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Seismic Exploration at the TP-2 Geothermal Borehole in Takigami Geothermal Field in Japan Using the DFOS (Distributed Fiber Optic Sensing) System

Kasahara, Junzo, Yoko Hasada, Shigetsugu Furuya, Masahiro Shimazaki Hitoshi Mikada, Hiroshi Ohnuma and Yoshihiro Fujise

836 Ohya,Surugaku,Shizuoka 422-8529, Japan

Junzo.kasahara@shizuokac.jp

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ABSTRACT

In 2022, we conducted a DFOS seismic study in the Takigami geothermal field in Kyushu, Japan. We installed an optical fiber cable to 2,000 m into the depth of the TP-2 geothermal borehole. We operated 12 seismic sources around the Takigami plant. The DTS temperature was 205ºC at 2,000 m depth. Based on the DAS data and calculated synthetic seismic waveforms, the East-West Vp depth profile shows a distinct vertical fault with an N-S strike concordant with the regional geology. Migrated reflection phases were obtained by F-K filtering for a better reflection image of the deeper part.

1. INTRODUCTION

Decades ago, optical fiber sensing technology called distributed fiber sensing (DFOS) (Hartog, 2017) was popular. Since 2018, we have conducted DFOS surveys in geothermal fields (Hasada *et al*., 2024, Kasahara *et al.,* 2020a, b; 2022a, b, c, 2024a, b). The DFOS has two major settings: distributed acoustic sensing (DAS) and distributed temperature sensing (DTS). This paper describes the results of the DAS and DTS survey 2022 at the Takigami geothermal field, NorthEast Kyushu, Japan (Fig. 1).

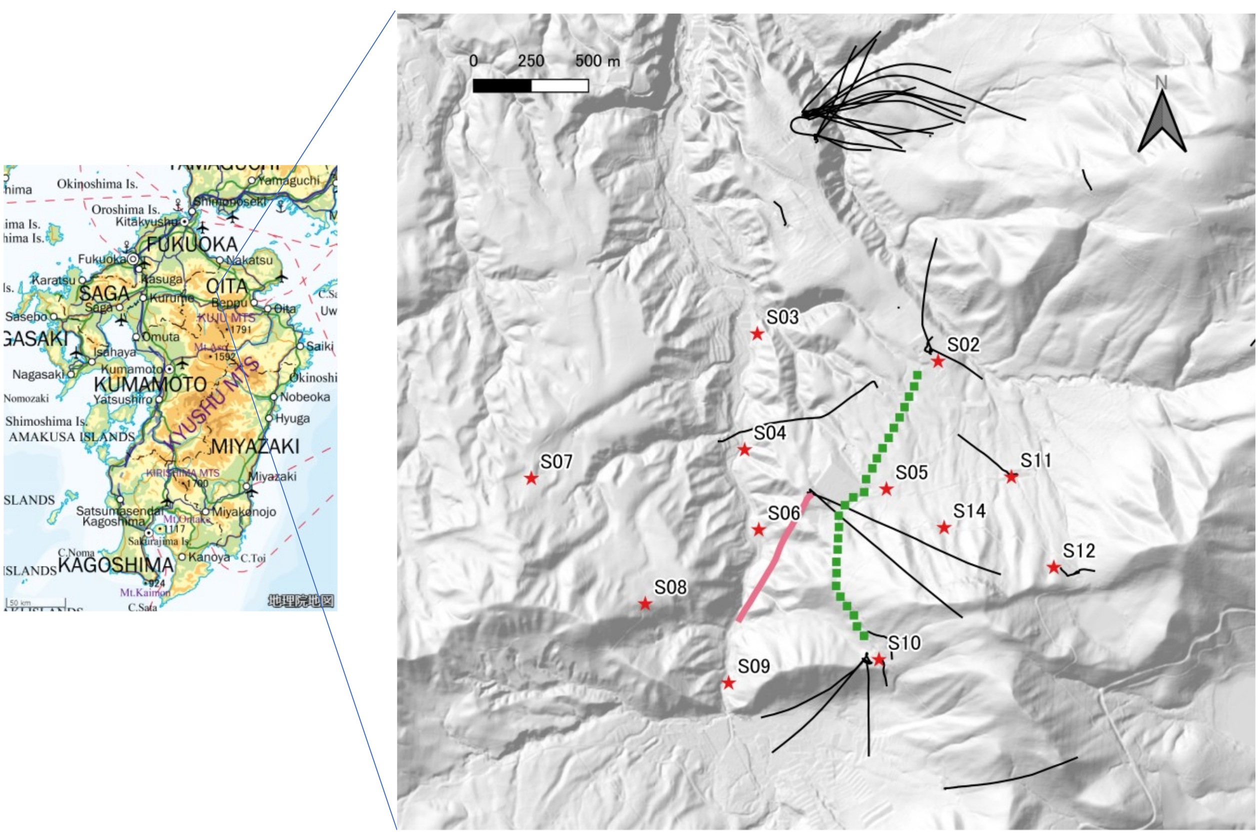

Figure 1: Location map of TP-2 geothermal well (pink line), seismic sources (red stars), and surface seismometers (green squares). Black lines are other wells. The hill shade map is based on the Geospatial Information Authority of Japan.

2. GEOLOGICAL BACKGROUND OF THE SURVEY AREA AND OUTLINE OF THE SURVEY

The Takigami Geothermal Power Plant owned by Idemitu Kosan Co. Ltd. started producing electricity in 1996. The Takigami field is geologically located north of the Beppu-Shimabara graven with an east-west strike, representing a North-South extensional force dominated in this area. The geology of the geothermal survey area was studied based on regional geology, subsurface structure, borehole data, resistivity measurements, and gravity field data from the late 1980s to the '90s. (Hoshizumi *et al*., 1988; NEDO, 1990; Takenaka *et al*., 1995, Motomatsu, 1999). A distinct vertical fault with an N-S strike that subdivides the geothermal system is inferred by the gravity distribution by Takenaka *et al*. (1995) (Fig. 2). The borehole geological data in the Takigami field (Idemitsu Kosan internal data) also supports the existence of an N-S fault. The inferred location of the fault is ca. 1 km east of the TP-2 wellhead, which is one of the Takigami geothermal wells close to the Takigami Geothermal Power Plant and was selected in the 2022 DAS and DTS survey.

