A 3D Model of the Yamagawa Geothermal System: Insights into Reservoir Structure and Future Field Management

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ABSTRACT

The Yamagawa geothermal power station has been operating since 1995 with an output capacity of 30 MW. It is located at the southernmost part of the Satsuma Peninsula on Kyushu Island, in the southwest of Japan. The exploration activity (including geological survey, gravity survey, and exploratory well drilling and testing) was carried out from 1962 to 1988. Through the various surveys and analysis in the exploration stage, and through the subsequent drilling, geologically complex structures and the presence of a high temperature reservoir have been better defined.

In this paper, all of the subsurface information acquired has been used to build a 3D geological model. This model shows the major structural trends and also shows the impacts of key formations within the reservoir. Natural state temperature data has been used to create a temperature model, which has shed light on the importance of major geological structure as they relate to fluid flow. The resistivity survey result also gives us information regarding the indication of geothermal fluid flow path. The combined 3D model will be a tool used to contribute to the evaluation and management of the geothermal reservoir at the Yamagawa geothermal power station.

1. INTRODUCTION

Yamagawa geothermal power station is located about 1 kilometer from the coast of the southernmost part of the Satsuma Peninsula on Kyushu Island, in the southwest of Japan (Fig.1). The exploration activity (including geological survey, gravity survey, and exploratory well drilling and testing) was carried out from 1962 to 1988. Through the various surveys and analysis in the exploration stage, and through the subsequent drilling, geologically complex structures and the presence of a high temperature reservoir have been better interpreted. In 1975, well SA-1 was drilled, had a temperature of 230°C at a depth of 500m and encountered good permeability (Okada, et al, 2000). Wells drilled subsequent to SA-1 showed a measured temperature of over 200°C. According to the findings of exploratory wells drilled in 1986, the power generation output in the Yamagawa field was estimated to be about 30 MW (Okada, et al, 2000).

In 1995, Kyushu Electric Power Co., Inc. (KEPCO) (electrical power generation) and JAPEX Geothermal Kyushu, Ltd (JGK) a subsidiary of JAPEX (Japan Petroleum Exploration, Co., Ltd) as steam supplier commenced the commercial operation of the Yamagawa power station with an output capacity of about 30 MW. In 2005, KEPCO took over the steam supply from JGK and has continued until the current operation. During the 2000s and 2010s, several make-up wells were drilled. In addition, Japan Oil, Gas and Metals National Corporation (JOGMEC) conducted a seismic reflection survey in the Yamagawa field to image the subsurface geothermal structure as a part of the resource & development scheme.

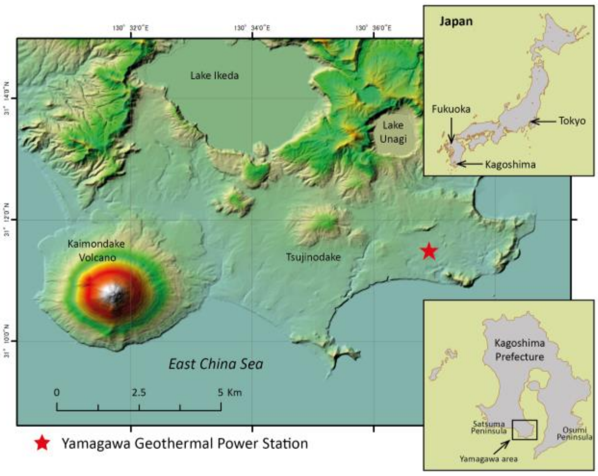

Figure 1: Shaded relief map showing the location of the Yamagawa power station.

