

Technical Development for Geothermal Exploration by Seismic Survey and the Second Verification Experiment

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ABSTRACT

To delineate detailed geothermal reservoir structures, we have progressed a R&D project for geothermal exploration since 2013. Gravity and electromagnetic surveys are commonly used for geothermal exploration in Japan. However, the resolution of these surveys is much broader than the size of faults or fracture zones we see from well data. Thus, there is considerable uncertainty to locate the reservoirs by these surveys. To resolve this problem, we focused attention on the seismic method which tends to have higher spatial resolution. As the first step of this project, we reprocessed a few legacy records with present data processing techniques and confirmed improvements in its data quality. Then, we acquired a 3D seismic test data in Yamagawa geothermal field. Analyses with a variety of advanced methods including 3D visualization of discontinuous structures indicating fractures, and integrated analyses with well and other geophysical data, demonstrated that the seismic survey provided detail subsurface models which help us to build a geothermal model. Meanwhile, Yamagawa field had a significant advantage that its flat geography made it easy to deploy survey instruments, which is very rare among Japanese geothermal fields. Therefore, we conducted the second verification seismic survey in Onikobe geothermal field in 2017 to confirm its efficacy even in mountainous areas where most geothermal resources are located in Japan.

In mountainous areas, the survey design is crucial because a limited number of survey lines are available. We visited and investigated the survey area several times before the survey to find as many available survey lines as possible. Four types of sources and two types of recorders were used according to surface conditions in the data acquisition. These efforts allowed us to obtain a 3D seismic volume in the deep part which included potential target zones in this field. In the data processing, static correction to compensate precipitous geography was important. Analyzed results showed consistency with existing data and added new insights in the reservoir structures.

1. INTRODUCTION

In most of the early stages of geothermal exploration in Japan, gravity and electro-magnetic (EM) surveys are commonly conducted as a surface geophysical investigation. These surveys are handy methods in terms of cost and/or surface footprint. On the other hand, the resolution of these surveys is much broader than the size of faults or fracture zones we see from well data, which results in considerable uncertainty to locate the reservoirs. Therefore, one of the strong demands on the geothermal exploration is to delineate geothermal reservoir structures with high resolution in order to reduce the subsurface uncertainties in geothermal development. To meet this demand, we launched a R&D project for geothermal reservoir exploration in 2013.

In this R&D project, we focus attention on the seismic method. 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, 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 in Japan (e.g. Horikoshi et al., 1996). However, those efforts could not accomplish expansion of the use of this method in the geothermal development field. The reason is thought to be difficulty of acquiring high-quality data in precipitous mountain regions with a limited number of survey equipment and inadequate computational power, at 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 us to deal with an enormous quantity of seismic data and apply advanced processing algorithms with reasonable computing time. This progress has been steadily improving the images of subsurface structure.

In this paper, first, we review the entire R&D project. Then, summary of the second verification seismic survey conducted in Onikobe geothermal field in 2017 is introduced. Finally, we summarize and discuss the contribution of this project to the application of the seismic method to geothermal exploration.

2. REVIEW OF CURRENT STATUS

In the first year of this project, major current challenges in the application of seismic method to the geothermal exploration were extracted by literature surveys and interviews with experts:

- Optimization of survey design
- Application of appropriate noise attenuation processing, especially static correction to compensate precipitous geography
- Reinforcement of interpretation skills of seismic data for geothermal developer
- Reduction of survey cost

We discuss the contribution of this project to these challenges in the discussion section.

In the first year, we also reprocessed several legacy records to confirm feasibility of current seismic processing technology. Fig. 1 shows an example acquired in Ogiri geothermal field more than twenty years ago. The modern advanced processing techniques highlighted fault structures. Then, we stepped forward into the first verification survey in Yamagawa geothermal field in Kagoshima prefecture.

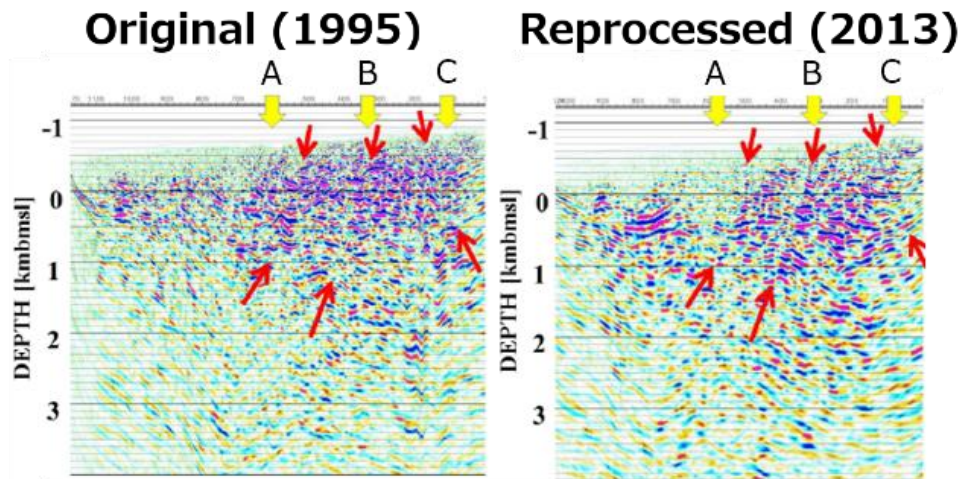


Figure 1: Comparison between original (left) and reprocessed (right) 2D seismic section in Ogiri geothermal field.