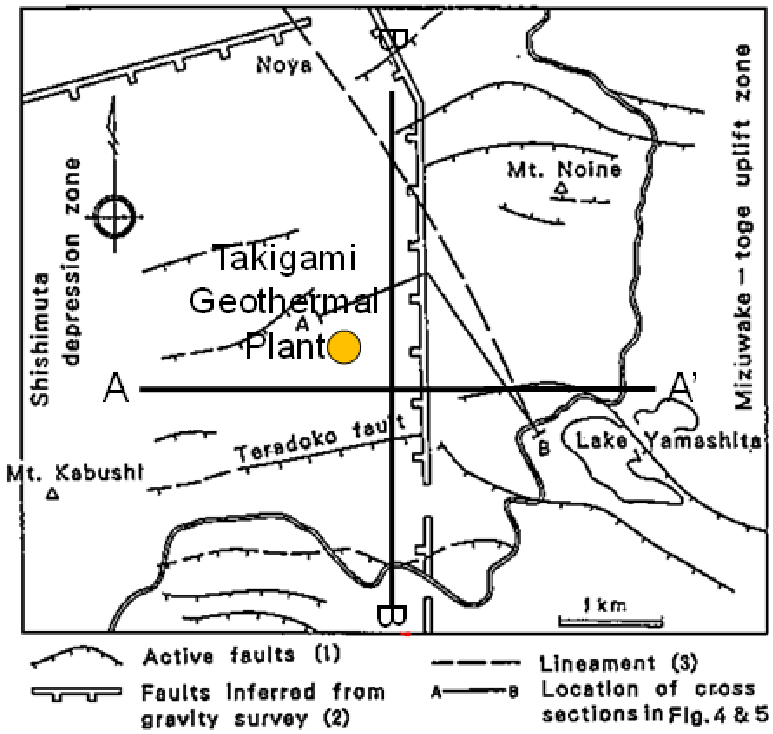

Figure 2: N-S fault inferred by gravity data (modified from Takenaka *et al*., 1995). The yellow circle shows the location of the Takigami geothermal power plant and TP-2 wellhead. The geological and geothermal cross sections along A-A' and B-B' are shown in Fig. 3.

The geological and geothermal cross sections in the Takigami area are shown in Fig. 3. The key layers are the Noine-dake volcanic rocks, the Ajibaru formation, the Takigami formation, and the Mizuwake andesite formation from shallow to deep. The Takigami formation's upper part is the sealing layer containing smectite and illite clays. Based on the well-to-well correlation in the Takigami field, the vertical displacement associated with the N-S fault is ca. 1,000 m, as shown in Fig. 3 (right section). The thicknesses of the Ajibaru and Takigami formations are thinner towards the east, and the depth of the Takigami formation is shallower in the east.

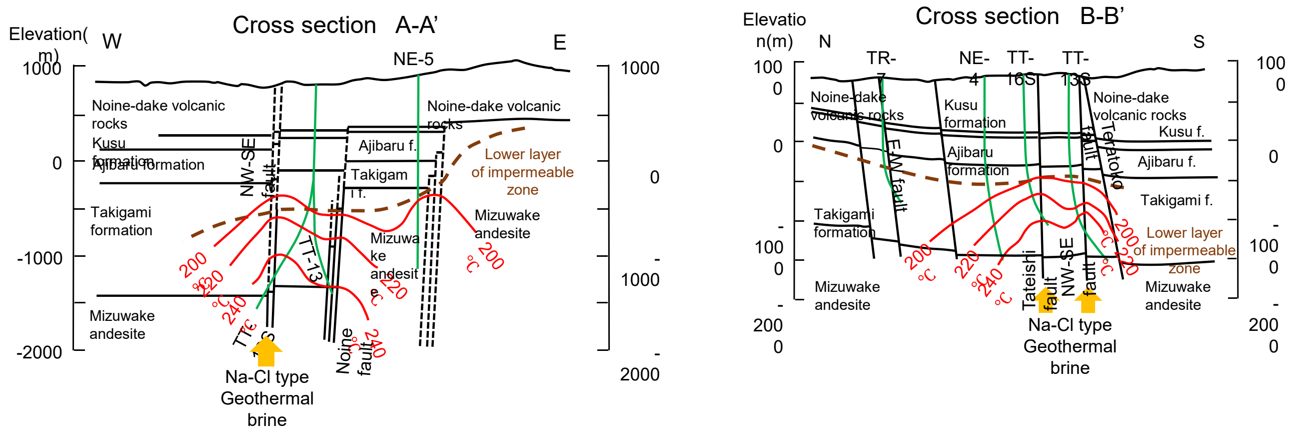

Figure 3: (Left) The east-west geological and geothermal cross section. (Right) The north-south geological and geothermal section. (non-publication, courtesy of Idemitsu Kosan, 2022). Four key layers are: Noine-dake volcanic rocks, Ajibaru formation, Takigami formation, and Mizuwake andesite, from shallow to deep. The location of A-A' and B-B' are shown in Fig. 2.

We conducted the DFOS survey, deploying the optical fiber system into the TP-2 geothermal borehole down to 2,000 m from May 15 to June 1, 2022. The locations of twelve seismic sources are shown in Fig. 1. At first step, we measured the temperature profile by the DTS. After the DTS measurement, we obtained seismic signals from the DAS. We set the parameters of the interrogator as 20 kHz ping rate, 1 kHz sampling, 16.4-meter gauge length, and every 1 m data acquisition. IVI EnviroVibe was used as the seismic sources at eleven locations shown in Fig. 1. At each location, the seismic source was operated for more than 480 times of a 30-second sweep from 10–75 Hz and 30 seconds. Surface seismometers were also used for seismic study (Fig. 1).

The stack records of the DAS and surface seismometers were obtained by weighted stacking to suppress the noise, and eliminate the source signature. The Vp depth profile along the east-west section was obtained using the P first arrivals of DAS and surface seismometer records. The synthetic seismic waveforms are calculated and compared to the observed records to get optimum Vp profile. Applying the F-K filtering to the DAS records, DAS records were separated into downgoing and upgoing waves. The upgoing waves seem reflection arrivals. Using the Vp depth profiles and reflection arrivals, the reflection images were obtained by the migration processing.