2. GEOTHERMAL SYSTEM IN YAMAGAWA FIELD

2.1 Regional geology of Yamagawa

In the southern Kyushu Island, four large, late Quaternary calderas exist with an alignment of NNE-SSW and with an interval of about 50 to 60 km; Kakuto-Kobayashi caldera, Aira caldera, Ata Caldera, and Kikai Caldera (Okada, et al, 2000). Yamagawa geothermal field is located inside the Ata Caldera, in the area where the Onkadobira fault lies in the NW of the caldera. In the surrounding area, numerous surface geothermal manifestations such as hot springs, and fumaroles exist, including the famous hot spring area named Ibusuki.

The stratigraphy in this area has been confirmed by the results of well drilling, and is composed of 6 units of lithology (Yoshimura et al., 1985). The lithology from upper consists of Kaimondake scoria, Ikeda pyroclastic rocks, Takeyama andesite, Fushime silt, Yamagawa Formation and Nansatsu Group. The deposit of Kaimondake scoria has the characteristic of having a thin distribution over a wide area.

Ikeda pyroclastic rocks in this area have a thickness of about 100m and consist of pumice. Alternating layers of Takeyama andesite and Fushime silt are laid above Yamagawa Formation with a depth of about 150 m to 1,500 m. The Nansatsu Group is divided into Upper Nansatsu Formation, Middle Nansatsu Formation, and Lower Nansatsu Formation. Furthermore, an intrusion of dacite is distributed in the Upper Nansatsu Formation with the characteristic feature being an andesite dyke.

Table 1. Stratigraphy of Yamagawa

Stratigraphy	Lithology	Age
Kaimondake scoria	It consists of scoria fall from Mt. Kaimondake. It is distributed in a wide area of Yamagawa.	Holocene ±1,000-4,000 year BP (Nakamura, 1971)
Ikeda pyroclastic rock		Ikeda Volcano, ±5,000-5,500 year BP (Naruo, 1983)
Takeyama andesite	It relates to Mt. Takeyama located in the SE of Yamagawa PS, consists of andesite.	Pleistocene ±26,000 year BP (Kamitani, et al, 1976)
Fushime silt	Light to dark gray tuffaceous silt, contains abundant foraminifera	Based on Foraminifera (3.3-110,000 year BP)
Yamagawa Formation	It consists of dacitic tuff and tuff breccia with thin beds of siltstone. It is a very thick formation.	Early Pleistocene N22 zone, N20-N21 zone (Okada, et al, 2000)
Fushime welded tuff	It appears locally detected by well drilling.	Late Pliocene
Nansatsu Group		Pliocene – Miocene Foraminifera N17-21 zone
Upper Nansatsu Formation	It consists of altered dacite tuff and tuff breccia	
Middle Nansatsu Formation	Andesitic lava and pyroclastic rock	
Lower Nansatsu Formation	Altered dacite tuff	

2.2 Structural geology of Yamagawa

The geological structures in Yamagawa are derived mainly from geophysical survey data and borehole data, since Yamagawa field is located in a topographically flat area and is covered by thick volcanic products at the surface. The Yamagawa area is estimated located to be located above a depressed structure which corresponds to the gravity lineaments and resistivity discontinuities. It is also confirmed by borehole lithology which can be used to compare the inside and outside of the fault. The trend of the northwest inferred fault is also coherent with the apparent resistivity contour (see Fig. 2). The appearance of a dyke is confirmed by drilled wells area also corresponded to the alignment of the Tsujinodake-Takeyama line (Fig. 2).

The geothermal system in this area is considered to be controlled by that depressed structure. A multiple fracture system is assumed to exist inside the depressed structure (Fig. 3 and 4). In addition, it is interpreted that the fractures could be the way of geothermal fluid generated by dacite intrusion as a heat source in the center area formed a great geothermal reservoir (Okada, et al, 2000)

2.3 Hydrothermal alteration

According to the geology of drilled wells, hydrothermal alterations are as follows; the silica mineral consists of α-cristobalite, trydimite, and quartz; the clay mineral is composed of smectite, smectite/chlorite mixed layer, sericite, and smectite/sericite mixed layer, the zeolite consists of clinoptilorite, heulandite, mordenite, analcime, and wairakite; the feldspar mineral consists of albite, K-fledspar, and others such as epidote, prehnite, calcite, gypsum, anhydrite, sphene, rutile, and apatite (Yoshimura, 1994).

