Integrated interpretation of multimodal geophysical data for exploration of geothermal resources – Case study: Yamagawa geothermal field in Japan

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Summary

In this paper, we have developed a novel approach to three-dimensional inversion and interpretation of multimodal geophysical data, which incorporates known geological/geophysical constraints. In a general case, the geophysical inverse problem is ill posed, i.e., it is non-unique and unstable. However, appropriate a priori information can help reduce the non-uniqueness and increase the stability of the ill-posed problem. The developed approach uses the principles of inversion "guided" by known information. In the framework of this approach, the 3D inversion itself is data driven, but a priori geological/geophysical model is used as the initial and reference model during the iterative inversion process. We have applied the developed method to the integrated interpretation of magnetotelluric, gravity, and magnetic acquired in Yamagawa geothermal field of Japan, using constraints based on seismic and well-log data acquired in the same area. The results have demonstrated that the developed method produces reliable 3D models of different physical properties, which provides a solid basis for geological interpretation of the complex subsurface structures in the survey area, critical for geothermal exploration.

Introduction

Japan Oil, Gas and Metals National Corporation (JOGMEC) has been developing the proper geophysical interpretation technology for exploration and appraisal of geothermal resources in Japan, which integrate multiple geophysical survey data (Fukuda et al., 2016). JOGMEC has conducted a wide variety of geophysical surveys in the Yamagawa geothermal field, located at the southern extremity of the Satsuma Peninsula, Kyushu, Japan (Figure 1).

The basement complex of southern Kyushu is composed mainly of the Shimanto supergroup, Miocene silicic plutonic rocks, and Neogene — Early Pleistocene volcanic rocks. The Shimanto supergroup, which is made up of highly deformed Mesozoic — Paleogene shales, sandstones, conglomerates, and minor pillow lavas, underlies the graben. The Shimanto supergroup is broken by step faulting and overlain by a densely welded ignimbrite which has been dated to about 2.9 Ma and marks the beginning of the formation of a volcano-tectonic depression. In the Yamagawa geothermal field, a dacite intrusion has been expected as a part of the heat source, associated with magma chambers in the most volcanically active areas in the Ata caldera (Matsumoto, 1943). The dacite intrusion is located at the center of the depression structure in the Yamagawa geothermal field. Several exploration and development wells have confirmed the presence of andesite dykes, igneous rocks, and the dacite intrusion in this area.

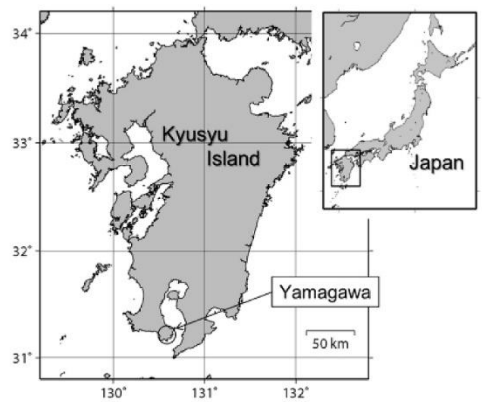

Figure 1: Location map of the Yamagawa geothermal field (after Fukuda et al., 2016).

In 2013, JOGMEC started a geothermal research project, which stimulated the development of the appropriate geophysical technology (Fukuda et al., 2016) to characterize the potential geothermal reservoirs and to promote the exploration and development of the geothermal fields. The project consisted of two phases: Phase I — 3D seismic data acquisition, and Phase II — integrated analysis and interpretation of multimodal geophysical data in the Yamagawa geothermal field (Mouri et al., 2017). The multimodal geophysical data consisted of magnetotelluric (MT), gravity, magnetic, and seismic data.

It is well known that the inversion of geophysical data is an ill-posed problem, i.e., it is nonunique and unstable, especially in the case of three-dimensional (3D) inversion. The use of appropriate a priori models or constraints can help solve this ill-posed problem (Zhdanov, 2015). We have developed a method of 3D inversion of multimodal geophysical data guided by known information, such as seismic and well-logging data. We have applied the developed method to the interpretation of multimodal geophysical data acquired in the Yamagawa geothermal field.