3. RESULTS OF TEMPERATURE MEASUREMENTS

The temperature profile along the TP-2 was measured by the DTS method (Fig. 4). The bottom of the TP-2 well reached the Mizuwake andesite formation, and the temperature at the bottom was 223°C at 2,000 m. The temperature above 800 m is nearly flat, suggesting meteoric water circulation occurs shallower than 800 m. The temperature gradually increases from 800 m to 1,400 m, ranging between 100 and 200°C, implying the dehydration process of smectite clay forming illite at 100 to 190°C. The recorded temperature profile is concordant with the previous surveys by Idemitsu Kosan.

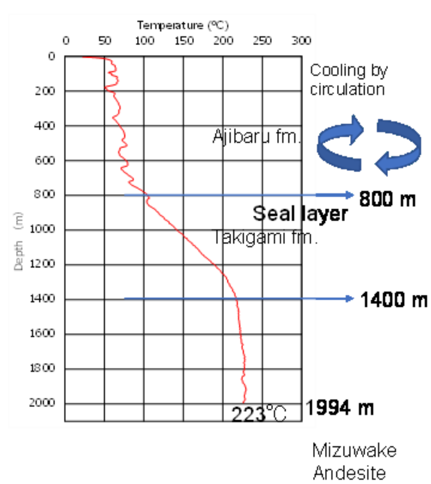

Figure 4: Temperature profile along the TP-2 borehole obtained by DTS measurement. The vertical axis is the depth of the well in meters. The horizontal axis is the temperature at °C.

4. DAS RECORDS, SYNTHETIC DAS RECORDS, AND VELOCITY ANALYSIS

We obtained twelve sets of DAS records representing each seismic source. The summary of the DAS records is shown in Fig. 5.

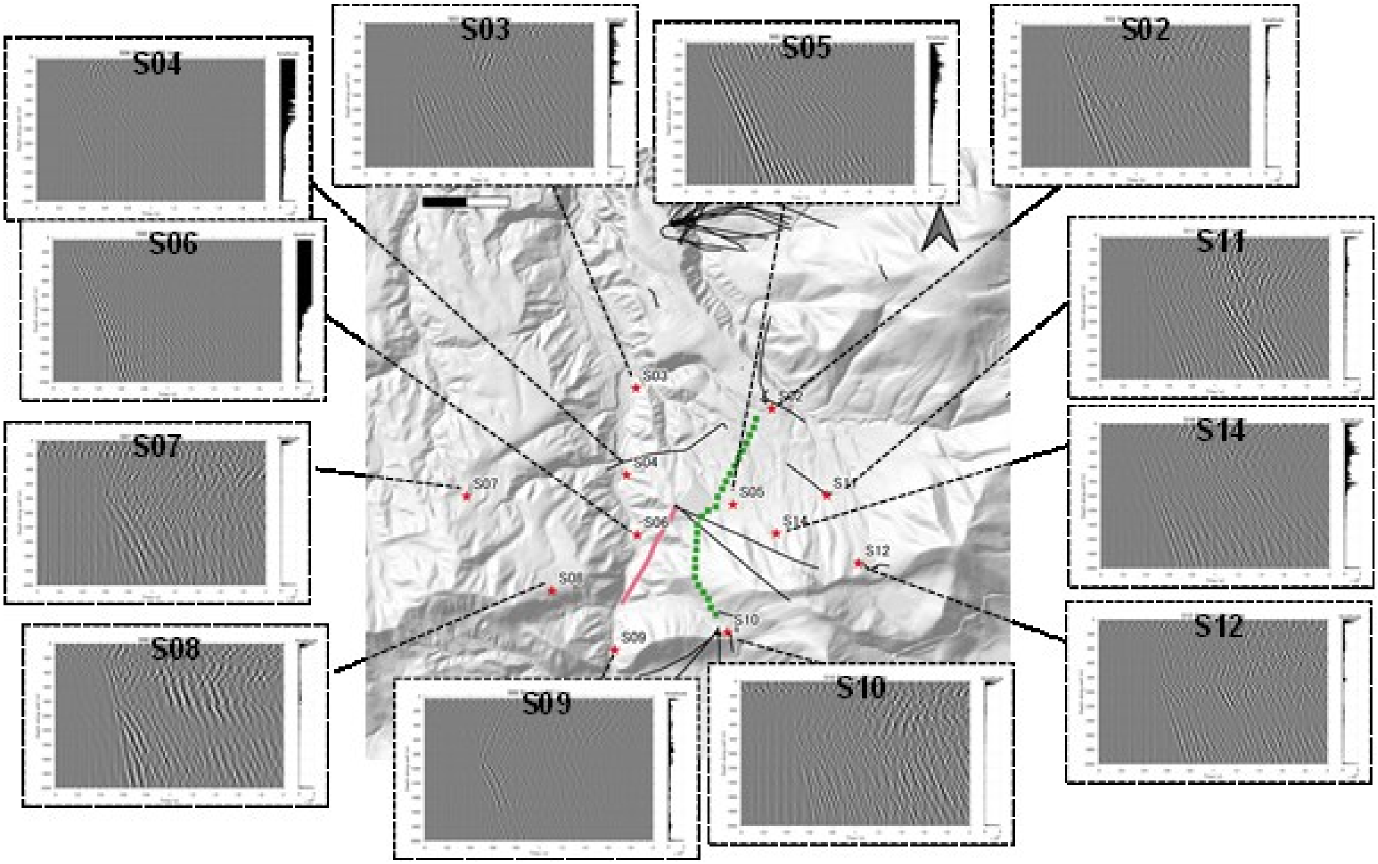

Figure 5: Seismic source location map with the related DAS records. Each DAS diagram's vertical and horizontal axes are depth and elapsed time, respectively. The hill shade map is based on the Geospatial Information Authority of Japan.

We used two existing Vp data to construct the velocity structure in the survey area. One is the refraction analysis done in 1979 (Ministry of International Trade and Industry report, 1980), and the other is the check shot data in a well near the TP-2 well (1998 Idemitsu Kosan, internal data). The start model (m000) shows a distinct N-S strike fault assumed to be located at 800 m east of the TP-2 wellhead. The vertical displacement of the lower layer (Mizuwake andesite) is 1 km. By the comparison of synthetic wave forms and observed seismic records we renewed the Vp model. After numeral examination of the Vp models, we obtained the best Vp profile (m023) that the N-S fault location is moved further west from the initial assumed location to match the observed P first arrivals (Fig. 6). The Vp depth profile model 023 is shown in Fig. 7. This was determined by the examination of S11 and S12 locations when we recognized significant travel time misfit between the assumed model and the observation. Because the zone we analyzed is altitude variation, we evaluated the surface layer effect (model 026) shown in Fig. 8.

