PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

The Second Seismic Study at the Geothermal Field in Southern Kyushu, Japan Using an Optical Fiber System and Surface Geophones

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Keywords: DAS, VSP, Geothermal field, *Vp/Vs*, high *Vp/Vs*, Poisson's ratio

ABSTRACT

Following our first seismic study at the Medipolis geothermal field in southwestern Japan in 2018, we conducted a second seismic study at the same geothermal field in 2019. We installed an optical-fiber system for distributed temperature sensor (DTS) and distributed acoustic sensors (DASs) measurements. We deployed the optical-fiber system at a 1,545-m depth in the IK-4 borehole. The temperature was measured to be 272.8 °C at a 920-m depth and 152.8 °C at a 1,530-m depth. We operated a MiniVib seismic source at five locations and performed a frequency sweep of 10–75 Hz 480 times each day, for seven days. We cross-correlated the seismic records and the source signature and stacked the correlated data to enhance the S/N. Stacking for 480 or 960 times considerably improved the arrival waveforms. Based on an analysis of DAS data, we constructed the 2D seismic profile. We estimated three major hydrothermal layers, at depths of 800–1,000 m, 1,300–1,600 m, and 3,600 m. The zone around 3,600 m suggests a high *Vp/V*s value and the possible presence of a fluid layer.

1. INTRODUCTION

To develop the most effective tools for determining the characteristics of any geothermal field, we have employed a seismic approach using ultra-stable seismic sources, distributed acoustic sensors (DASs), distributed temperature sensors (DTSs) using fiber optics, and full-waveform inversion (FWI) methods. Recently, geothermal studies have used optical-fiber sensing technologies (*e.g*., Mellors *et al*., 2018; Trainor-Gutton *et al*., 2018). In 2018 and 2019, we conducted seismic studies at the Medipolis geothermal field in the southern part of Kyushu, Japan. The Medipolis geothermal power plant generates 1.4 MW of power using a binary system, through the IK-1 well. The production zone of steam is around 1,300 m deep from wellhead. Hereafter, we use the "depth" from the wellhead of the IK-4 well. Geothermal studies at the Medipolis area were also conducted by the New Energy and Industrial Technology Development Organization (NEDO) in 2008–2010 (NEDO, 2008, 2009, 2010).

In 2018, we used the IK-4 well, which is one of four wells at the Medipolis geothermal field (Kasahara *et al*., 2019b). We installed optical fibers down to a depth of 977 m and measured the temperature and seismic waves using the DTS and DAS modes, respectively. The highest temperature was measured to be 264 °C. Using the DASs, we observed seven natural earthquakes over four and a half days, we estimated the interval velocities of P waves (*Vp*) in the surroundings of the well (Kasahara *et al.* 2019b). However, the DAS measurements did not show any nearby earthquakes that could be useful for evaluating the geothermal characteristics. Using surface geophones in the same field, we identified a P-to-S conversion phase and suggested the existence of a high-*Vp/Vs* zone at a depth of approximately 4 km in the study fields (Kasahara *et al*., 2020). To obtain a more detailed seismic structure of the Medipolis geothermal field, in 2019, we conducted an offset VSP study using the same IK-4 well at the same geothermal field.

2. FIELD STUDY AND RAW DATA

We installed a fiber-optic system at the bottom of the IK-4 well, at a 1,545-m depth. Using the optical fiber in the well, we measured the temperature and the seismic waves using the DTS and DAS modes, respectively. The DTSs measurements were conducted three times. The DAS data were obtained using a 10-m gauge length, and the waveforms were collected by one-m spacing. Additionally, we installed 3C-26 surface geophones. We operated a MiniVib at five locations. The locations of the IK-4 well, surface geophones, and sources are shown in Fig. 1. The offset distance was between 0 and 2 km. We operated a frequency sweep between 10 Hz and 75 Hz for 30 s. To obtain a better S/N ratio, we stacked the data collected over 16 h at distances of 2,000 m and 1,600 m. For 800-m and 300-m distances, we used 8 h-long data. At the zero-offset location, we activated the source only once.

