INTEGRATED ANALYSIS USING 3D SEISMIC SURVEY IN THE YAMAGAWA GEOTHERMAL FIELD, SOUTHWESTERN JAPAN

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ABSTRACT

Most of the geothermal reservoirs in Japan are composed of steeply dipping faults or fracture zones. Gravity survey is commonly conducted to identify the reservoir structures. However, the resolution of the gravity survey is much broader than the size of faults or fracture zones and we cannot locate the fault/fracture zones by only the gravity survey. To resolve this problem, we focused our attention on the 3D seismic method, which reveals the detailed reservoir structure with higher spatial resolution, and applied it to geothermal reservoir exploration in order to verify the efficacy on that and obtain experimental solutions. The 3D reflection seismic survey and the refraction survey were conducted in Yamagawa geothermal field in Japan.

In this study, we addressed a variety of advanced analyses. Full waveform inversion (FWI) depicted a complicated velocity structure of the volcanic region and Ant-tracking enhanced planar structures of indications from the coherence analysis. Geophysical models from seismic, magnetotelluric and gravity surveys, as well as well information, were integrated with geostatistical techniques, joint/simultaneous inversion and multi-attribute analysis. As a result from the integration flow, we built 3D lithofacies and temperature models which would be useful for geothermal exploration. We also found that interpolation processing is effective and useful to compensate the lack of data, which encouraged us to conduct seismic surveys in mountainous areas where limited number of survey lines and seismic data are available.

1. INTRODUCTION

In most of the early stages of geothermal exploration, gravity and electro-magnetic (EM) surveys are commonly conducted as a surface geophysical investigation. One of the strong demands on the geothermal exploration is to delineate geothermal reservoir structures with high resolution in order to reduce subsurface uncertainties in geothermal development. It is considered in general that the seismic survey provides subsurface information with high spatial resolution, as compared with the other surface geophysical surveys. In addition to this, it adds different physical aspects, such as elastic behaviors, from these surveys, which is very helpful in understanding geological structures.

A couple of decades ago, there were some attempts to apply seismic survey method to geothermal exploration (e.g. Horikoshi et al., 1996). However, those efforts could not accomplish expanding the use of this method in the geothermal development field. It is thought to be the cause of difficulty of acquiring high-quality data in precipitous mountain regions with a limited number of survey equipment and inadequate computational power of the time for advanced data processing. On the other hand, seismic survey technology has been astoundingly improved in oil and gas exploration field by the rapid expansion of computational power during the last decade. The high performance of the computer allows to deal with an enormous quantity of seismic data and applies advanced processing algorithms with realistic man-hour. This progress has been steadily improving images of subsurface structure.

From mainly these reasons, we focused our attention on the seismic technology and launched a technology development project aiming to apply the seismic method to geothermal reservoir imaging. In the project, both 3D seismic reflection data and refraction data were acquired in Yamagawa geothermal field of southwest Japan in 2015. The processing, a brief analysis, and interpretation were conducted (Fukuda et al., 2016). Then, we addressed a wide range of advanced analyses to the data in 2016.

In this paper, first, we introduce the Yamagawa geothermal field and a brief summary of the acquisition and processing of the survey. Analyses using only the seismic data, and integrated analyses using other geophysical and well data are main topics of this paper. Finally, we conclude with benefits of using the seismic method, as well as some discussions.

2. YAMAGAWA GEOTHREMAL FILED

We chose Yamagawa geothermal field in Kagoshima prefecture as a verification test field (Fig. 1). The field is located on a relatively flat terrain as compared with other geothermal fields so that it is relatively easy to design a 3D seismic survey and deploy measurement instruments.

Yamagawa power plant started the operation in 1995 at the center of the Yamagawa geothermal field. Kyushu Electric Power Co., Inc. operates a single flash system with an install capacity of 25,960 kW. Two-phase geothermal fluid is produced by five active production wells (1,800 ~ 2,105m depth) and reinjected by ten wells (990 ~ 2,505m depth) (Thermal and Nuclear Power Engineering Society, 2016)

In this area, gravity survey, magnetotelluric (MT) survey and magnetic survey have been conducted as well (NEDO, 2001, NEDO, 1997, Nakatsuka, 2001). Moreover, many well data are available around Yamagawa power station to use for the integrated analyses and/or the validation of analyzed results.