Multimodal geophysical data in Yamagawa geothermal field, Japan

There are following geophysical datasets and other information available in the Yamagawa geothermal field:

- Magnetotelluric (MT) data (impedance tensors processed using remote reference station data) acquired by New Energy and Industrial Technology Development Organization (NEDO) in 1997 and Ibusuki City in 2016;
- Gravity data (Bouguer anomaly data corrected using a base density of 2.6 g/cm^3) acquired by NEDO in 2001;
- Magnetic data (total magnetic intensity (TMI) data) from Aeromagnetic Anomaly Database of Japan (Nakatsuka, 2001);
- Seismic data (3D Seismic Reflection and Refraction data, and their interpretation results) acquired by JOGMEC in 2015;
- Well-log data (total 8 wells with velocity, resistivity, and density logs)

Figure 2 presents maps of multimodal geophysical data acquired in Yamagawa geothermal field, and Figure 3 shows geological boundaries (surfaces; near-surface high-velocity volume, top Nansatsu formation, and top Dacite) interpreted from seismic data.

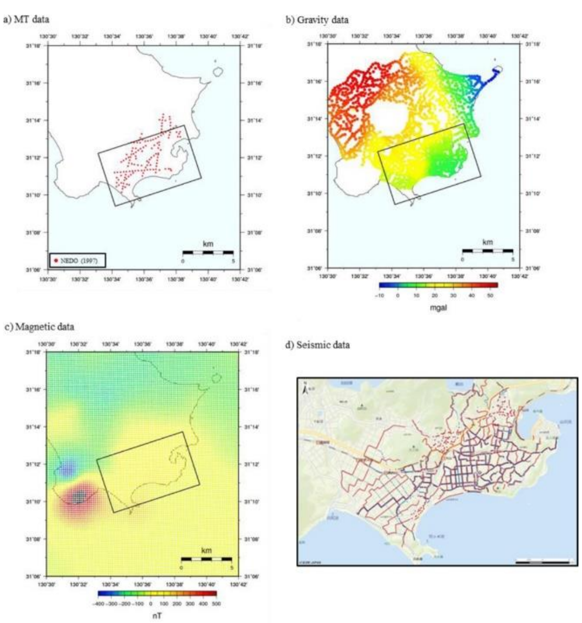

Figure 2: Maps of multimodal geophysical data in Yamagawa geothermal field: a) MT data, b) gravity data, c) magnetic data, and d) seismic data. The black rectangles shown in a) to c) are areas of seismic surveys.

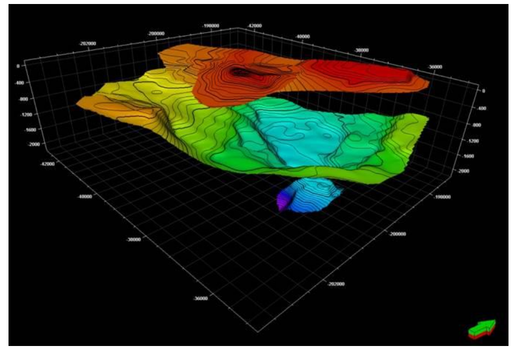

Figure 3: 3D view of seismic surfaces (near-surface high-velocity volume, top Nansatsu formation, and top Dacite).

Integrated interpretation of multimodal geophysical data

Inversion workflow

Figure 4 shows the workflow of seismically guided 3D inversion of the multimodal geophysical data and integrated interpretation.

We conducted 3D inversions of all geophysical data using the conjugate gradient method with adaptive regularization (Zhdanov, 2015).

There are two stages in this workflow:

- Stage 1: unconstrained 3D inversions
- Stage 2: seismically guided (constrained) 3D inversions

In stage 2, the a priori models of corresponding physical properties of the rock formations are constructed in order to reduce the non-uniqueness of the inversion. We have created 3D a priori models based on the interpreted seismic horizons, seismic velocity model, and the well-logging data available in the survey area. Note that, these a priori models are used as initial models only, and all model parameters (physical properties) are free to be updated during the inversion (in other words, the inversion is data driven). We have also inverted the gravity and magnetic data jointly based on Gramian constraints (Zhdanov, 2015), which enforces the correlation between the different model parameters and their attributes.

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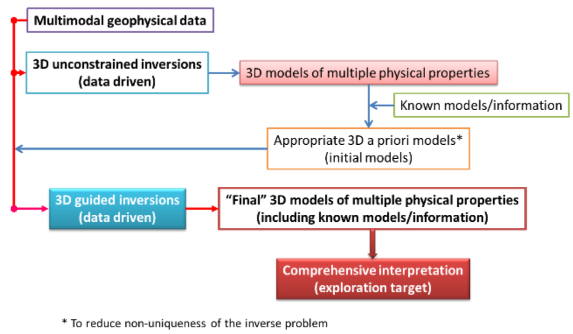

Figure 4: Workflow of seismically guided 3D inversion of multimodal geophysical data and integrated interpretation.