The results obtained using the DTSs are shown in Fig. 2. The maximum temperature was 272.8 °C, which was slightly higher the value obtained our 2018 study. The temperature decreased to 152.8 °C at the bottom of well. Because the production zone of the IK-1 production well is around 1,300 m deep, the temperature at the production zone is approximately 180 °C.

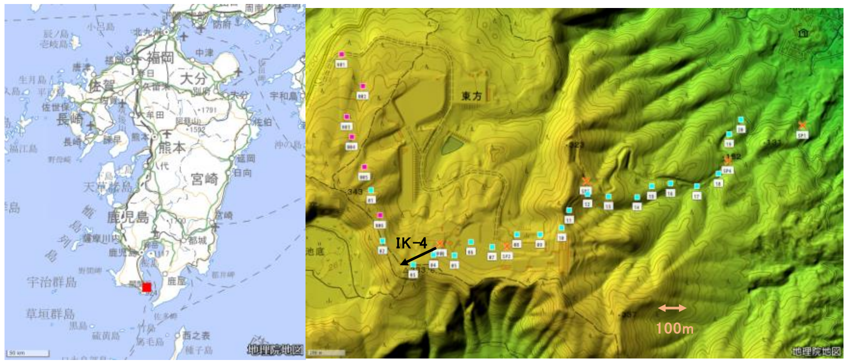

Figure 1: (Left) Kyushu island, Japan and the Medipolis geothermal field (red square). (Right) the Medipolis geothermal field.

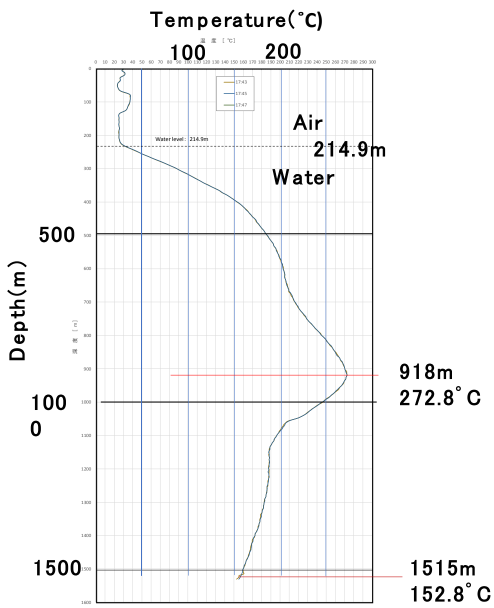

Figure 2: Temperature profile observed using the DTS mode.

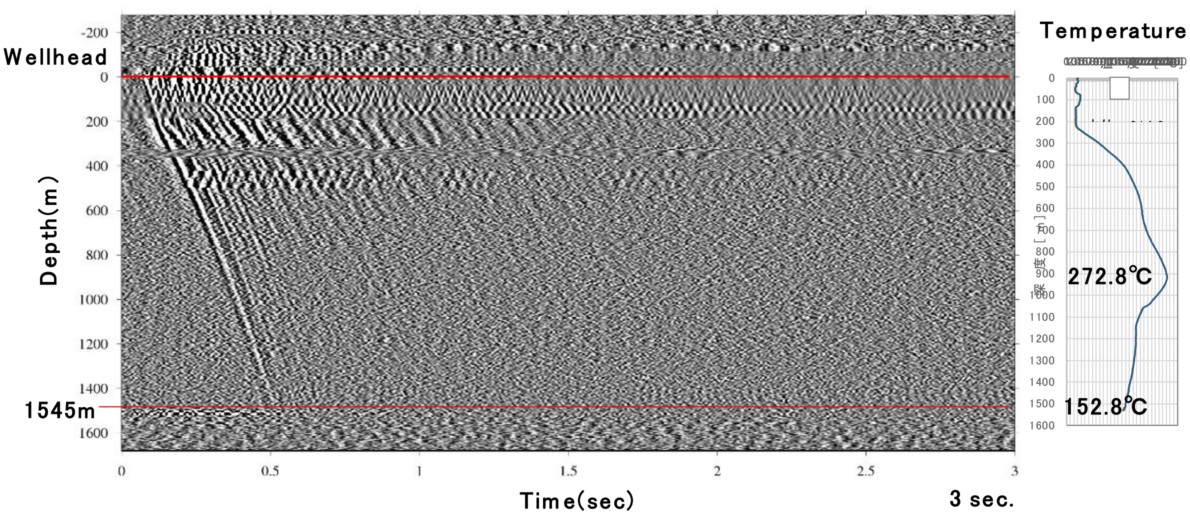

Figure 3: Zero-offset VSP records obtained using the DAS mode (left) and the temperature in the IK-4 well (right). The MiniVib source was operated for only 30 s. The seismic traces are spaced 1 m apart.