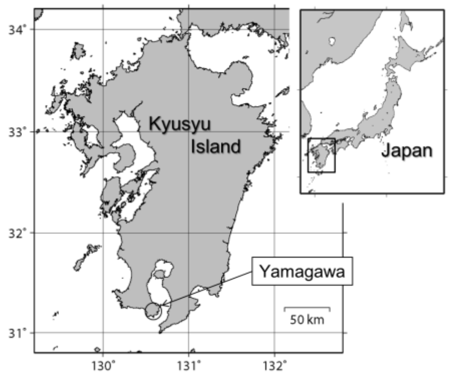

Figure 1: Location of the Yamagawa Geothermal Field (after Fukuda et al. 2016).

Yamagawa geothermal field is located on western side of the Ata caldera currently submerged in the Kagoshima Bay (Matumoto, 1943). There have been several small eruptions until historic period. The heat source of these volcanic activities is believed to exist in the deep part of the Ata caldera, and several magma ascents have generated lava dome along tectonic lines (e.g. Takeyama-Tsujinodake tectonic line (TTL)) through the various paths.

It is considered that an intrusive dacite created the productive fracture reservoir zone (Fig. 2). The dacite also functions as a local heat source of the Yamagawa geothermal system. Okada et al (2000) pointed out the high reservoir temperature over 350 °C and the high salinity production fluid as characteristics of Yamagawa geothermal fluid.

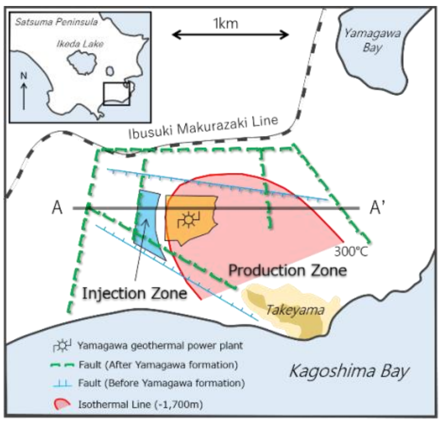

Figure 2: Composite map around Yamagawa geothermal power plant (after Sakuma, 1999).

3. FIELD SURVEY AND PROCESSING

A high density 3D seismic reflection and refraction data were acquired in Yamagawa geothermal field in 2015 (Fig. 3). The survey area was 36 km^2 (imaging area was 12 km^2), the number of source and receiver were 3,262 and 4,989, respectively. Four vibrator trucks were used as seismic source. Stand-alone measurement played an important role especially in residential areas in this acquisition.

As for data processing of the reflection data in 2015, careful noise suppression combining several types of the algorithm, interpolation filling the lack of data and post-stack time migration were applied. Refraction velocity tomography analysis was also conducted in parallel with the reflection data processing. These data acquisition and processing are described in detail by Fukuda et al. (2016).

In our study, pre-stack time migration (PSTM) was applied instead of post-stack time migration for the following advanced analyses. In general, pre-stack migration provides more appropriate imaging results than post-stack migration. By adopting PSTM, the quality of the seismic image was actually improved in our study.

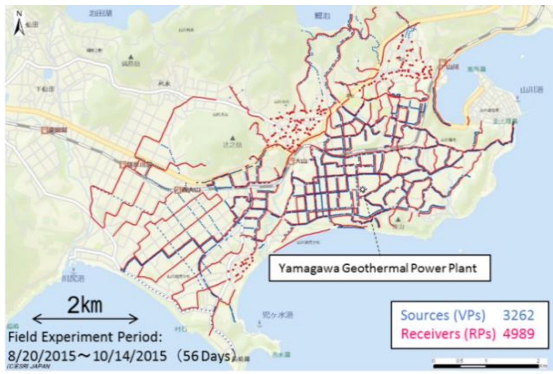

Figure 3: Survey line deployment of Yamagawa seismic survey project (after Fukuda et al. 2016).

4. ANALYSIS AND DISCUSSION

A workflow of this study including the integrated analysis is summarized as shown in Fig. 4. Outputs of each section of the workflow contribute to building a geothermal system model which is essential to consider drilling targets and/or manage a geothermal reservoir. Then, we will examine each section respectively next.