3. VERIFICATION EXPERIMENT IN YAMAGAWA GEOTHERMAL FIELD

The objective of this survey was to acquire seismic test data for consideration of measures to solve the challenges and figure out whether the seismic method is applicable to geothermal reservoir imaging. The number of case studies applying seismic method in geothermal field is not very large in Japan. Thus, as a first step, the seismic survey was conducted with dense sampling, that is, with many source and receiver points. Yamagawa geothermal field has flat geography, which makes it easy to deploy survey instruments. This advantage suggested us to choose Yamagawa area as a first test field.

The detail of Yamagawa field, data acquisition, processing and brief analysis is described by Fukuda et al. (2016) and a variety of advanced analyses applied to the same data is described by Mouri et al. (2017). We briefly review the survey and results in this section.

3.1 Yamagawa Geothermal Field and Data Acquisition

Yamagawa geothermal field is located on the southern tip of Kyushu Island. Yamagawa geothermal power plant has an installed capacity of 26 MW with single flash system. A lot of hot springs exist around the geothermal field. Sakuma (1999) describes the general concept of the geothermal model for this field (Fig. 2). According to literature describing geological structure in this region, it is considered that an intrusive dacite created the productive fracture reservoir zone. Moreover, the dacite also functions as a local heat source of the Yamagawa geothermal system.

Fig. 3 shows the survey lines of high density 3D seismic survey. The number of source and receiver points were 3,262 and 4,989, respectively. Based on surface conditions, not only wire telemetry recording systems and large-size (19 ton/vehicle) seismic vibrators which are often used, but a stand-alone measurement system and middle-size (7.9 ton/vehicle) vibrators were also used in the acquisition. It took about two months to acquire reflection and refraction data.

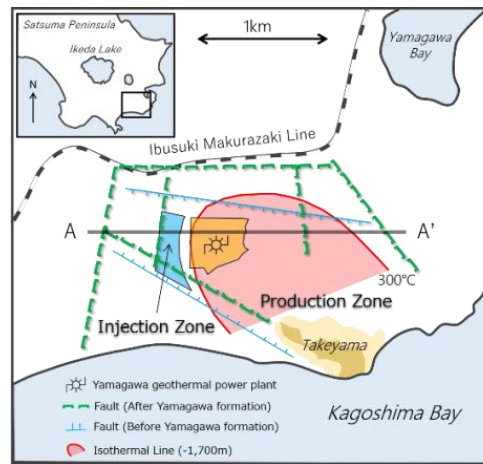


Figure 2: Composite map around Yamagawa geothermal power plant (after Sakuma, 1999).

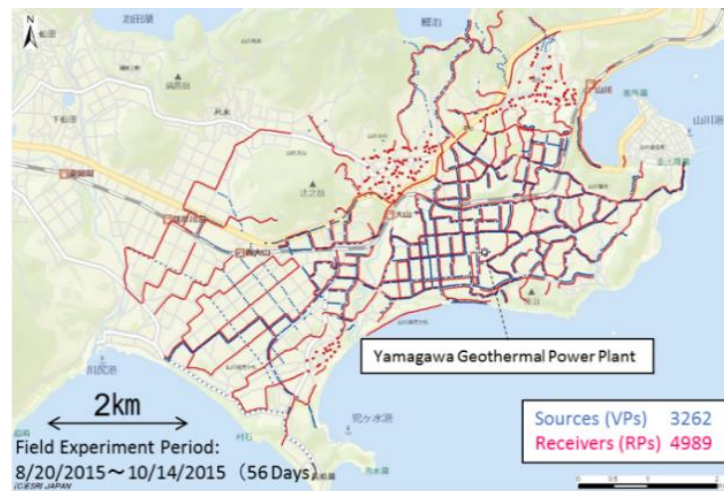


Figure 3: Survey line deployment of Yamagawa seismic survey project (after Fukuda et al., 2016).

3.2 Geometric Attribute Analysis and Integrated Analysis

In 2016, a variety of advanced analyses were applied to the Yamagawa seismic data. We summarized these analyses into a workflow to build geological models which are fruitful for building a geothermal model (Fig. 4). Among these analyses, geometrical attribute analysis and integrated analysis with different types of geophysical data and well data would be worthy to be referred to here.

We tried to visualize fracture distribution by geometrical attributes which evaluate geometry on seismic events. One of the geometrical attributes, coherence attribute is used to extract the discontinuities of the seismic events. Fukuda et al. (2016) showed that the distribution of the coherence attribute anomalies was consistent with the location of the dacite intrusion, where productive fractures are expected to be generated, and the injection zone. Furthermore, Ant-tracking (Pedersen et al., 2002) enhanced the planar structures of the anomalies detected by coherence analysis (Fig. 5). Part of the Ant-tracking results showed correspondence with feed points and fractures recognized by FMI logs (Mouri et al., 2017).