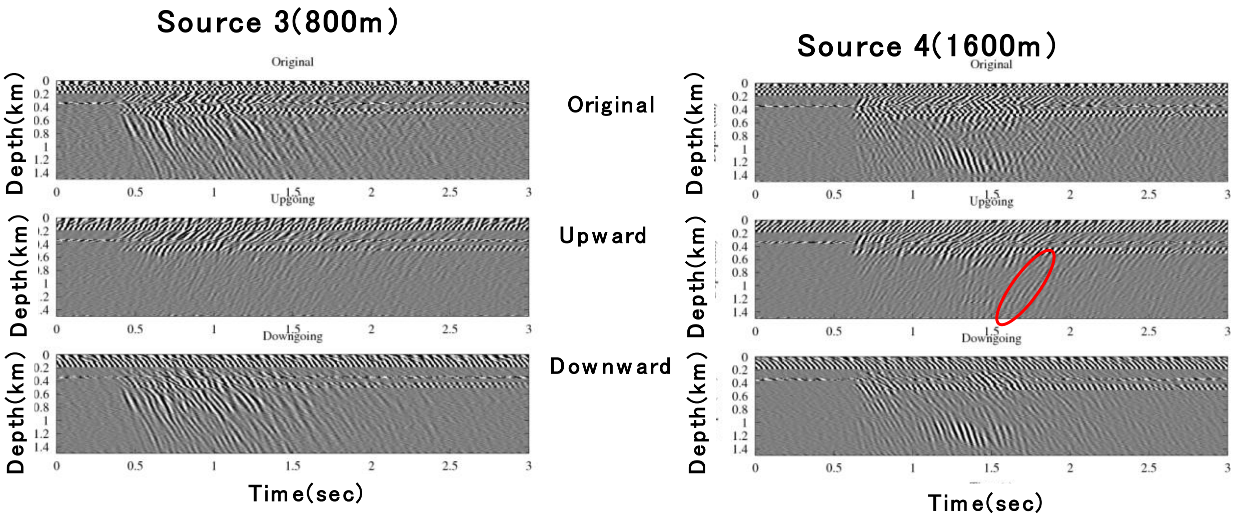

Figure 4: Offset VSP records for 800-m offset (left) and 1,600-m offset (right). We stacked the data of 8 h and 16 h for the 800-m and 1,600-m offset distances, respectively. All original DAS data (top row) were separated into upward (middle row) and downward (bottom row) types. An ellipsoid in the right-middle row is interpreted as the reflected phase from an approximately 3.6-km depth.

The results of the DAS VSP were obtained at offset distances of 0, 300, 800, 1,800, and 2,000 m. The zero-offset VSP is shown in Fig. 3. Although the temperature at 920 m was 272.8 °C, the zero-offset VSP did not show clear evidence of a high-temperature zone.

The DAS VSP data at 800 m and 1,600 m are shown in Fig. 4. We separated downgoing and upgoing arrivals for all five locations, as shown in the Fig. 4. The offset VSP data at 800 m and 1,600 m show distinct changes in the arrivals at a depth of approximately 800–1,000 m. We can identify numerous upgoing arrivals, which suggest the presence of deeper reflection zones.

3 DATA ANALYSIS

We obtained the *Vp* distribution through the travel time inversion, using the first P arrivals by the DASs and surface geophones (right in Fig. 5). We obtained migrated records using the upgoing arrivals in the VSP data (Fig. 6). Based on a comparison between the observed and synthetic waveforms (Fig. 7), we obtained 2D distributions of *Vp, Vs* and *Vp/Vs* in the Medipolis area, through forward modeling (Fig. 8) and superposition on the migration image (Fig. 6). The reflected zone at 3.6 km is well-matched.