Based on the zonation of hydrothermal alteration, from lower to higher temperature are Zone I (smectite zone) where the temperature is below 160°C, Zone II (transition zone) which is characterized by smectite/chlorite, mixed layer sericite and smectite/sericite. Zone III (chlorite zone) has a temperature of 180-200 to 250°C and consists of quartz, albite and wairakite and Zone IV (epidote zone) with a temperature above 250°C which is characterized by the appearance of epidote. Zone IV is widely distributed in the deeper area with high permeability zone where developed in the geothermal reservoir with quartz, albite and chlorite are commonly found (Okada, et al, 2000).

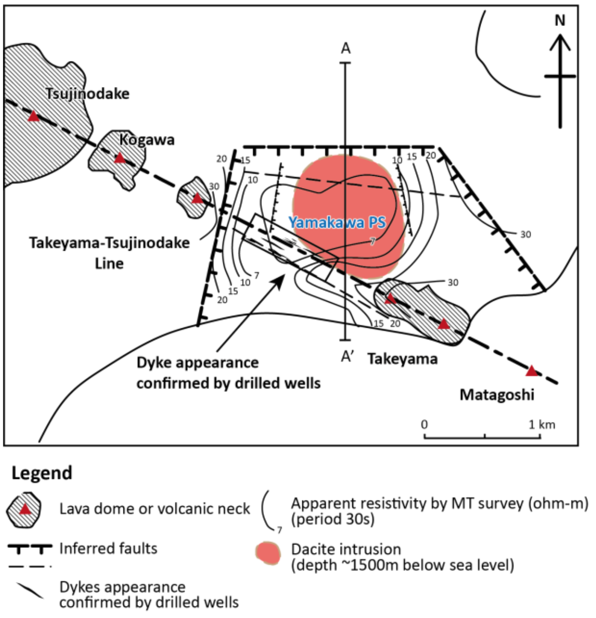

Figure 2. Geological structure along with resistivity survey result in Yamagawa power station surrounded area, modified from Okada, et al (2000).

2.4 Subsurface temperature

Based on the temperature profile from the exploratory wells, many of the wells show a convection type profile, followed by a temperature inversion at around 1,000 m in depth. Therefore, subsurface temperature can be divided into three zones, a shallow high temperature zone with a depth of less than 800 m, the inversion temperature zone with a depth of 800-1,200 m, and a deep high temperature zone with a depth of more than 1,200 m. The production zone in this area is above the deep high temperature zone (over 350°C). The loss zone during well drilling in the boundary between the Yamagawa Formation and Nansatsu Group is considered to be main geothermal reservoir.

2.5 Current power generation status

In December 2014, KEPCO changed the output capacity from 30,000 kW to 25,960 kW after a turbine inspection. In the future, KEPCO plans to install new turbine blades to return the output capacity to 30,000 kW (described in the KEPCO press release 5 January 2015). As of March 2016, Yamagawa power station has been generating a total installed capacity of about 12,100 kW with 10 production wells, 12 reinjection wells, and 1 monitoring well (Thermal and Nuclear Power Engineering Society Report, 2016).