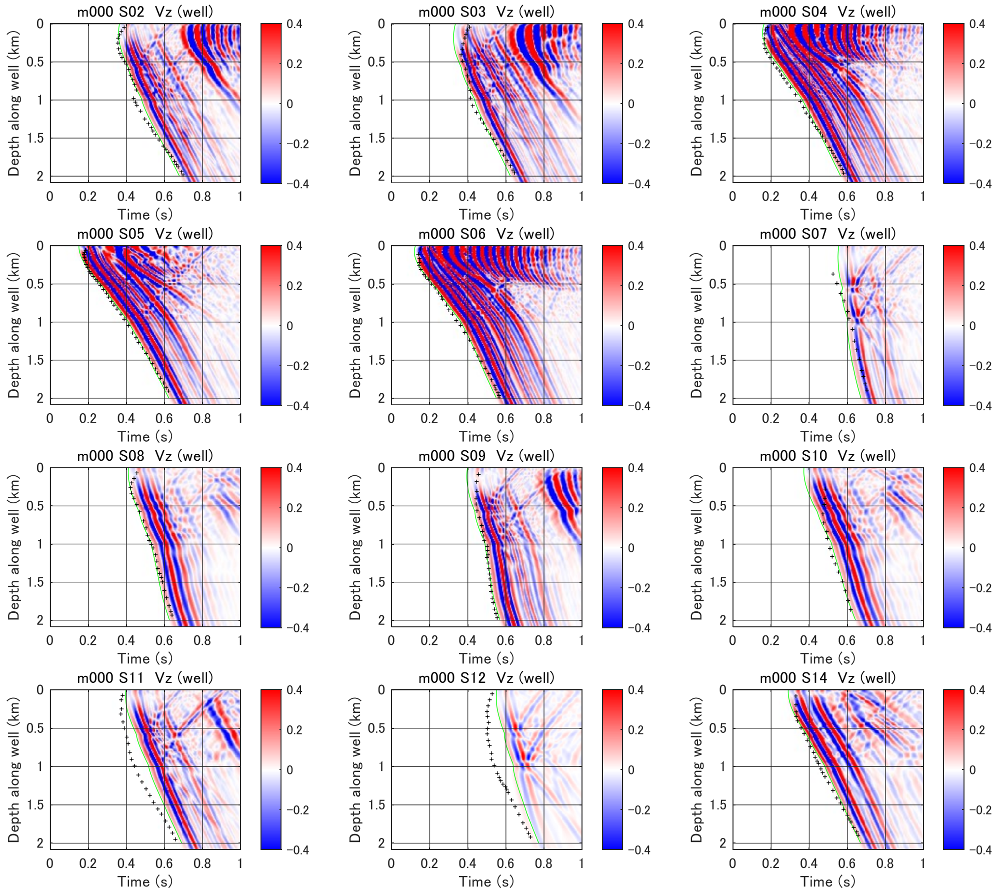

Figure 6: Synthetic DAS waveform at twelve source locations calculated by the m023 model. Dots show the observed P first arrivals. Each diagram's vertical and horizontal axes are the depth of the TP-2 well and the travel time, respectively. The amplitude scale is shown on the right side of each diagram. S11 and S12 show significant travel time discrepancies.

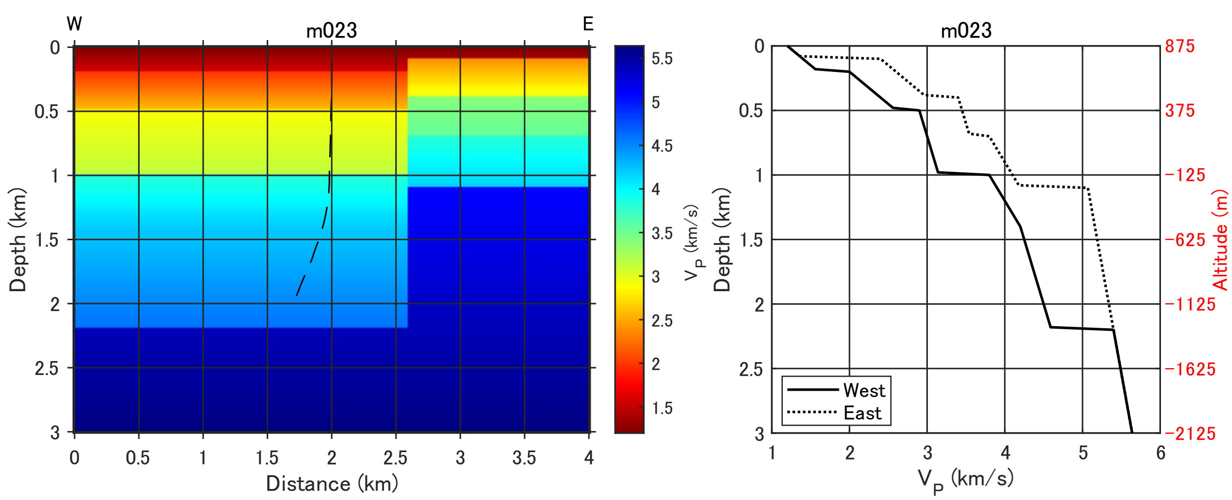

Figure 7: Vp depth model (m023) along the E-W profile across the TP-2 wellhead. It is the best match for the observed DAS data. The N-S vertical fault is modeled ca. 600 m east from the TP-2 wellhead location. A broken black line shows the TP-2 well trace. The boundary of the Ajibaru Formation and Takigami Formation is at around 1 km depth. On the right is the depth profile of the east (dotted) and west (solid), and on the left is the velocity model. The horizontal axis of the distance in km from the west.

