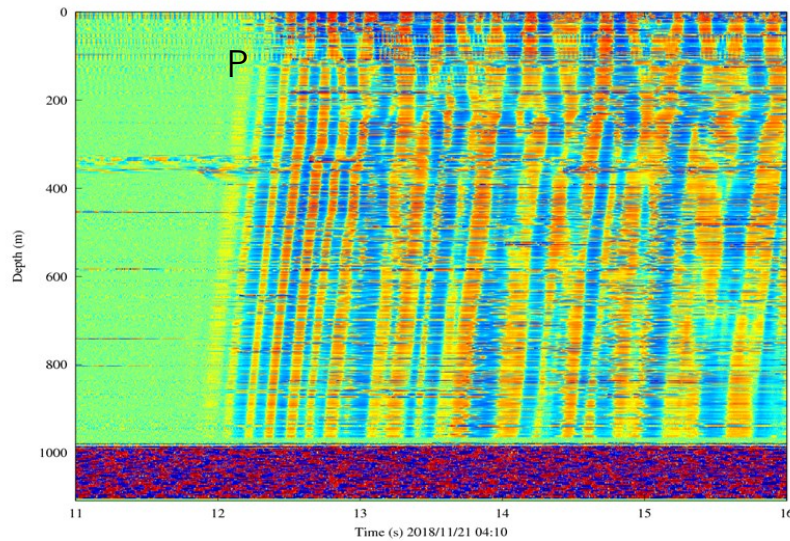


Figure 6: An $M5.2$ natural earthquake occurring 100 km focal distance and 123km focal depth recorded by the DAS. The vertical axis is depth from 0 m (top) to 977 m (bottom). The horizontal axis is the arrival time in seconds.

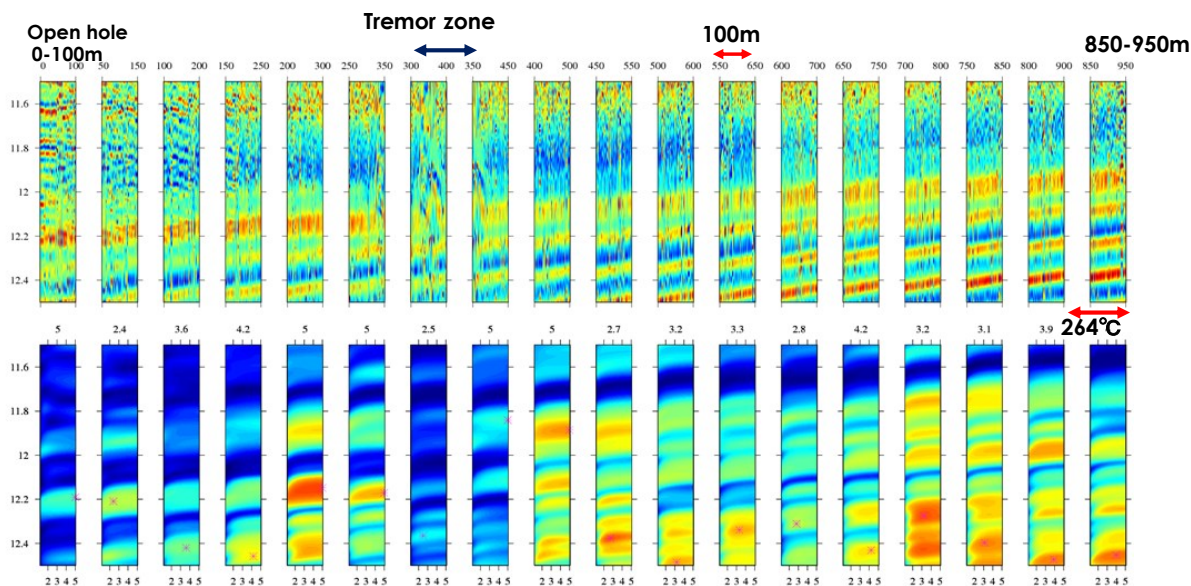


Figure 7: Semblance analysis of the M5.2 earthquake. (Upper panel) Waveforms of 1 m-interval DAS records of every 100 m depth-interval. The vertical axis is the travel time in seconds. (Lower panel) Semblance analysis panel for each 100 m depth-interval. The 264°C zone is in the 914 m depth.

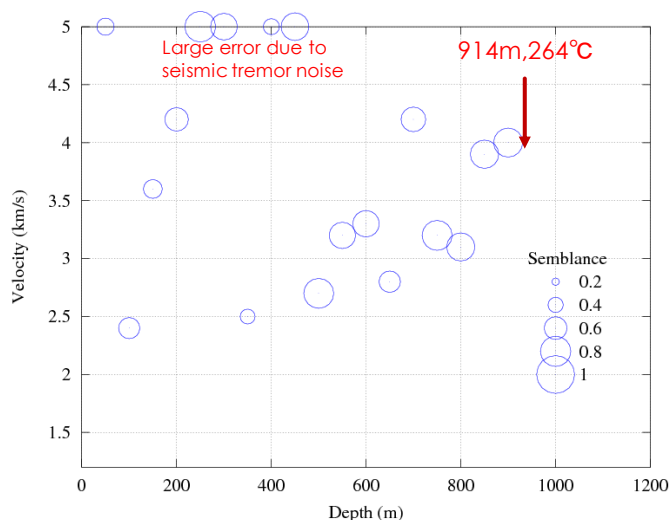


Figure 8: Results of semblance analysis of the M5.2 earthquake.

4. DISCUSSION AND CONCLUSIONS

We carried out feasibility study using the geothermal well in the Medipolis geothermal field. We measured temperature and seismic waves in the IK-4 borehole down to the 977 m depth using DTS and DAS modes with the same optical fiber. The highest temperature was 264°C at the 914 m depth. By DAS method, we observed seven natural earthquakes occurring nearby Kyushu Peninsula. Although, no significant attenuation of P arrives was observed by the DAS records around the highest temperature zone at the 914 m depth. Between 800 m and 977 m the Vp profile in the borehole show 4 km/s, and it seems no or less effects by the high temperature zone. The reason for these measurements might be explained by the longer wavelength of natural earthquakes because the dominant frequency of P is approximately a few Hz, and the wavelength is order of km and the thickness of high temperature zone seems less than km.

There is tremor like vibration around the 350 m depth. At the 350 m depth the borehole temperature was 120°C. The cause of this tremor is under investigation. Vp around the 350 m depth is not well determined due to large tremor noises. The presence of tremors degrades the Vp estimation by semblance due to low S/N.

Although we observed seven natural earthquakes, the incident angles of all earthquakes are near vertical, and it seems no reflected phases from the deep intrusive body. However, surface seismometers records suggest presence of P to S converted waves, and the conversion could be happened just below the Medipolis field. By use of large size active seismic source we could obtain PP or PS reflection from the possible intrusive zone.

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