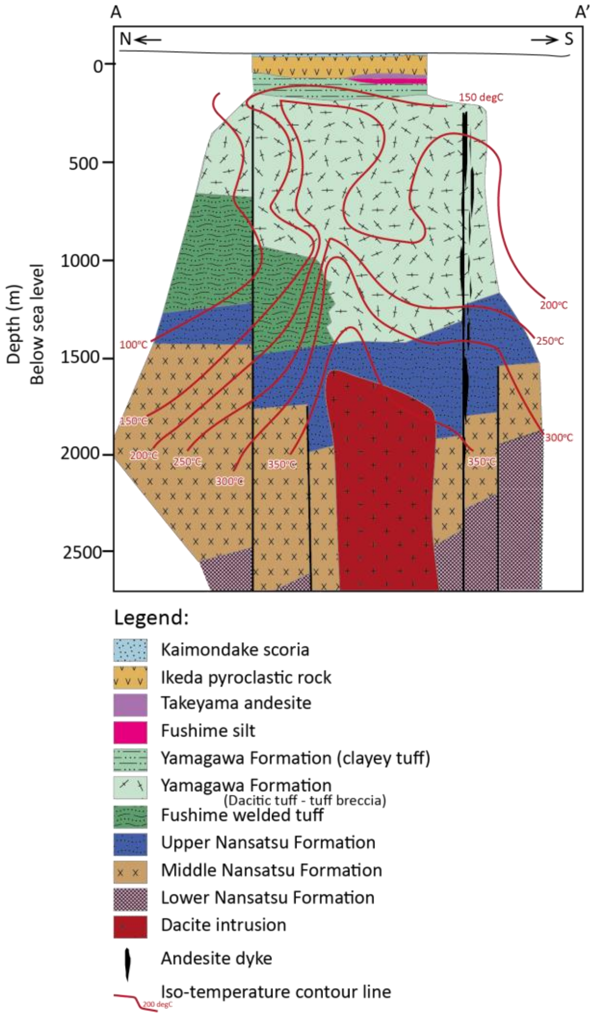

Figure 3. Geological cross section along with subsurface temperature distribution, modified from Okada et al, 2000.

3. DATA AND WORK METHOD FOR 3D MODEL CONSTRUCTION

Yamagawa geothermal field and its surrounding area have been explored for more than 50 years. A great deal of data has been collected with various platforms and formats. In order to construct a geological model, it is necessary to select the most appropriate data to be integrated using Leapfrog Geothermal software.

The following data was used in order to construct 3D model of the Yamagawa geothermal system.

Table 2. Summary of data integrated into model.

Data	Remarks
Surface data	Topography, DEM, surface survey map
Well data	Lithology, formation, mineral, casing point, directional survey, loss circulation, collar
Well logging data	Temperature, pressure, spinner, FMI, BHTV
Geophysics data	Magnetotellurics, gravity survey, 3D seismic

The following are the details of the process used to build the Yamagawa 3D model.

- Determining the boundary of the model area
  This model is focused on the Yamagawa power station and the surrounding area; adjust to geothermal drilled wells with extent of about 5 km. The model is constrained vertically by the topography (5 m resolution of DEM) provided by the Geospatial Information Authority of Japan (GSI).
- Importing data into Leapfrog Geothermal software
  After selecting the most appropriate data (such as borehole data including collar, survey and lithology, fault location, and loss circulation), the data was imported using a specific format into the Leapfrog Geothermal software.
- Building geological stratigraphic sequence
  To create the geological model, it is necessary load into Leapfrog the stratigraphy contact point which is derived from borehole data. Additional manual editing is necessary and the polyline function is used to adjust the contact stratigraphy to be more realistic. The type of stratigraphy can be defined based on the stratigraphic genesis of the lithology unit such as intrusion, deposit, vein, erosion, etc.
- Building geological structure
  The fault model was created based on the current understanding of faults delineated by JAPEX Geothermal Kyushu, Ltd (JGK) by subsequent studies. Most of the faults were assumed to have dip of 80° to vertical. The relationship between the faults and lithology were designed to create a geologically consistent and realistic geological framework.
- Building interpolant model
  MT data and temperature were created using a 3D interpolant tool derived from numeric data. The estimates for unknown points while varying the distance from known point values is controlled by the radial basis function interpolant in Leapfrog.
- Inputting additional supporting data
  Cross sections with various directions prepared by KEPCO and West JEC were uploaded to validate the lateral distribution of lithology. In addition, 3D seismic data images provided by JOGMEC also are used to improve the 3D model
- Adjusting surface topography
  The surface was manually edited using a surface geology map to adjust the area with no borehole information. In addition, topography was used to support the lateral distribution. Manual editing was also applied in order to have a geologically realistic shape.