Integrating multiple data such as geophysical and well data can not only generate different types of rock characteristics, such as physical, mechanical, hydraulic parameters and lithofacies, but also improve the accuracy of geophysical models. Besides the seismic data, gravity, EM, magnetic data and well data were available in this region. Geophysical models derived from these data were improved by the co-gridding method with well data, guided inversion using the seismic survey results as a priori information and simultaneous inversion with the seismic data. 3D lithofacies and temperature models were generated by cross-plot analysis and multi attribute analysis (Fig. 6).

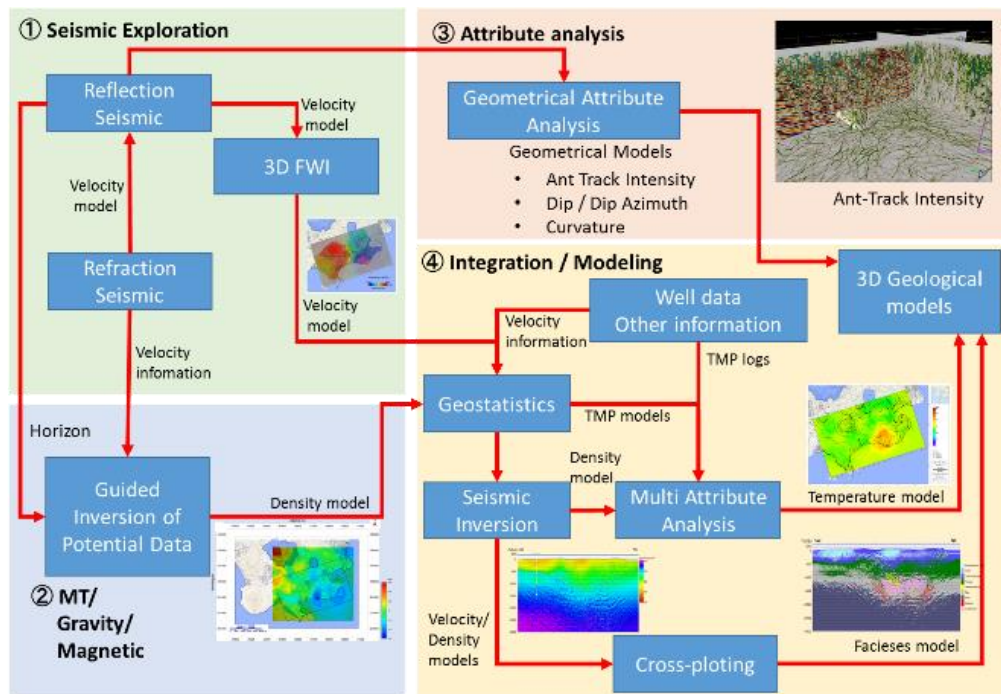


Figure 4: 3D geological model building workflow (after Aoki et al., 2017).

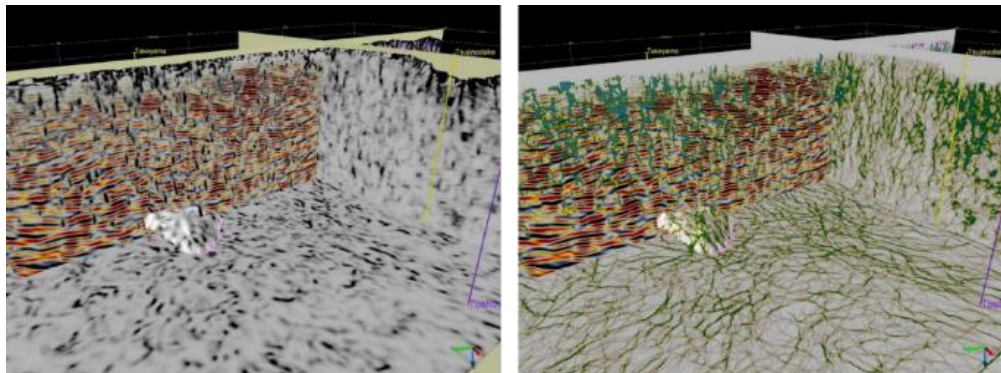


Figure 5: Planar structure enhancement: (left) Semblance, (right) Ant-tracking intensity (after Aoki et al., 2017).