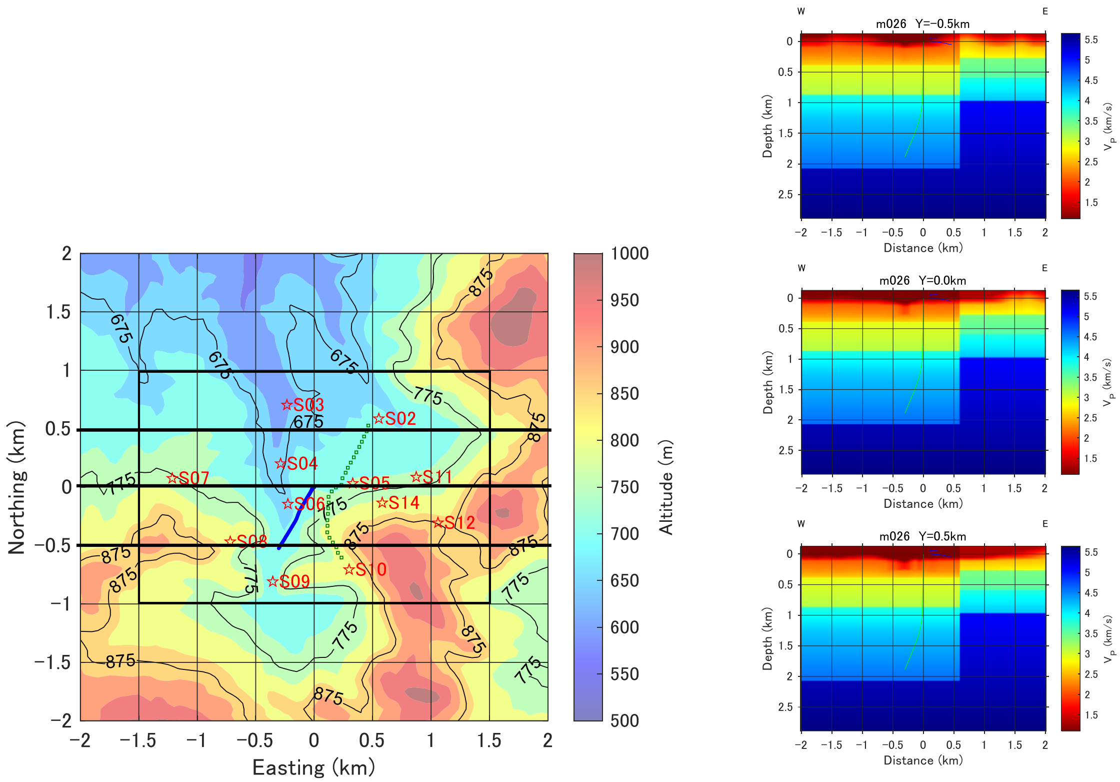

Figure 8: (Left) Surface altitude. (Right) East-West Vp depth profile considering surface layers at 0.5 km north, 0 km across the TP-20 wellhead, and -0.5 km south of the wellhead line (m026 model).

Fig. 9 shows the best location of the N-S fault after examinations. It is 600 m east from the TP-2 wellhead, compared with the initial location of 800 m east from TP-2.

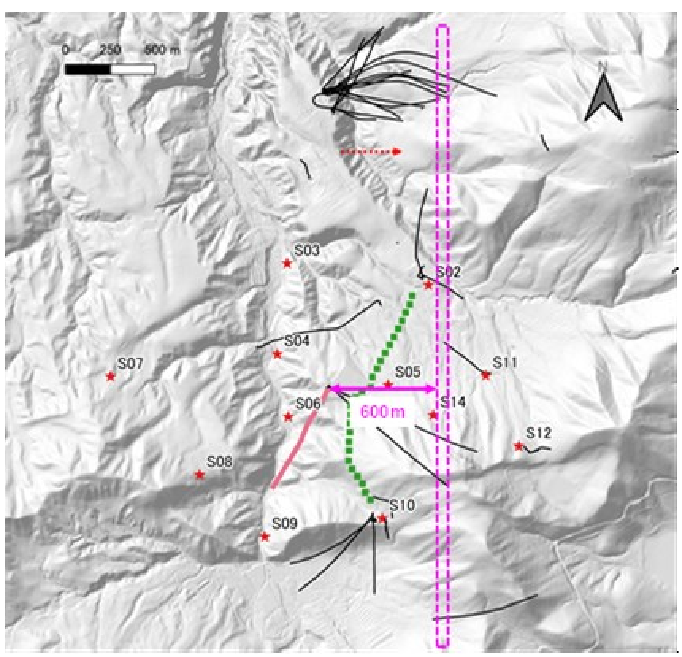

Figure 9: Inferred final location of the N-S fault (pink rectangular box) 600 m away from the TP-2 wellhead towards E (pink arrow). Lines show the trajectory of wells in the Takigami geothermal field. The red stars are seismic source locations, and the green squares are surface seismometers. The hill shade map is based on the Geospatial Information Authority of Japan.

5 REFLECTED PHASES AND MIGRATED IMAGE

Using the F-K filtering, we applied DAS waveforms to separate the down-going and up-going phases. The down-going phases correspond to direct arrivals, and the up-going phases correspond to the reflected phases. Results of filtered DAS records at S02, S08, S09, and S12 are shown in Fig. 10. The source locations of S01, S08, S09 and S12 are shown in Fig. 1. Numerous reflectors can be identified in the up-going panels. It is also reflected in P arrivals and down-going S arrivals around 1 km depth. This means there is a significant physical condition change in formation at the depth, and the depth coincides with the top sealing layer.