4. THE 3D MODEL

4.1 Surface data

Surface data including DEM, geological map, structural map, and borehole wellhead locations were inputted to show the boundary of the research area. The lateral distribution of the shallow depth was based on borehole data. Kaimondake scoria and Ikeda pyroclastic rocks dominated in the shallow depth.

4.2 Lithological model

Subsurface information was derived from a total of 10 production wells, 12 reinjection wells and 1 monitoring well along with the drilling results of the sidetracked wells. The information (including lithology, alteration, casing point, directional survey, and PTS logging data) was used to construct the trajectory in the 3D model. Most of the wells are deep wells with depths exceeding 1,500 m.

The lithological model was built based on lithological column prepared using cuttings collected every 5 m. XRD analyses were also conducted using cutting sample with range at every 20 m to interpret the stratigraphic formation and hydrothermal alteration.

Based on the drilled wells, the lithology that has been encountered in the shallow depth (ranging up to a depth of 100 m) includes Kaimondake scoria, Ikeda pyroclastic, Takeyama andesite and Fushime silt. Takeyama andesite and Fushime silt are found locally during drilling. Below the above lithology unit is a thick Yamagawa Formation consisting of mostly dacite tuff and tuff breccia

Kaimondake scoria is a blackish brown scoria that gushed out from Mt. Kaimondake located about 8 km west of Yamagawa power station and covers the surface of the area. The Ikeda pyroclastic deposit is a volcanic ejecta originated from volcanic activity that formed Ikeda Lake which is located about 7 km northwest of Yamagawa power station, an is mainly composed of white pumice and gravel. It is positioned under Kaimondake scoria with thickness of about 100 - 120 m. It is found in almost all wells during drilling. Takeyama andesite is related to the Takeyama volcanic neck which is located near the Yamagawa power station. The thickness is less than 15 m, appearing locally on the borehole and the distribution is relatively limited.

The Fushime Silt Formation is composed of light to dark gray tuffaceous silt which is distributed about 10 m below the Takeyama andesite. It is found locally in some wells which pinched out to Ikeda pyroclastic deposits. The Yamagawa Formation is a porous rock formation consisting of dacite tuff and tuff breccia and also contains pumice. This formation is found in all over wells to a depth of about 1,500 m below sea level. It is widely distributed in Yamagawa area. Fushime welded tuff shows a welded structure with dark brown to black color. The distribution is locally, but reaches 500 m in thickness.

The Nansatsu Group is divided into an upper, middle and lower formation based on its rock formation. The upper formation is composed of white, light gray and green gray tuff and tuff breccia, and is silicified and dense. The middle formation consists of hard and dense pyroxene andesite lava and andesite tuff. The lower formation consists of white to pale green dense silicified dacite tuff. An intrusion which is present in the Nansatsu Group is composed of dacite distributed with stock shape.

These above lithologies are adjusted geological model boundary by drilled wells, and bounded vertically by topography to a depth of about -2,500 m. Lateral distributions to locations which have no borehole information were derived by cross section and supported by 3D seismic reflection survey. To construct the stratigraphic sequence, geological model was built using borehole data as the primary input for “deposit” except for the dacite intrusion that intruded into the pre-existing formation.

Fault surfaces were interpreted using the gravity and resistivity survey conducted by KEPCO. The faults were traced using GIS polylines from the surface, refer to available cross sections to control for subsurface conditions with a dip of vertical to 80°. This step was done in order to build a fault block in 3D model. Lithology data was used to control the displacement across the faults, taking into account the subsurface conditions. The geological cross sections were acquired by KEPCO and West JEC and are used to control the lateral distribution using manual editing. Local polylines were added to define the geometry of the formation body in order to be more geologically realistic. Once the stratigraphic sequence and fault model were defined, the output volume can be created to visualize the 3D model.