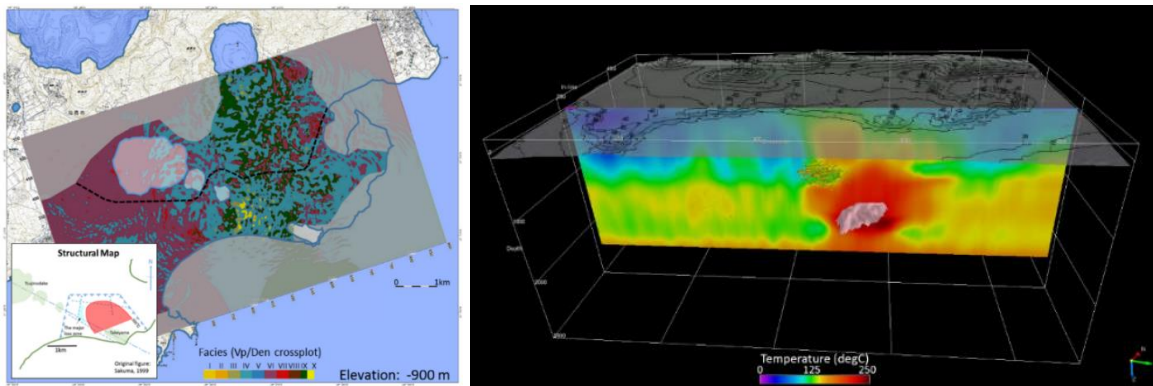


Figure 6: (Left) A slice map of the 3D facies model at 900 m depth from MSL (after Mochinaga et al., 2017). The structural map in lower left corner shows the characteristics in the Yamagawa geothermal field (after Sakuma, 1999). (Right) A 3D view of a temperature profile, a facies geobody (in yellow) and the horizon of dacite intrusion (in pink) (after Mochinaga et al., 2017).

4. THE SECOND VERIFICATION TEST IN ONIKOBE GEOTHERMAL FIELD

The verification test in Yamagawa area demonstrated the efficacy of the seismic method in geothermal fields. Its flat geometry allowed us to relatively freely deploy seismic survey instruments. However, this condition is very rare among geothermal fields in Japan, because most of them are located in mountainous areas where a limited number of survey lines is available. Thus, we decided to conduct the second validation test in Onikobe geothermal field to confirm the efficacy of seismic method even in those mountainous areas.

4.1 Onikobe Geothermal Field

Onikobe geothermal field is located in mountainous region of Miyagi prefecture in North-East Japan. Almost all of the field is within the Kurikoma Quasi-National Park. Part of the field shows precipitous geography. Onikobe geothermal power plant, a few geothermal manifestations and hot springs exist around the geothermal field and show the potential of the geothermal resource.

This field is inside the Onikobe caldera. A lot of eruptions after caldera formation indicates continuing volcanic activity in this region. At the western fringe of the caldera, a major tectonic line called Onikobe-Yuzawa mylonite zone exists. It is estimated that the tectonic line strikes in the NNW-SSE direction and its movement was active in the pre-Tertiary period. However, it is pointed out that the tectonic line might also affect subsequent geological structure (NEDO, 1985). Geological literature state that horst and graben structures are formed and the NNW-SSE striking faults are dominant in the field.

A basic geothermal model in this field was built through past geological, geophysical, geochemical surveys and well drilling. Geothermal reservoir distribution is expected to be mainly controlled by faults. Faults related to caldera formation would work as recharge zones and faults related to the horst structures work as discharge zones. Katayama steaming ground, where Onikobe geothermal power plant is located, is estimated to be near the main discharge zone.

4.2 Survey Design

In mountainous areas, the survey design is crucial because a limited number of roads that can be used for seismic survey lines are available. We visited and investigated the survey area several times before the survey to find as many available survey lines as possible. However, orthogonal geometry of seismic lines which is required for 3D seismic survey was not realistic. Therefore, we introduced a quasi-3D survey geometry.

Fig. 7 explains survey geometry for 3D, quasi-3D and 2D survey. The quasi-3D method deploys multiple 2D survey lines which are basically parallel. Each shot should be simultaneously recorded with all 2D receiver lines. This survey geometry allows us to obtain seismic sections between 2D lines. Strangely, a quasi-3D survey with severely crooked lines allowed us to obtain a continuous 3D seismic volume in the deep part, though large data gaps still exist in the shallow part between 2D lines.

The quasi-3D survey geometry of Onikobe geothermal field is shown in Fig. 8. The distance of an area of interest in North-South, East-West and vertical depth direction was about 2.5km, 5km and 2km, respectively. Taking into account the margin for data processing of reflection data and velocity tomography of refraction data, survey instruments were deployed outside the area of interest, which made the distance of the survey area in North-South and East-West directions was about 4km and 8km, respectively.

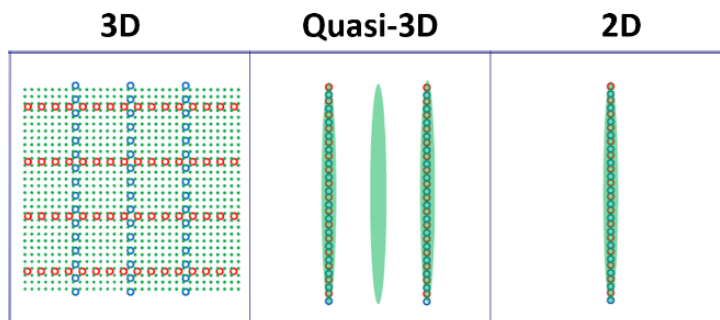


Figure 7: Comparison of survey geometry. Red and blue circles are source and receiver points, respectively. Green dots represent reflection points.