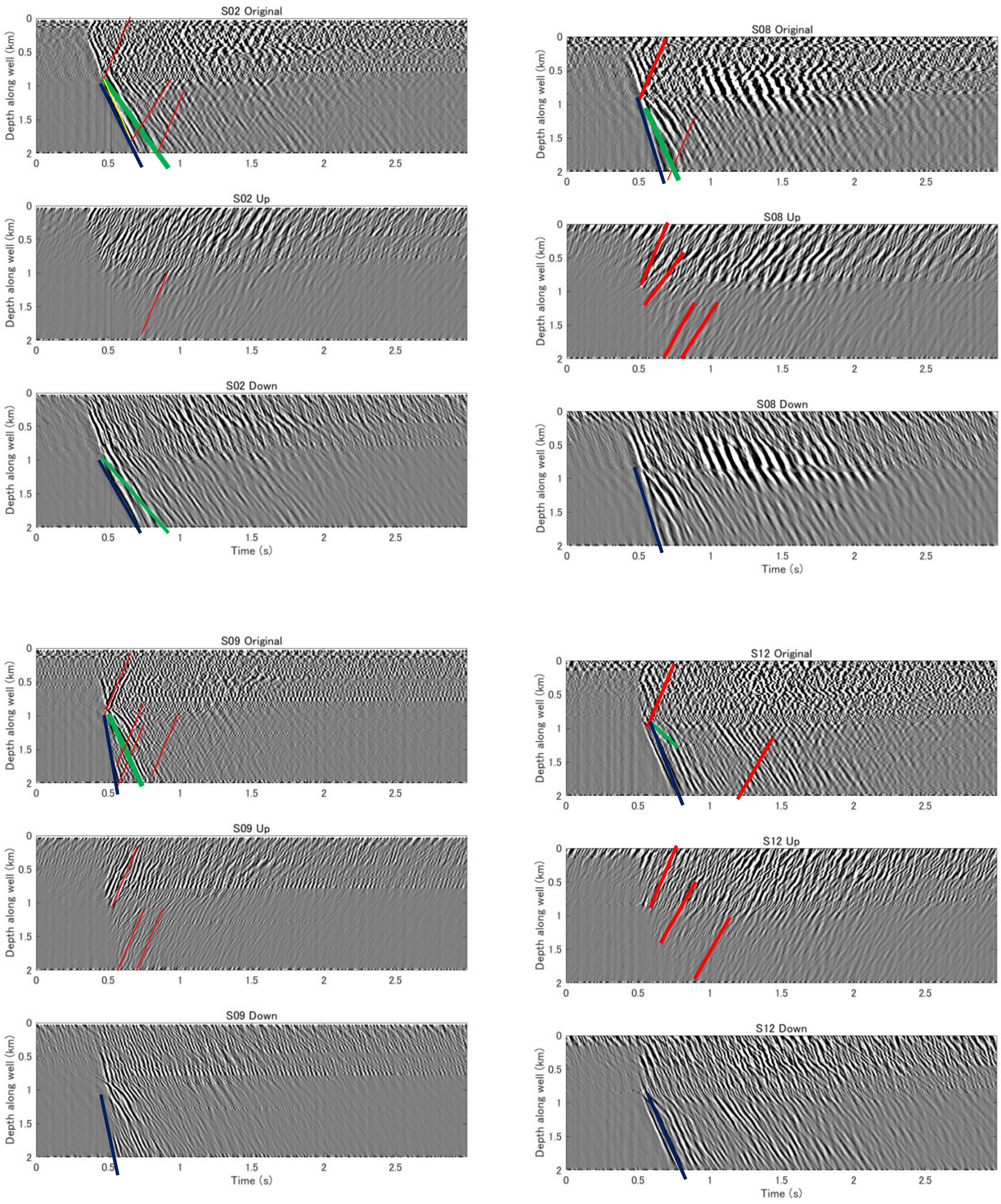

Figure 10: Four sets of observed DAS waveforms at S02(top left), S08(top right), S09(bottom left), and S12(bottom right). Blue lines: P first arrivals, red lines: reflected P phases; green lines: S phase.

The reflected P arrivals were migrated to obtain reflection images. The locations of migration cross-sections are shown in Fig. 11, and the 2D cross-section is shown in Figs. 12 and 13. It is identified that there are two high amplitude anomalous zones, at 1 km (see NS-2 and 3 in Fig. 12 and EW-8 in Fig. 13) and 2 to 3 km (see EW-6, 7, and 8 in Fig. 13) in depth. The three-dimensional image in Fig 14 has a better areal distribution.

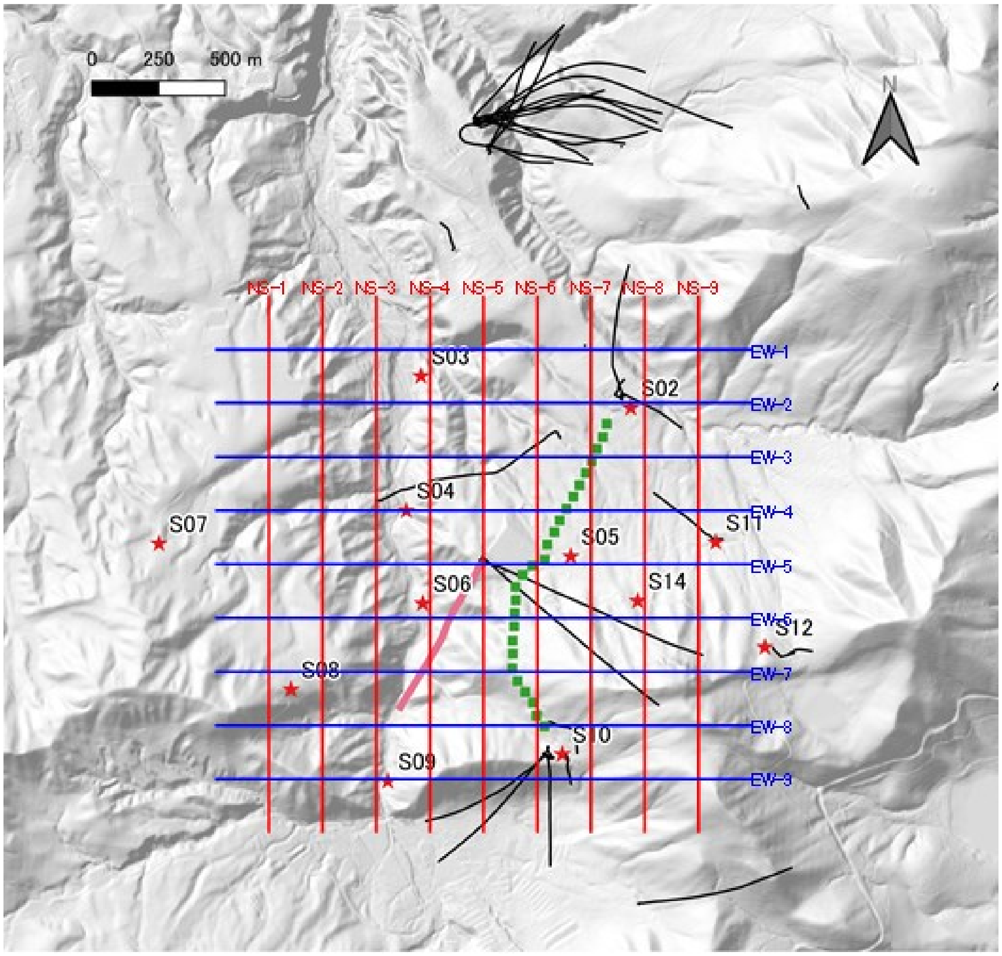

Figure 11: Locations map for North-South and East-West migration cross sections. (Pink thick line): TP-2 well profile (Red stars): Active source locations, (Green squares): Surface seismometers. Blacklines: production and injections wells of Takigami Geothermal Power Co. The hill shade map is based on the Geospatial Information Authority of Japan.