4.3 Interpolant model

a. 3D Seismic Model

Seismic survey was conducted by JOGMEC in the Yamagawa area in 2015 and data processing has been carried out since 2016. A seismic interpretation was carried out for visualizing the geological features in the Yamagawa area. Distributions of the upper Nansatsu Formation and dacite intrusion were also estimated by interpreting the results of the coherence analysis and also considering the lithology of wellbores as a control point. The estimated upper depth of the Nansatsu Formation shows the largest values near the Yamagawa power station. A rapid change of upper depth of Nansatsu Formation is detected below the western part of Yamagawa power station (see Fig. 5). Based on the coherent analysis of 3D seismic, the upper Nansatsu Formation has a depression morphology as shown in Fig. 6. This depression has elevation -1,000 m at the upper part then forms basin-shape like to about -1,500 m at the centre of the field. The rapid depth change parts have a consecutiveness with NW-SE structural trends in the western part of the Yamagawa power station and are associated with the Takeyama-Tsujinotake tectonic line (JOGMEC, 2017).

b. Resistivity Model

Magnetotelluric survey was carried out in 2015 by the Ibusuki city with a total number of MT data sets for 25 stations. These stations were spread over an area which included the Yamagawa power station. A 3D resistivity inversion analysis was conducted using this data and existing MT data (11 data sets) acquired by NEDO (New Energy and Industrial Technology Development Organization) in 1998.

An overburden layer with a resistivity value of more than 20 ohm-m, a middle layer of less than 3 ohm-m and a lowest resistivity layer of more than 20 ohm-m were detected from the results of the 3D resistivity inversion analysis in a large sense. The low resistivity zone detected at the middle layer is considered to show the existence of fluids, including sea water or hydrothermally altered zones containing considerable amounts of smectite (Zone I) and/or interstratified clay minerals (Zone II). On the other hand, the high resistivity zone at lowest layer is considered to possibly indicate the existence of hydrothermal altered minerals (such as illite and/or chlorite, which are usually formed under high temperatures greater than approximately 200°C) which may be associated to Zone III on zonation of hydrothermal alteration. Resistivity discontinuities with an N-S trend and with a NW-SE trend were also detected from resistivity distributions. These resistivity discontinuities may give indications of geothermal fluid flow paths.

c. Subsurface Temperature

Equilibrium temperatures derived from calculation of recovery temperatures were used from selected wells both production wells and reinjection wells that represented natural state reservoir condition. Temperature data as numeric values plotted at different depths in each well. By using numeric modelling tool in Leapfrog Geothermal software, it gives representative contours of the subsurface temperature distribution in 3D.

Yamagawa geothermal field has unique characteristic of subsurface temperature distribution. It is divided into 3 zones. A shallow high temperature zone with down to 800 m. An inversion zone encountered by some wells at depth of 800-1,200 m, and the deep high temperature zone below 1200 m respectively as shown in Fig 4. The highest temperature in Yamagawa was recorded to 353°C from SKG-17 wells drilled towards WNW direction with measured depth to 2,000 m. It intersects to the area of Dacite intrusion delineated by 3D lithological model.

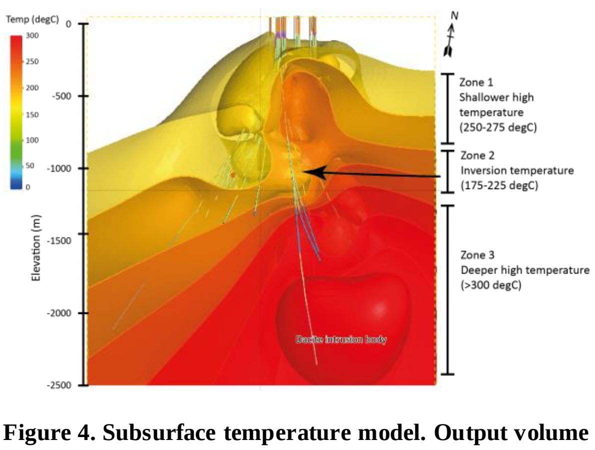

Figure 4. Subsurface temperature model. Output volume of the model is isotherm of interpreted temperatures from borehole data. Section is shown from South direction. Black arrow shows area of Zone 2 (inversion temperature area).