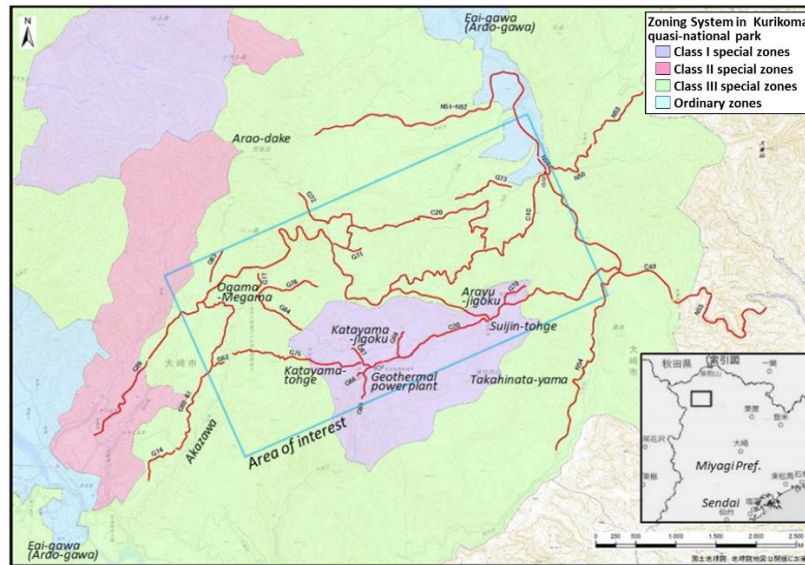


Figure 8: Quasi-3D survey geometry of Onikobe geothermal field. Seismic lines and the area of interest is shown on the map of Kurikoma Quasi-national Park.

4.3 Data Acquisition

Depending on surface conditions, four types of sources and two types of recorders were used in the data acquisition.

The large-size and middle-size vibrators were used on wide and narrow roads, respectively. We used explosive sources with 2.5kg charge in forest areas where the vibrator cannot pass through. In particular, those with 300g charge were used in mountain climbing trails and steep geography area. This small charge explosive source played a significant role in filling the data gaps in the shallow part (Fig. 9). Wired recorders were mainly used for pavements and stand-alone receivers were deployed in forest areas with precipitous geography.

It took about 1 month to record the entire seismic dataset. Furthermore, two-month-drilling for 92 explosion wells was needed before the acquisition.

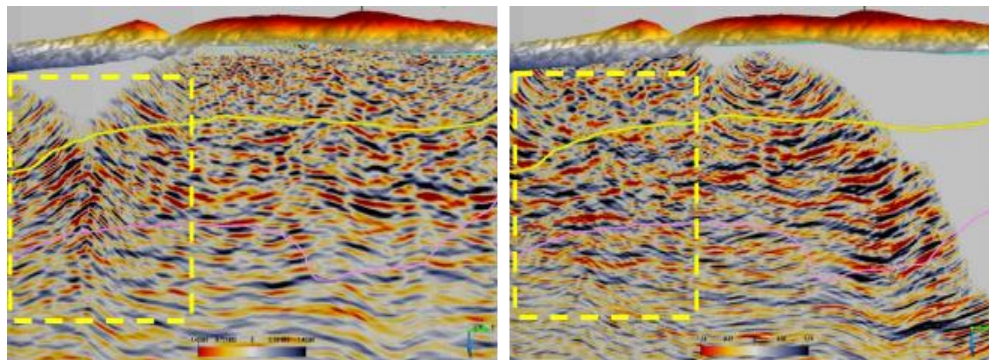


Figure 9: Comparison between seismic sections: (left) vibrator, (right) explosive source with 300g charge.

4.4 Data Processing

The acquired seismic data was processed by the data processing flow shown in Fig. 10. Some particular procedures were needed to deal with sparse irregular survey lines and precipitous geography.

Difference among source signatures were compensated in the early step. As mentioned above, four types of sources, which are broadly categorized into the vibrators and the explosive sources, were used in the acquisition. Since the source signature of vibrators and explosive sources is different, we made a transform operator to compensate for the difference. In this case, the records by the explosive sources were transformed by the operator.

Static corrections were carefully applied. In mountainous regions, large variations in elevation, and rapid spatial velocity changes of near-surface, cause degradation of imaging quality of seismic surveys. Static correction mitigates these negative impacts. An optimal elevation model was used to compensate for the elevation variation, after several models from different methods were carefully examined. For the correction of the weathering near-surface layer, the spatial velocity variation was estimated and compensated.

Spatially irregular sampling can generate noise through the migration process. According to synthesized results by numerical simulation, migration noise was found at locations where the data density was low. Therefore, we designed a mask based on the data density to cover the zones affected by the migration noise, so as to avoid misleading in the following data analysis and interpretation procedures.

Pseudo-2D line, an arbitral line along each receiver line which can be extracted with a 3D visualization tool, was helpful for quality control (QC) of the data processing. Usually some vertical planes in in-line and cross-line direction are selected to check the improvements in each processing step. However, these planes might be useless when there are a lot of data gaps and large quality variations. Pseudo-2D lines had relatively regular quality and showed continuous images of shallow part, thus they were suitable for grasping geological structures and helpful for QC.