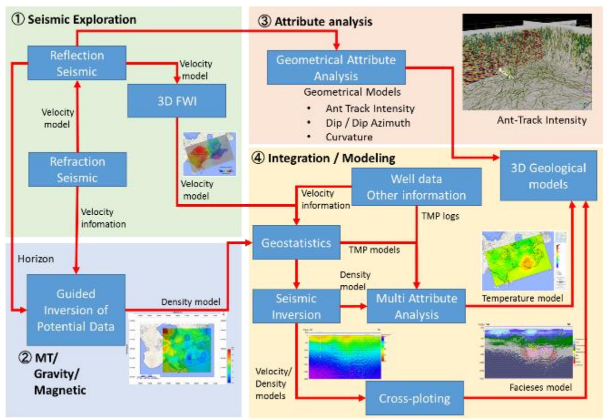

Figure 4: 3D geological model building workflow.

4.1 Full Waveform Inversion (FWI)

Seismic velocity is a different type of physical property from the density and resistivity investigated by gravity and EM surveys and useful to delineate geological structures. In the brief analyses in 2015, we conducted the tomographic velocity analysis using the refraction data (Fukuda et al. 2016), then we tried an advanced velocity model building in our study. Full waveform inversion (FWI) is an inversion method to provide a velocity structure with higher resolution than that of the refraction velocity tomography by using not only first breaks but also following waveforms. It is often used recently in the oil/gas development field.

FWI result shows consistent velocity profile with sonic logs up to about the depth of 600 ~ 800 m (Fig. 5). The fitting to the sonic logs is improved as compared with that of the refraction velocity tomography. Fig. 6 shows map view of the velocity structure at the depth of 800m. The area around Yamagawa power plant is characterized by a low-velocity zone. There is a rapid velocity change at the same location where a major fault was interpreted by the gravity survey.

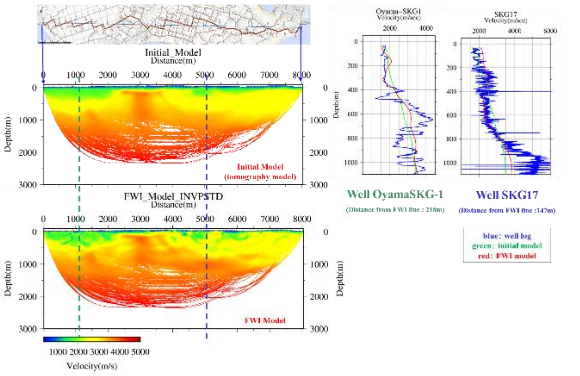

Figure 5: FWI velocity model and comparison with well logs (after Nibe et al., 2017).

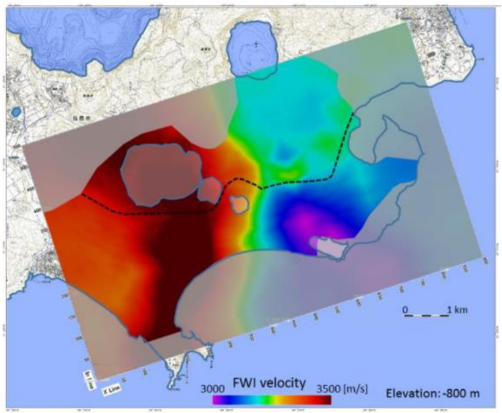

Figure 6: A slice map of FWI velocity model at 800 m depth from MSL (after Nibe et al., 2017).

4.2 Guided inversion

In many cases of geothermal exploration, gravity and EM survey results are used in determining a drilling target. It is expected that results of gravity, EM and magnetic inversion improve by putting information about the velocity structure and/or interpreted geological boundaries from seismic surveys into their initial models (Guided inversion).

Fig. 7 shows a workflow of the guided inversion. The workflow consists of two parts, the unconstrained inversion and the guided inversion. First, the acquired geophysical data were inverted without any other information in the unconstrained inversion. Then, this inverted model was used as a known information with other information in guided inversion. Gravity and magnetic data were jointly inverted (Zhdanov et al., 2012; Zhdanov, 2015). The difference between density models from the unconstrained inversion and the guided inversion is shown in Fig.8 as an example. It was found that the fitting to well logs got better by adding other information in the initial models.