5. DISCUSSION

Integrating multidisciplinary data at Yamagawa allows to have a better understanding of the geothermal system in this area. This model integrates surface information, borehole data, and geophysics data.

5.1 Interpretation of geothermal system based on integrated 3D model

Geological interpretation from surface and borehole data integrated with geophysical survey allows us to produce a 3D model that provides a fair reflection of the subsurface conditions. The wells encountered Kaimondake scoria, Ikeda pyroclastic rock, Takeyama andesite, local Fushime silt, thick Yamagawa Formation, Nansatsu Group, and a large dacite intrusion (Fig. 6).

The Yamagawa geothermal field is characterized by the presence of a temperature inversion in the shallow depths as shown in Fig.4 where a temperature of more than 250°C appears in elevations of about 500 m below sea level, then decreases to about 175-225°C. Below this zone, the temperature reaches about 350°C at a depth of below 1,500 m.

A 3D seismic survey interpreted by JOGMEC considering borehole data as a control point shows the highly displaced nature of the Upper Nansatsu Formation. Another clear seismic reflection is also observed at the top of the dacite intrusion which correlates well with the dacite intrusion logged in the well cuttings. The seismic data allows the spatial variation in the Upper Nansatsu Formation to be taken into consideration away from areas of dense well data.

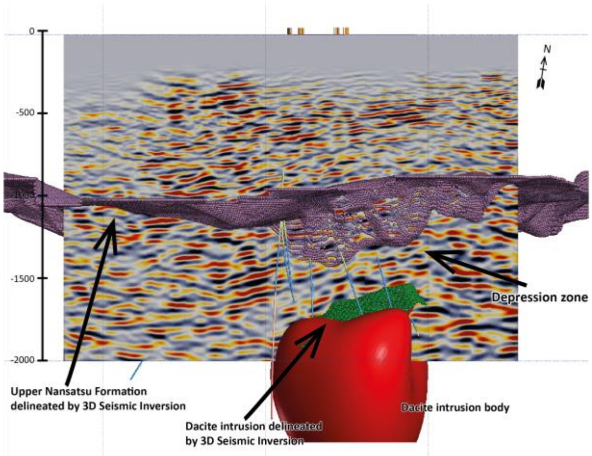

Figure 5. 3D seismic horizon delineated with borehole lithology as a control point. The profile is shown from South direction.

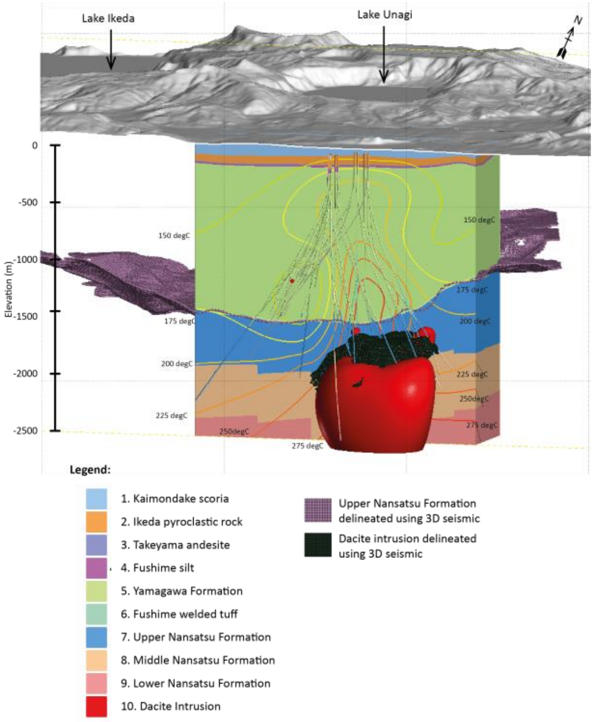

Figure 6. A 3D view of the geological model with borehole along with interpretation of 3D seismic horizon. Dacite intrusion is also displayed