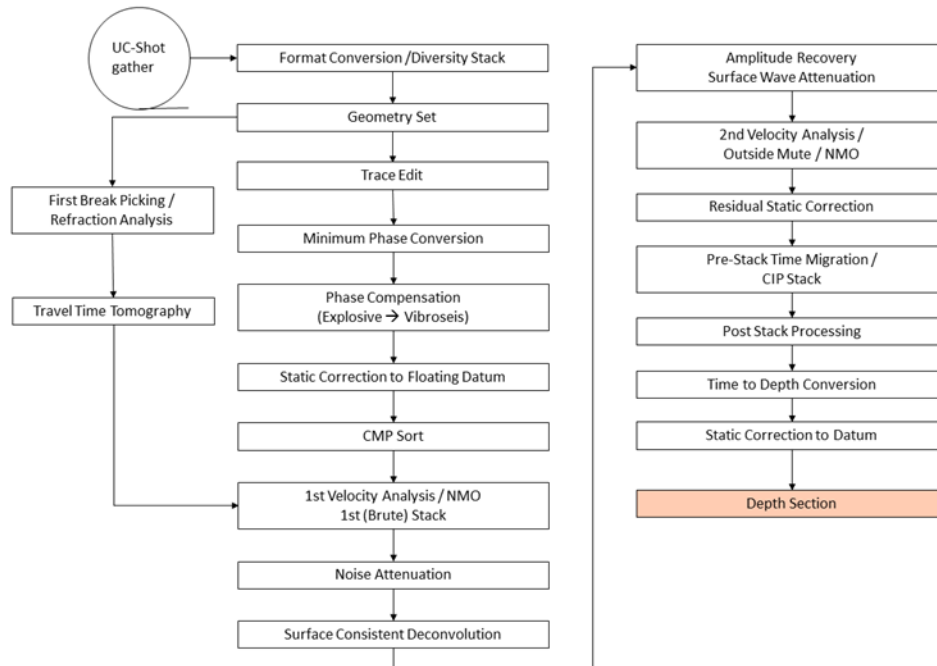


Figure 10: Processing flow chart.

4.5 Velocity Tomography

The refraction data was analyzed with 3D velocity tomography. In general, refraction tomography is affected by an initial model. On the other hand, initial model randomization method (Shiraishi et al., 2010) which was adopted in this analysis uses a stochastic approach to deal with the initial model dependence. A group of randomized initial models is analyzed. Fig. 11 illustrates the randomized initial models. Then, an average velocity model and a standard deviation model over the analyzed models are provided. In this study, the method was extended in 3D, though it had been mainly used in 2D. Moreover, a median velocity model was adopted instead of the average model because the average model is prone to be influenced by outliers.

Fig. 12 shows iso-velocity surface for 3,500 m/s derived from the result of the tomography analysis. Upwarp structures were found near the two steaming grounds, Ogama-Megama fumarole and Arayu-steaming ground. On the other hand, there was a low velocity anomaly at Katayama steaming ground. This may be caused by hydrothermal alteration in the subsurface.

The velocity structure derived from the refraction tomography is independent of the reflection survey. Hence, it gives us objective information for the interpretation of the reflection data. Utilizing both results can serve more reliable interpretation. Fig. 13 shows pseudo-2D sections of refraction tomography result superimposed on reflection data.

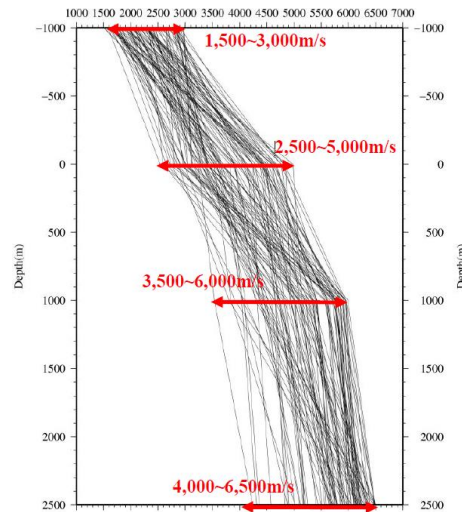


Figure 11: Velocity profile of randomized initial models.

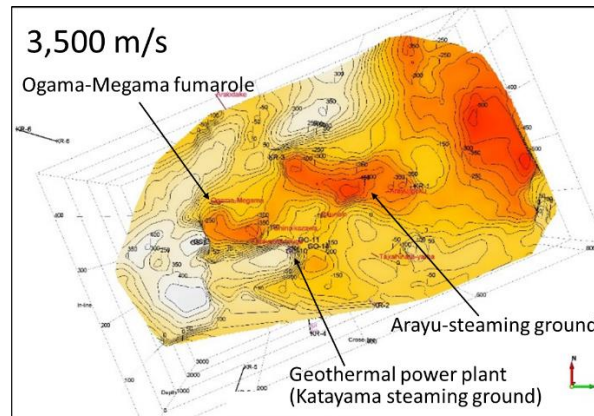


Figure 12: Iso-velocity surface of 3,500m/s.