Inversion results and integrated interpretation

There is a preliminary interpreted geological section available in the Yamagawa geothermal field (Figure 5). The intrusive rock (Dacite) exists inside Nansatsu formation (basement) which is covered by Yamagawa formation. In this section we show our 3D inversion and integrated interpretation results along this section.

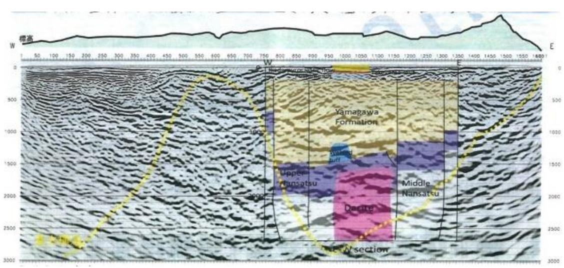

Figure 5: Preliminary interpreted geological section in Yamagawa geothermal field.

Figures 6 through 8 show vertical cross sections of 3D resistivity, density, and magnetization vector (magnitude) models recovered from unconstrained and seismically guided 3D inversions. As one can expect, the 3D models recovered from the guided inversions (bottom panels in these figures) provide more consistent and detailed images of the subsurface formations than those recovered from unconstrained 3D inversions. These 3D models obtained by the guided inversions agree well with the seismic and well-logging data, and at the same time, the final misfits between the observed and predicted data are about the same for both unconstrained and constrained (guided) inversions. This fact illustrates the importance of using the constraint (guided) inversion in interpretation of multimodal geophysical data.

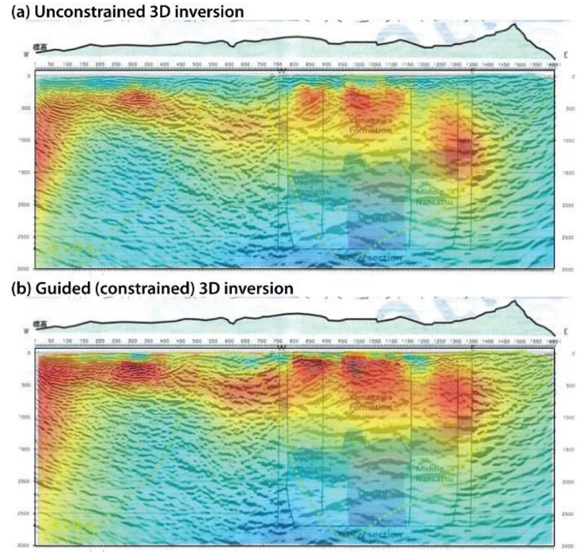

Figure 6: Vertical cross sections of 3D resistivity model recovered from unconstrained 3D inversion (top) and from seismically guided 3D inversion (bottom).

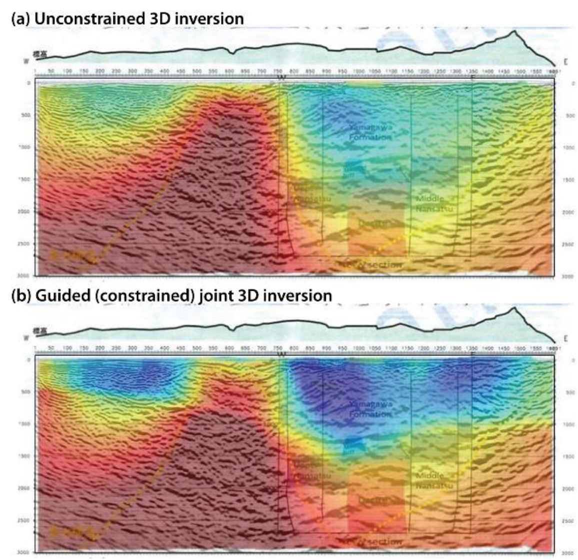

Figure 7: Vertical cross sections of 3D density model recovered from unconstrained joint 3D inversion (top) and from seismically guided joint 3D inversion (bottom).