Based on the observed geological structure and subsurface temperature distribution, hot fluids rise from the area of the dacite intrusion where the largest depression is seen in the interpreted upper Nansatsu Formation horizon. The hot fluid flows up through the relatively permeable tuff and tuff breccia of the Yamagawa Formation which host the main geothermal reservoir. The zone of temperature inversion is located on the eastern edge of the depression and nearby to interpreted faults which could act as conduits for cooler fluids to create the inversion. Further investigation is required to fully understand the nature of the inversions at Yamagawa after the insights provided from 3D model (see Fig. 5 and Fig. 6).

The temperature inversion is restricted the eastern part of the field, with the temperature distribution in the rest of the field showing no temperature reversals. It can be concluded that the temperature reversal is strongly controlled by depression structure in the eastern part depression zone. Therefore, the understanding of the geological structures related to depression zone is key in better understanding the natures of subsurface temperature distribution and geothermal fluid flow in Yamagawa field, especially for the targeting of reinjection wells. Also the nature of the interaction between the depression and the overlying Yamagawa Formation which hosts the majority of production for the geothermal field.

Leapfrog Geothermal has multiple functions that allow visualization of data in different ways. Symbology, transparency can be modified and the model can be sliced option at each layer from any direction. This also can be visualized in 360° at any direction.

5.2 Field management

By constructing a 3D model, the distribution of the high temperature zone, lateral lithology, and feed zone of each borehole, etc. can be clearly defined. Regarding the management plan, the 3D model will help to decide the drilling targets for production and reinjection wells. Yamagawa Formation shall be the first priority on drilling target for production wells. It drills toward the eastern area of Yamagawa, which have already been proven to have good permeability and high temperatures (more than 350°C). On the other hand, reinjection wells shall be targeted to the western part that far away from intrusion. The model can also be used to create the grid for reservoir simulation in TOUGH2. This allows us to monitor the cooling of the reservoir caused by the intrusion of low temperature fluid into the reservoir and to maximize the capacity of power station.

5.3 Forecast simulation

In 2016, KEPCO announced that a geothermal binary power station project will be constructed at Yamagawa with an output power capacity of 5MW. The binary system effectively utilizes the geothermal resources that cannot be used by the current Yamagawa power station. KEPCO will supply the heat, while Kyushu Mirai Energy will generate the electricity.

Leapfrog Geothermal Software can create, import and visualise simulation software such as TOUGH2 simulation, input and output. It can be used to directly create the flow model in Leapfrog Geothermal or to synchronize using TOUGH2. Flow models can be displayed in the scene, and time-dependent output data can also be visualized. Leapfrog Geothermal software is highly efficient and provides a good opportunity to carry out the simulation.

Given this opportunity, it is advantageous to conduct simulations in order to grasp the influence of reduction of low temperature of geothermal fluid on the reservoir, along with the introduction of the binary system and examine the appropriate operation method.

6. CONCLUSION

This paper demonstrates the integration of geological, structural, geophysical and surface data to gain a better understanding and create a conceptual model of the Yamagawa geothermal field. Leapfrog Geothermal software offers a complete solution and was used to construct and visualize the 3D model. Interpolated interpreted temperature data integrated with structural geology allows us to examine the subsurface conditions in this area in more detail. In addition, 3D visualisation also provides a tool to improve the level of confidence regarding the management plans in the future.

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