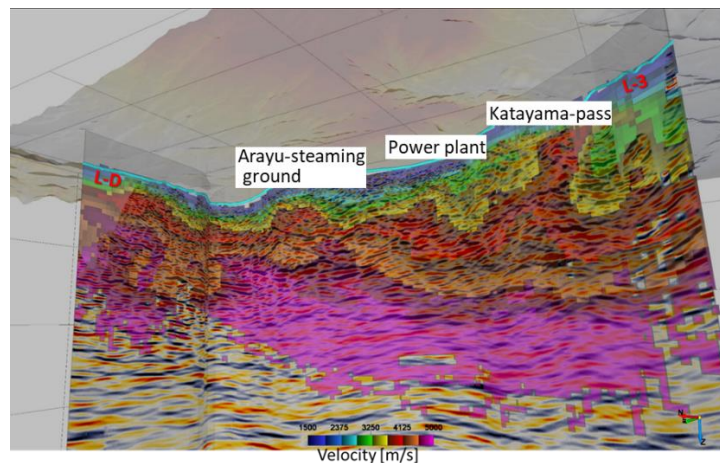


Figure 13: Pseudo-2D sections showing refraction tomography velocity superimposed on reflection data.

4.6 Geometrical Attribute Analysis

We applied geometrical attribute analysis to the reflection data. In this analysis, we used Thinned Fault Likelihood (TFL) (Hale, 2013) instead of Ant-tracking which was used in the analyses of Yamagawa’s data, as well as other attributes such as dip, azimuth and curvature. TFL is also one of the attributes to extract planar structures of discontinuity in the reflection data and provides evaluation of the strike, the dip and the likelihood which is represented by the value ranging from 1 to 0.

Although geometrical attributes evaluate geometry of seismic events, they are also sensitive to noise. Thus, preconditioning was conducted before the analyses. The median filter was applied to attenuate the noise. Then, we applied a filter to enhance the edge of seismic events, which leads to provide reliable results in geometrical attribute analyses. Fig. 14 shows a general flow of TFL analysis. We found that the amplitude around the edges of seismic events increased and they were successfully enhanced.

Fig. 15 is an example of a depth slice of TFL analysis result. Detailed distribution of discontinuities is expressed by TFL. Furthermore, we found that TFL in NW-SE and NE-SW direction are relatively dominant, which accords with general geological structure in this region. Fig. 16 is a comparison between a geothermal reservoir model based on Abe (1985) around Katayama steaming ground and TFL results superimposed on the seismic section at corresponding locations. The TFL results show good consistency with the reservoir model.

Geometrical attributes provide quantitative information such as continuity and geometry of seismic events. Hence, the results of geometrical attributes are also utilized in interpretation of reflection data. As is the case with the velocity from the refraction tomography, they are objective and help with reliable interpretation. Indeed, the processed reflection data was interpreted with referring to the results of refraction tomography, geometrical attribute analyses and past surveys. Moreover, based upon the results of this seismic survey, the geothermal model in this field was updated. A potential zone of geothermal resource was identified through consideration of the past geophysical surveys and the velocity structure newly added by this seismic survey. Then, TFL results from the reflection data provided a detail of drilling target candidates in the potential zone.

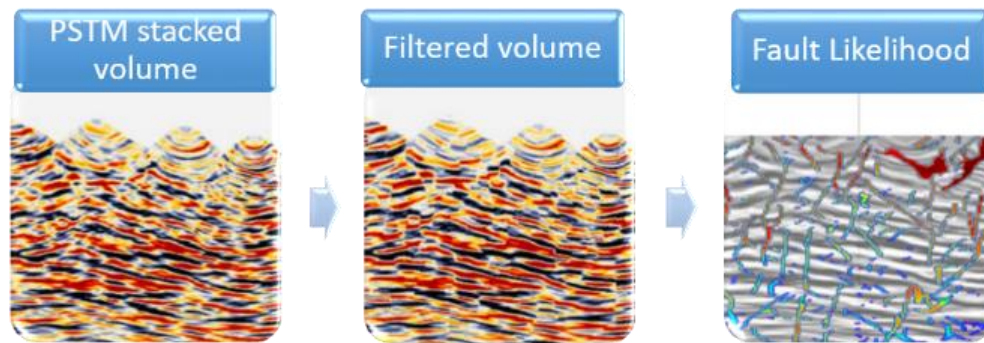


Figure 14: A flow of TFL analysis. (left) seismic section before preconditioning, (middle) seismic section after preconditioning, (right) TFL superimposed on seismic section.