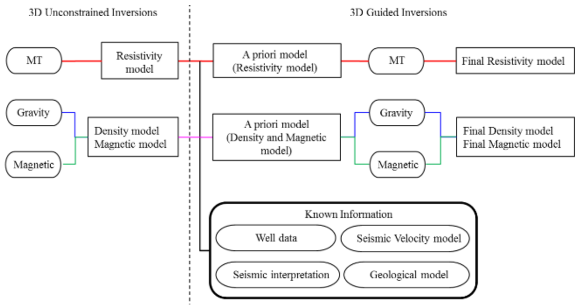

Figure 7: Workflow of three-dimensional inversion of MT, Gravity, Magnetic data using seismic data (after Miura et al., 2017).

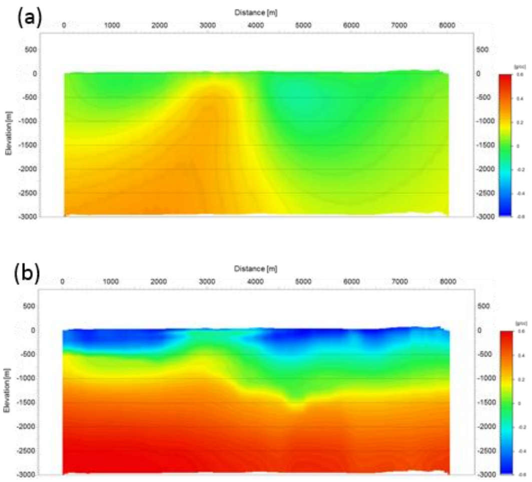

Figure 8: Vertical cross-section (E-W) of 3D density model inverted by; (a) unconstrained inversion, (b) guided inversion with an initial model built using an interpreted horizon and velocity information (after Miura et al., 2017).

4.3 Geometrical attribute analysis

Coherency analysis was conducted to extract the distribution of the discontinuities of the seismic events in 2015. Coherency attribute is used as an index for the discontinuity structure. It was shown that the distribution of the coherence attribute anomalies was consistent with areas of the dacite intrusion and injection zone (Fukuda et al. 2016). In our study, we applied Ant-tracking (Pedersen et al., 2002) to the coherence volume to enhance the planar structures of the extracted anomalies. Ant-tracking is a name of the algorithm after the nature of ants which remains pheromone on the way to their feeds and makes a track to them. Many artificial agents distributed at a regular interval are allowed to move along the extracted anomalies in the volume with emitting pheromones. In searching the anomalies, the ranges, the allowable deviations and others are controlled by some parameters which a user decides. As the result of Ant-tracking, anomalies with higher continuity in the volume are strongly marked by more pheromones. Fig. 9 shows a comparison of the coherency volume and an Ant-tracking volume. It seems that the continuity of the anomalies detected by the coherence analysis is enhanced by applying Ant-tracking.

Fig. 10 shows rose diagrams of the strikes of dipping surfaces made from Ant-tracking results at the depth of 800 ~ 2,000 m in several areas. Generally, the surfaces tend to have strikes in N-S ~ NNW-SSE direction, but these directions vary over the locations. On the other hand, taking into account the tectonic setting such as TTL, the regional stress trend has been thought to be the NW-SE direction. This discrepancy might represent that the current local stress field is perturbed by tectonic events such as the intrusion and/or volcanic activities more than we have thought.

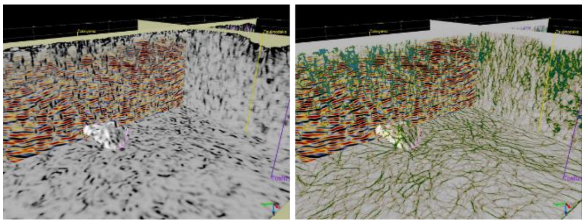

Figure 9: Planar structure enhancement; (left) Semblance, (right) Ant-track intensity.