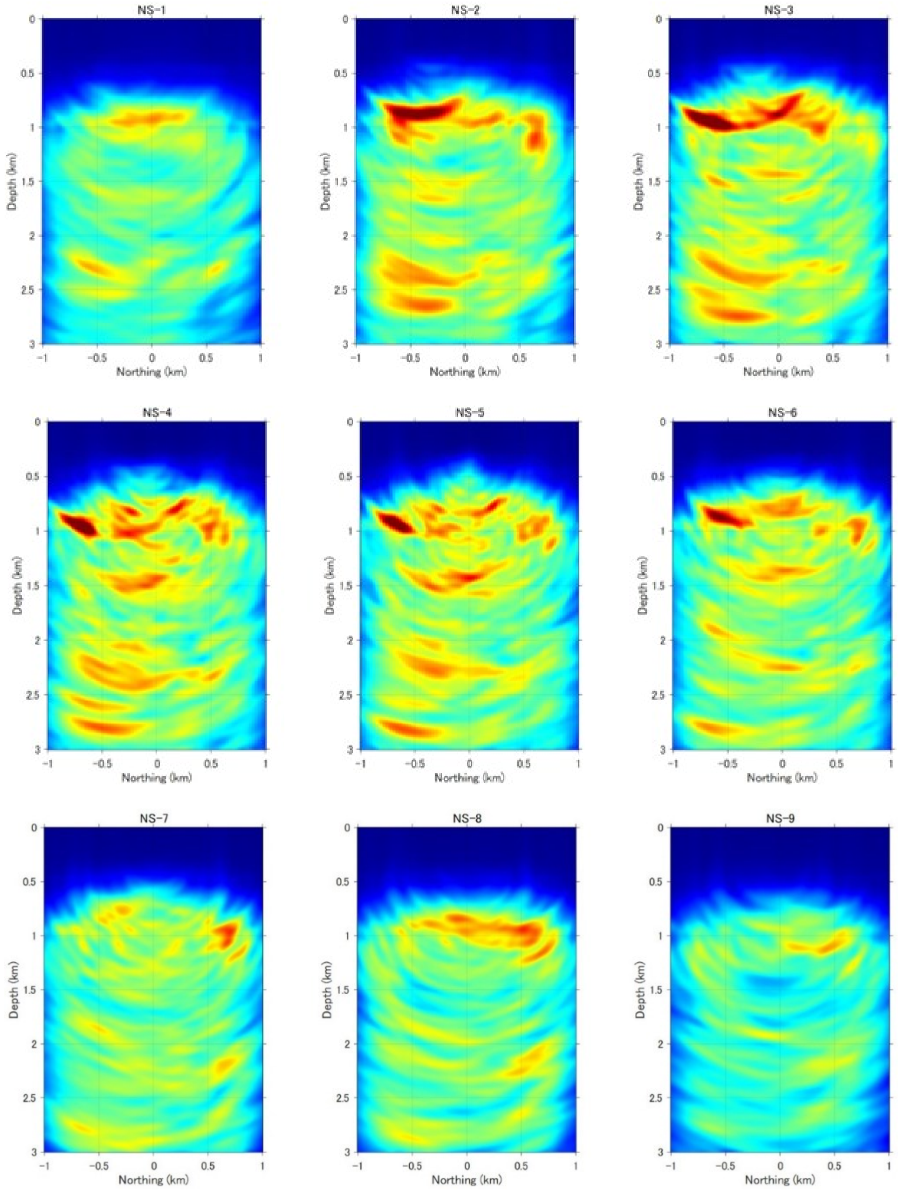

Figure 12: North-South cross sections of the migration result. The color shows the intensity level of migration from blue (low) to red (high). The vertical axis of each diagram is depth in km and the horizontal axis is distance in km.