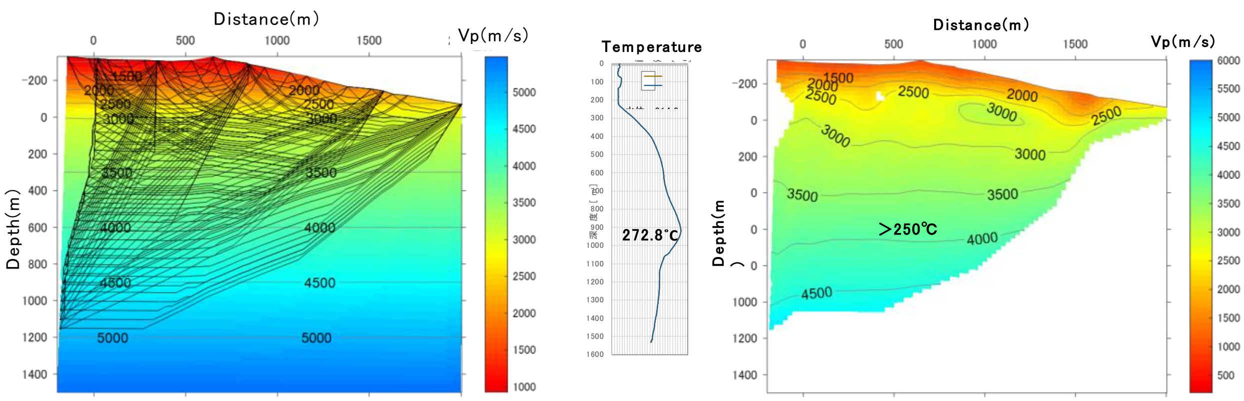

Figure 5: (Left) Ray diagram of the initial model for the travel-time inversion. (Middle) Temperature distribution along the IK-4 well. (Right) *Vp* distribution obtained through travel-time inversion using the P-wave first arrivals obtained by the DASs and surface geophones. Note that the depths of these figures are calculated from the sea-level. The horizontal axis is the distance from the wellhead.

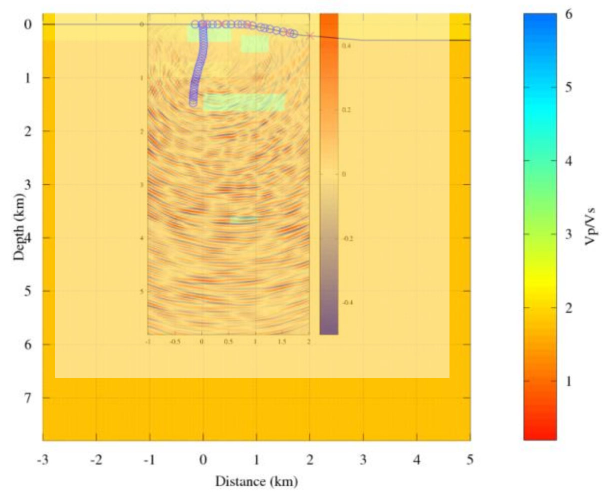

Figure 6: Superposed results of the migrated offset VSP data and *Vp/Vs* obtained through forward modelling.