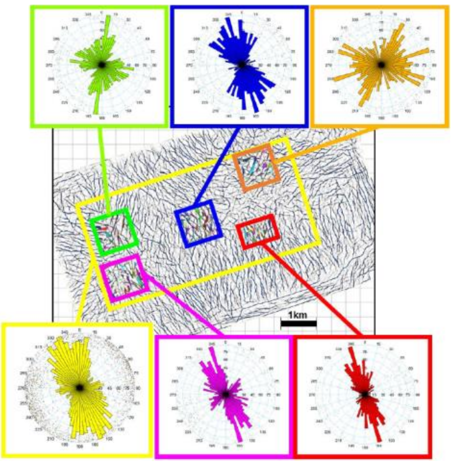

Figure 10: The rose diagrams of the strike of dipping surfaces detected in some portions of Ant-Track attribute volume.

Formation microimager (FMI) logs are available in a few wells (Okada and Yamada, 2002). The Ant-tracking result was compared with the FMI logs at the section where the FMI logs are available. It was found that a part of them corresponded to fractures recognized by the FMI logs.

4.4 Integrated analysis

By integrating multiple data such as geophysical and well data, other rock characteristics, such as physical, mechanical, and hydraulic parameters, as well as lithofacies can possibly be modeled. Cross plot analysis is one of the simple ways to classify the lithofacies. We found that density vs P-wave velocity is the best pair among many pairs for the classification in this area after a lot of combination tests using core data and well logs (Fig. 11). The density and velocity models are used to expand this lithofacies classification from the wells to the entire 3D volume. Therefore, we took two steps to obtain more appropriate geophysical models.

The first step is to apply co-kriging method which uses a geostatistics technique. The density and velocity models were calibrated by well data as shown in Figs. 12a and 12b.

Simultaneous seismic inversion is the second step. Final density and velocity models which could generate the acquired seismic volume were inverted by the simultaneous seismic inversion, where a constant Vp/Vs ratio of 1.73 based on Matsubara and Obara (2011) was used. The inversion result is shown in Fig. 12c and the final density and velocity models were used to build a lithofacies model shown in Fig. 13.

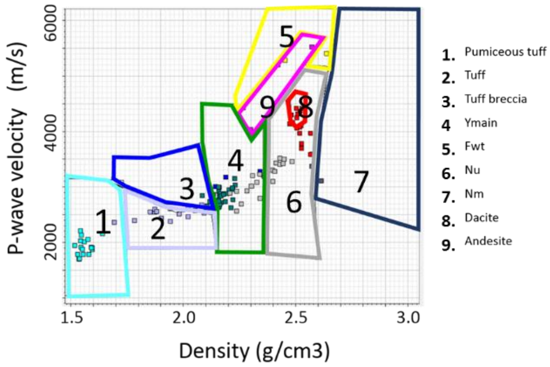

Figure 11: Facies classification example on a cross-plot of p-wave velocity and density logs (after Mochinaga et al., 2017).

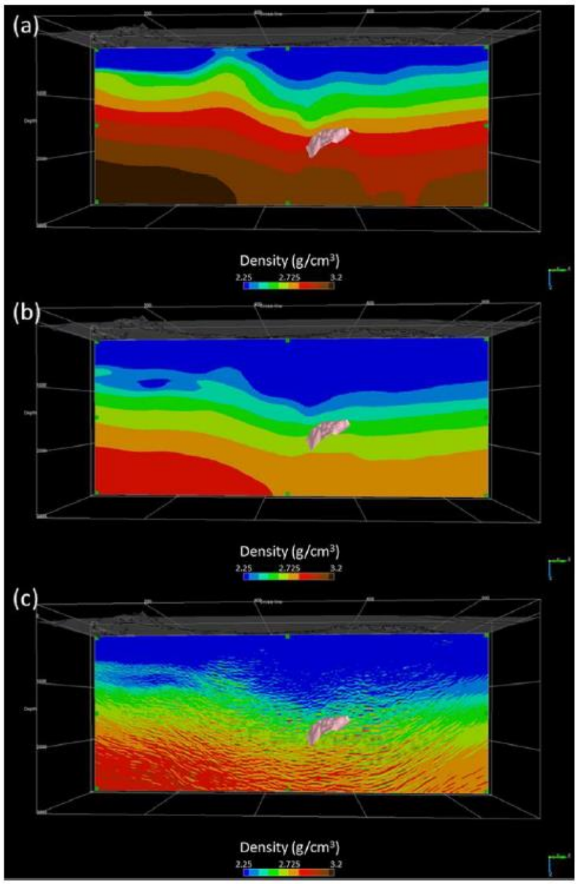

Figure 12: Comparison of the estimated density models; (a) the density jointly inverted using gravity and magnetic data, (b) the estimated density model by geostatistical integration of density logs and the model shown in (a), (c) the inverted density model by simultaneous seismic inversion using the initial model shown in (b) (after Mochinaga et al., 2017).