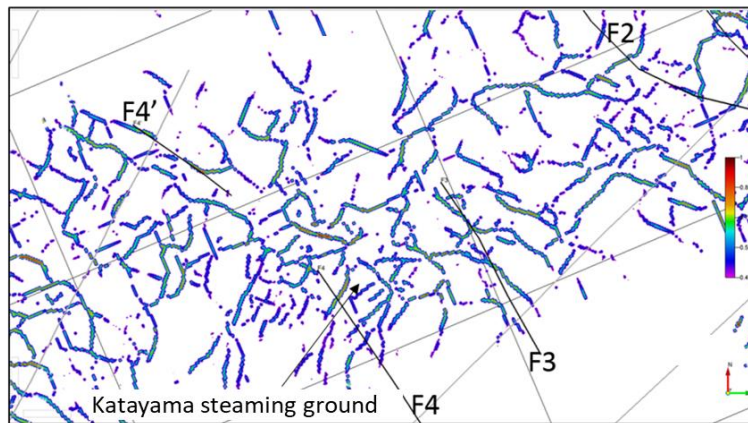


Figure 15: An example of depth slice of TFL results.

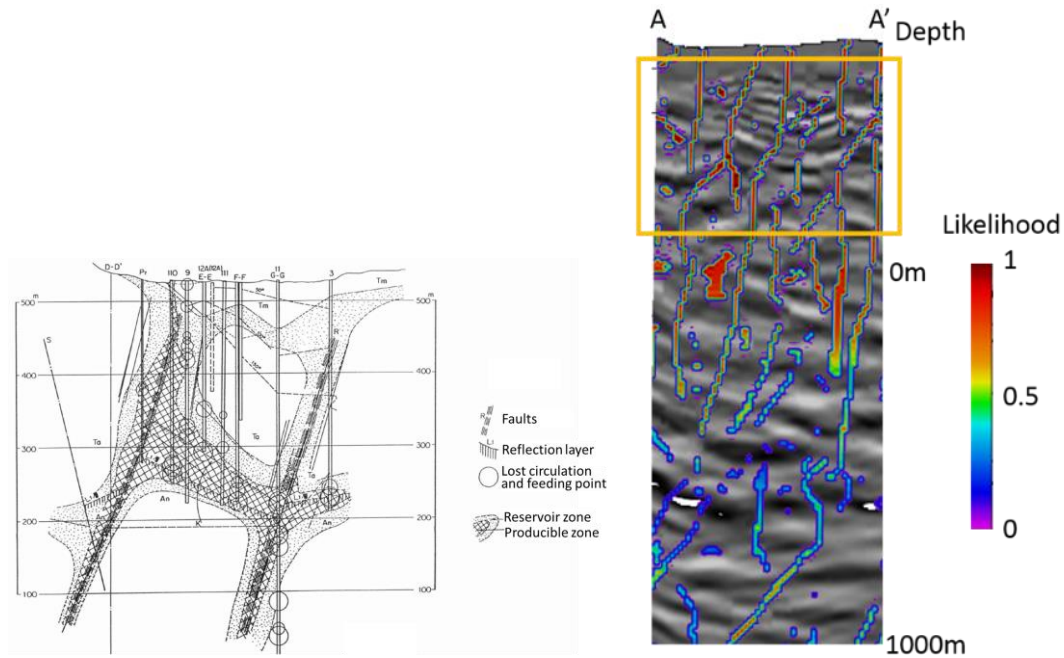


Figure 16: Comparison between (left) the geothermal reservoir model based on Abe (1985) and (right) a TFL superimposed on seismic section.

5. DISCUSSION

As mentioned above, we identified major current challenges in the application of the seismic method to geothermal exploration in the first year of this R&D project. We review the contribution of this project to these challenges and introduce newly identified challenges in this section.

- In mountainous region, investigating the field and finding as many survey lines as possible are important. Furthermore, adopting multiple types of survey instruments based on the surface condition is required. The second verification survey in Onikobe field demonstrated that we could obtain quasi-3D seismic data, even in the mountainous region, by these efforts. Saving cost and time for the field investigation is a remaining challenge.
- Noise attenuation processing that suits the characteristics of contained noise was effective. Spatial and time variant processing was also useful to deal with local issues. There were spatial velocity variations near surface in both two test fields, and large elevation variation in Onikobe, but we could mitigate them with conventional methods. In the case that these effects are significant, advanced processing techniques and/or additional field survey will be required.
- We made a guide book to help geothermal developers to consider and/or conduct seismic surveys. This guide book includes the essence of the results obtained in this project. We hope it contributes to building up the interpretation skill of the seismic data for many geothermal developers. The accumulation of case studies of seismic survey in geothermal fields is also required for it.
- Quasi-3D seismic survey serves to reduce costs as compared with a full 3D survey. Indeed, the experiment cost in Onikobe field took about half of that in Yamagawa field. However, careless cost reduction will result in low quality data. Thus, the balance between cost and performance is important.

6. CONCLUSION

We have progressed a R&D project for geothermal exploration for five years to delineate detailed geothermal reservoir structure. In this project, the two seismic verification experiments were conducted in geothermal fields in Japan. The efficacy of the application of the seismic method to geothermal exploration was demonstrated through these verification tests. The essence obtained from this project was summarized in a guide book intended for geothermal developers. We hope this guide book is utilized and the case studies of seismic survey in geothermal fields accumulates. The accumulation will contribute to further development of seismic survey techniques in geothermal fields.

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