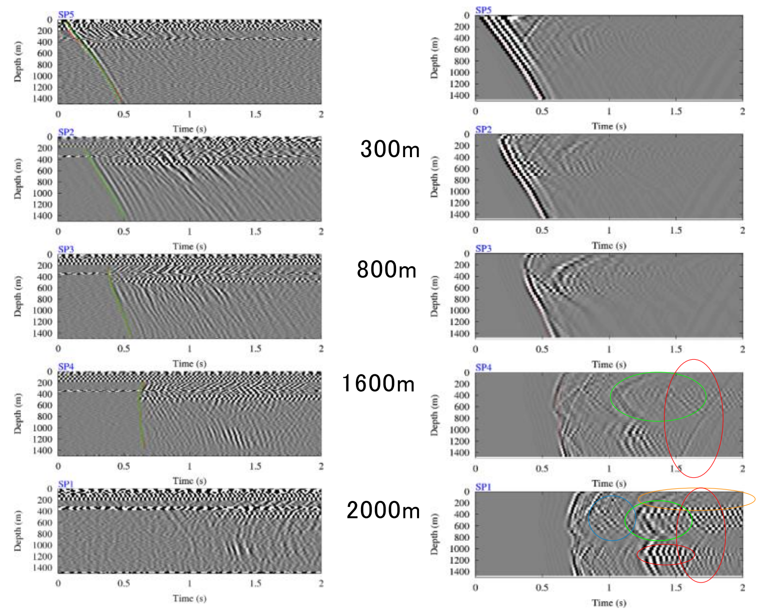

Figure 7: The observed VSP records at 0, 300, 800, 1,600, and 2,000 m from top to bottom. The DAS VSP data were stacked 8 h or 16 h, except for the zero-offset. The original data and synthetic DAS records are shown in the left and right columns, respectively. Purple, green, and red ellipsoids indicate the reflected phases at a 3.8-km depth, the shallow reverberations, and the SS reflected phase at a depth of 1,300–1,600 m depth, respectively.

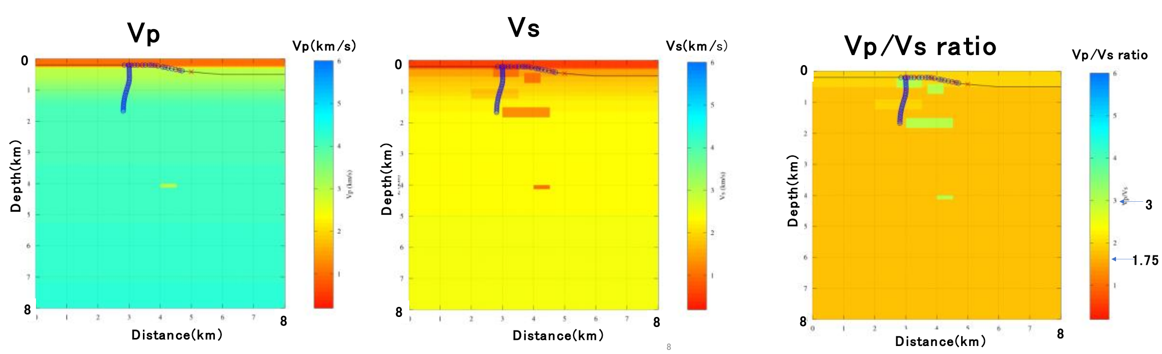

Figure 8: Results of *Vp*, *Vs* and *Vp/Vs*, obtained through forward modeling.

4 DISCUSSION AND CONCLUSIONS

We conducted an offset VSP study at the Medipolis geothermal field using DASs in the IK-4 well, down to a depth of 1,545 m. To enhance the S/N ratio. we stacked 8-h and 16-h data obtained using a MiniVib source.

The high-*Vp/Vs* zone was observed at a depth of approximately 3.6 km depth. This appears to be the same high-*Vp/Vs* zone that was obtained from a previous P-to-S conversion analysis (Kasahara *et al.*, 2020). The *Vp/Vs* is related to the Poisson's ratio. When *Vp/Vs* is 3, the Poisson's ratio is 0.467 (Kasahara *et al*., 2020). The temperature at a 1,500-m depth is 155 ℃. If we take 10 ℃/100 m, the temperature at 4 km is estimated to be 410 ℃, which appears to exceed the supercritical limit of water (374 ℃ at 22.1 MPa). This zone is a candidate for the supercritical water reservoir.

ACKNOWLEDGEMENTS

This study was supported by the New Energy and Industrial Technology Development Organization (NEDO). Medipolis Energy Co. kindly allowed us to use their IK-4 geothermal well. Mr. Kimura provided us with the Schlumberger hDVS measurements. WELMA Co. provided us with the borehole fiber-optic system and assisted in the measurement of temperature in the borehole. The staff of West Japan Engineering Consultants, Inc. helped us during the field study. The MiniVib source was operated with assistance from Dia Consultants Co., Ltd.

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