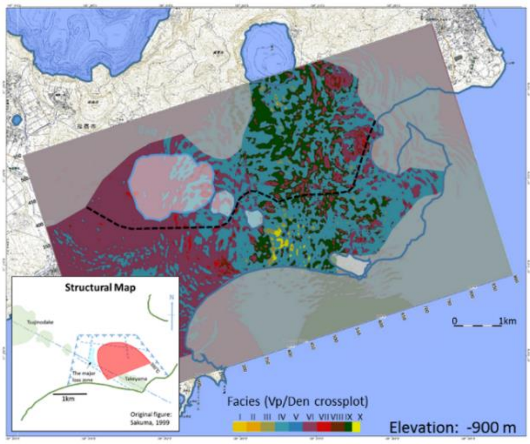

Figure 13: A slice map of the 3D facies model at 900 m depth from MSL (after Mochinaga et al., 2017). The structural map shows the characteristics in the Yamagawa geothermal field (after Sakuma, 1999).

A temperature model was built by multi attribute analysis (MAA) as shown in Fig. 14. MAA has been usually used to predict the spatial distribution of a rock property from multiple attributes by finding a relationship between the rock property and the multiple subset attributes. In this case, there were two subset attributes. One was an initial temperature model made by a co-kriging method with temperature well logs, temperature response test measurements and geothermal gradient data (Tanaka et al., 2004). The other one was the final density model used to build the lithofacies model. The density seemed to be related to the dacite intrusion regarded as the heat source and the geothermal reservoir composed by faults/fractures in this area. Fig. 15 shows the comparison between the predicted temperature and actual measured temperature at 8 wells which were used in MAA. The predicted temperature shows good fitting with the measured one under the temperature about 150 ºC. For the temperature upper than 150 ºC, there is some discrepancy between both temperatures in absolute value, but the general trend is consistent.

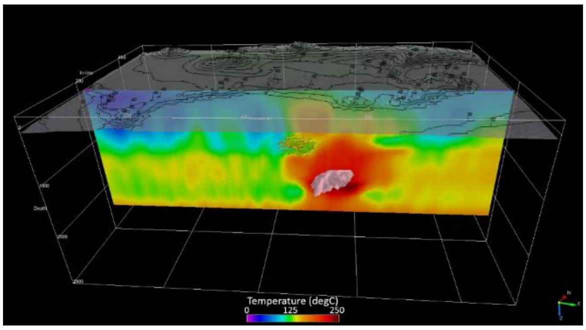

Figure 14: A 3D view of a temperature profile, a facies geobody (in yellow) and the horizon of dacite intrusion (in pink) (after Mochinaga et al., 2017).

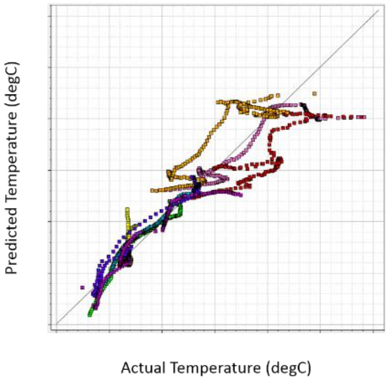

Figure 15: Predicted vs actual temperature logs of the 8 wells in MAA (after Mochinaga et al., 2017).

4.5 Decimation test

Most of the geothermal resources in Japan exist in mountain areas where limited number of survey lines are available. The restriction in survey configuration significantly affects data quality in general. On the other hand, the data acquisition and processing techniques to mitigate the issue have been developed recently. Therefore, we tested the efficacy of the interpolation processing against decreasing number of survey lines by a decimation test. Three decimated survey layouts were examined in the decimation test as shown in Fig. 16a and Fig.16b shows their corresponding fold maps in three offset ranges. It is obvious that decimating survey lines more significantly impacts number of folds in shorter offset range. This results in lack of data or low signal noise ratio in shallow parts. Fig. 17 shows stack sections for the three survey layouts with and without interpolation processing in a certain location. Indeed, upper stack sections in this figure for layout 1 and 2 lack data in shallow parts. However, it is found that these parts of lower stack sections are filled to some extent as compared with those without interpolation processing. This shows that the interpolation processing is effective to mitigate the problems due to the small number of survey lines. This encourages us to apply seismic surveys in the mountain areas.