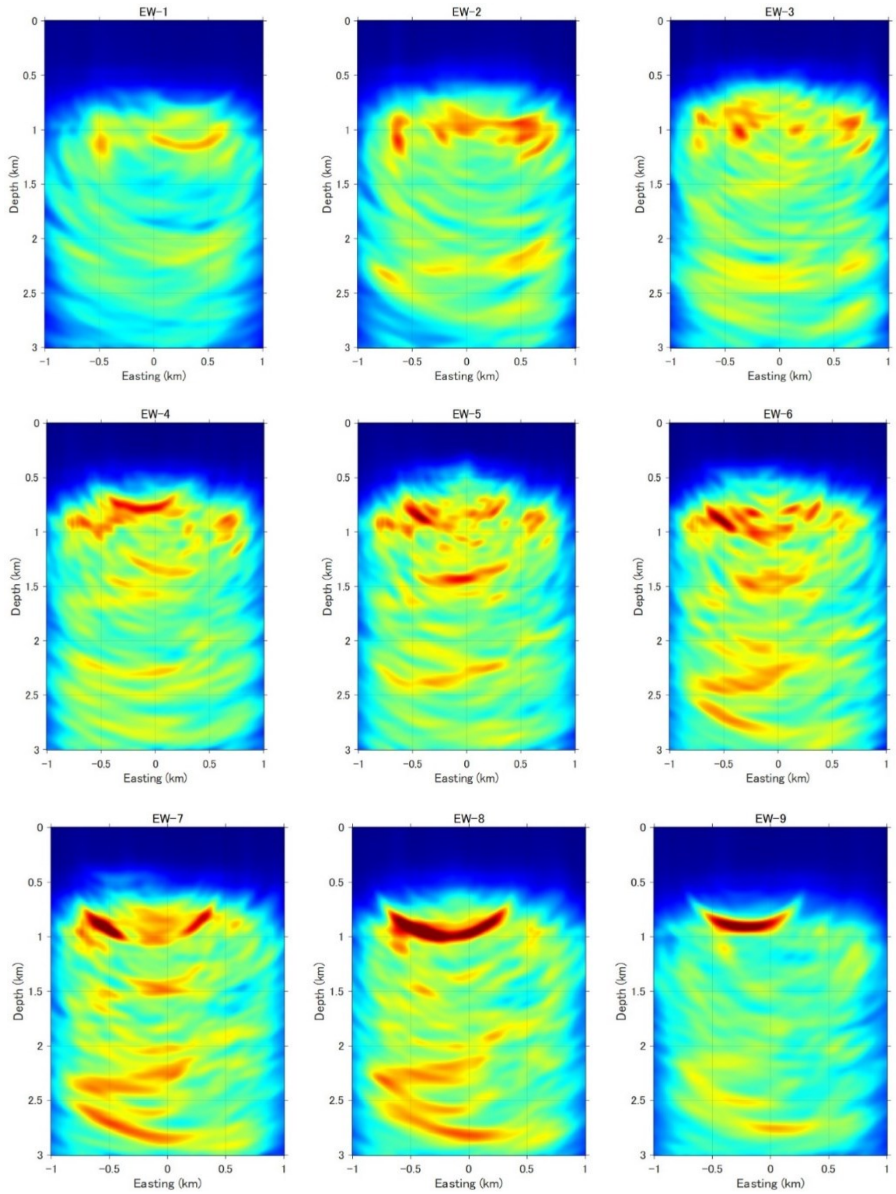

Figure 13: East-West cross sections of the migration results. The vertical axis of each diagram is depth in km and the horizontal axis is distance in km.

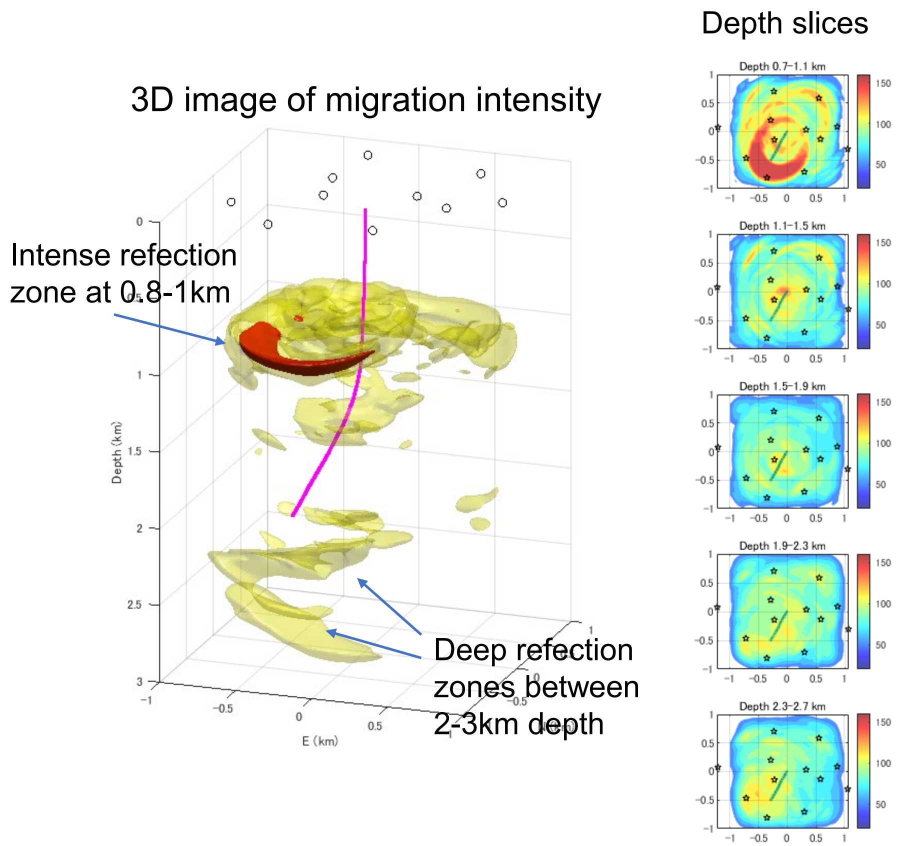

Figure 14: (Left) The three-dimensional image P reflections. The pink line shows the TP-2 trajectory. (Right) depth slices. The green lines are the TP-2 trajectory. Green stars are seismic source locations. The most intense reflection is at around 1 km depth. The 2-3 km reflections exist southwest of the TP-2 bottom hole location. Colors show migration amplitude intensity higher (red) to lower (yellow).

6. DISCUSSION AND CONCLUSIONS

Based on the results of the DAS and DTS survey carried out in 2022 at the TP-2 geothermal well in the Takigami geothermal field, we have the following observations and conclusions. The obtained temperature profile is the same as the previous measurements by Idemitsu Kosan. This means that the DTS survey validates and reproduces the necessary information using DTS technology to deploy optic fiber cable into the well. The survey results show essential geological features of the dehydration process of smectite clay forming smectite-illite at 100 to 190°C at a depth between 800 m and 1,400 m, implying the existing sealing layer of the Takigami geothermal field.

After utilizing all the measured and calculated data derived from DAS and surface seismometer, we obtained the final Vp structure with the North-South vertical fault located 600 m east of the TP-2 wellhead. The vertical displacement across the N-S fault is approximately 1,000 m. By the migrated reflection image, two major reflection zones are identified. The shallow one exists at around 1,000 m, almost over the survey area, whereas the deeper one distributes the southwest area from the TP-2 wellhead between 2,000 m and 3,000 m. The shallower reflection zone is probably the bottom of the Ajibaru Formation and/or the boundary of the Ajibaru and Takigami Formation, and the meteoric water circulation within the Ajibaru Formation causes a flat temperature profile. The intense reflection at around 1,000 m suggests higher fluid saturation at this depth. The time-lapse gravity research indicated temporal gravity change around the TP-2 wellhead (Nishijima *et al*., 2000). They suggested higher fluid saturation by migration data at this depth may be the reason for gravity change. The deeper one may be a new geothermal reservoir.

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