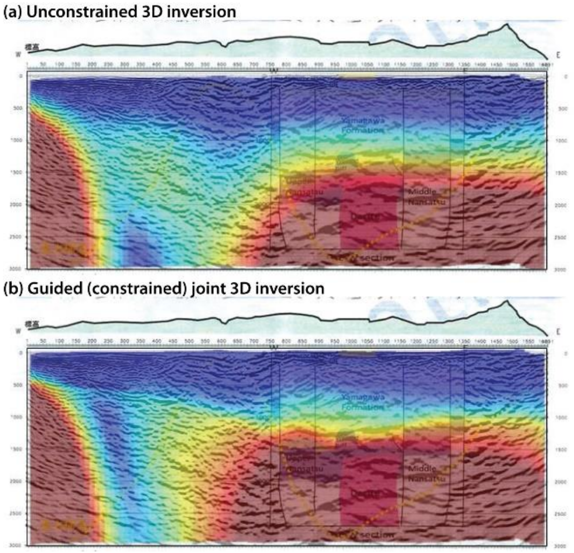

Figure 8: Vertical cross sections of 3D magnetization vector (magnitude) model recovered from unconstrained joint 3D inversion (top) and from seismically guided joint 3D inversion (bottom).

Figures 9 and 10 present vertical cross sections of resistivity and density recovered from seismically guided 3D inversion overlaid with recovered magnetization vector. One can estimate different geological units using different physical properties, i.e., resistivity, density, and magnetization vector (magnitude and direction).

Figure 11 shows the geological section interpreted from the results of the seismically guided 3D inversion of multimodal geophysical data. It was demonstrated that our method of integrated interpretation of multimodal geophysical data can construct reasonable and reliable geological model, which helps the exploration of geothermal resources.

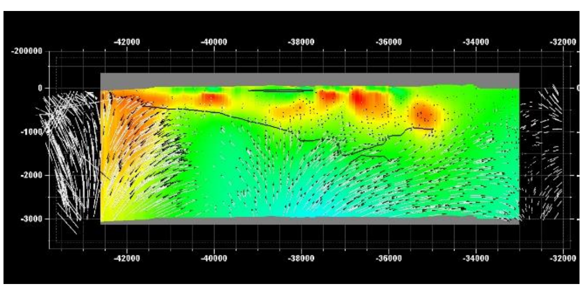

Figure 9: Vertical cross section of 3D resistivity model recovered from seismically guided 3D inversion overlaid with magnetization vector.

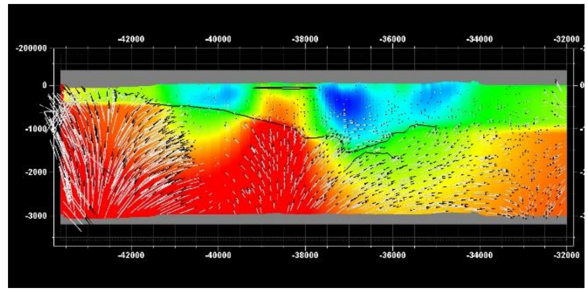

Figure 10: Vertical cross section of 3D density model recovered from seismically guided 3D inversion overlaid with magnetization vector.

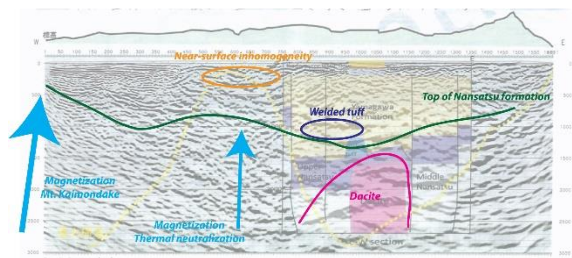

Figure 11: Interpreted geological section from seismically guided 3D inversion of multimodal geophysical data.

Conclusions

We have developed a novel approach to the integrated interpretation of multimodal geophysical data, based on guided inversion. This approach was applied to the field data acquired in the Yamagawa geothermal area. It was demonstrated that the selection of appropriate a priori models constructed using known geological/geophysical information, helped improve the quality of the inversion results. In the current project, we used seismic and well-logging data (including the results of their interpretation) to create the a priori model of the subsurface geological formation; however, other geological/geophysical information could have been used as well.

We should note that the developed workflow can be used in the different stages of geothermal resource development. Especially in the later stages, when more information is available (e.g., additional well-logging data), it is possible to produce a more robust inversion result.

Finally, the developed method and workflow can be applied for integrated interpretation of the multimodal geophysical data acquired for oil, gas, and mineral exploration as well.

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