5. CONCLUSIVE REMARKS

There has not been plenty of examples that the seismic survey is applied to geothermal exploration in Japan. In this study, we addressed a variety of advanced analyses not only using seismic data acquired in Yamagawa geothermal field in 2015 but also integrating other types of geophysical data as well as well data. Geometrical attributes generated from the seismic data were effective tools to visualize the fault/fracture distribution with high resolution which had been one of the problems that other geophysical surveys have in geothermal exploration. Moreover, the seismic method brought us new insights in delineating geological structures by adding velocity property, which was used to achieve more accurate physical models (e.g. the density, resistivity, magnetization and (indirectly) temperature model) and the lithofacies model. We summarized these works into the workflow.

Increasing experiences of adopting the seismic method will contribute to further improvement in utilizing it in geothermal exploration. This will lead the improvement of other geophysical survey techniques, too, because these are interactive through such the integrated analysis. However, evaluation techniques of the geothermal system with acquired results from these geophysical surveys should be also improved in the future.

Japan Oil, Gas and Metals National Corporation (JOGMEC) has developed the techniques to apply the seismic method which has been improved in oil and gas development field, to domestic geothermal development field. We will keep on proceeding research and development projects for geothermal exploration.

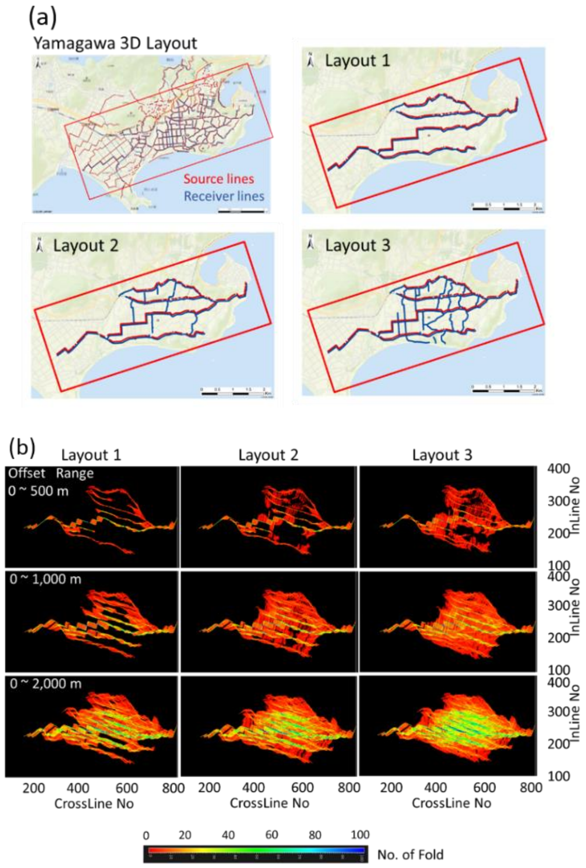

Figure 16: (a) Evaluated three pseudo-3D layouts in a decimation test, (b) their fold maps in three offset ranges.

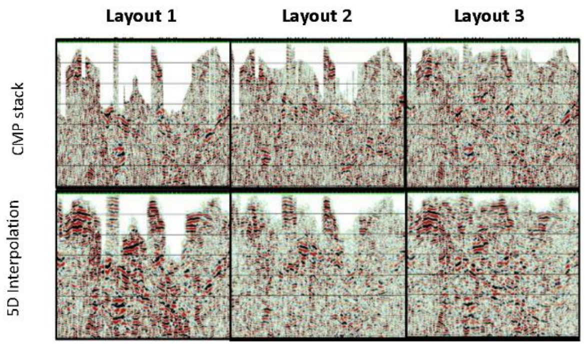

Figure 17: Comparison between stack sections for 3 layouts processed without (upper) and with interpolation processing (lower).

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