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A Conceptual Model of the Wasabizawa Geothermal Field, Akita Prefecture, Japan

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ABSTRACT

An extensive exploration program consisting of geological, geochemical, and geophysical surveys, core hole drilling, well drilling, and pressure transient testing has been carried out at the Wasabizawa geothermal field, located in northeastern Honshu, in Akita prefecture. Construction of a new 46.199 MWe geothermal power station was commenced in 2015, and commercial operation was initiated in May 2019. This paper presents a newly developed conceptual model based on the available data, which provided technical basis for planning the power station.

The field is located in mountainous area with surface elevation varying between +600m ASL and +900m ASL. The subsurface stratigraphy consists of a sequence of volcanic rocks overlying naturally-fractured granitic basement rocks. The geothermal reservoir is hosted by naturally-fractured granitic rocks, and the reservoir top is located between about +200 m ASL and -200 m ASL depending on the horizontal location, with reservoir temperatures of 280 - 290 °C. Correlation of pressure with equivalent feedpoint elevation shows that almost all wells in the area are in good pressure communication with each other, except two wells (YO-8 and AY-5) located to the west near Akinomiya hot spring area: the feedpoint pressure of these two wells are about 1 MPa lower than those of other wells relative to the same elevation. The feedpoint pressures of the latter wells suggests that the reservoir is isolated from nearby Akinomiya hot spring area by a relatively impermeable zone, and this inference is also supported by results of isotope analysis of hot spring water and brine. Inferred temperature distribution in the area delineates the horizontal reservoir extension. It is likely that the reservoir is also isolated from nearby Kawarage fumarole and Doroyu hot spring located to the east, based on the inferred temperature distribution and chemical composition of these hot springs. Fault systems striking along NW-SE, NE-SW and E-W trends are indicated by geophysical surveys (gravity and MT & CSAMT surveys). Reservoir fluid is neutral NaCl type brine with chloride concentration between 400 mg/L and 2,400 mg/L. The low Cl concentration of water may be due to dilution by steam condensate and/or possible recharge water from the eastern part. Reservoir temperature and pressure profiles as well as the chloride concentration suggest that a two phase region (steam cap) may exist just below the cap rock in eastern part of the field. Based on the conceptual model, and considering the surface topography and location of existing exploratory wells, the location of production well pads and reinjection well pads were planned to be set about 2 km apart from each other, and the production and injection strategy should allow sustainable operation in the future. A numerical reservoir simulation based on the conceptual model also showed that 46 MWe will be sustainable. Total of 11 production and reinjection wells, other than five existing exploration wells which will be converted to production and injection wells, were drilled during construction of the power station, and an extensive heterogeneity of fracture distribution in the granitic basement rock was observed. Large excess total production capacity was obtained relative to required flow rate for 46.199 MWe output.

1. INTRODUCTION

An extensive exploration program consisting of geological, geochemical, and geophysical surveys, core hole drilling, well drilling, and pressure transient testing has been carried out at the Wasabizawa geothermal field, located in northeastern Honshu, in Akita prefecture. Over 30 exploratory wells have been drilled in the area so far, and the reservoir character is relatively well delineated (Figure 1). The Japanese New Energy and Industrial Technology Development Organization (NEDO) supported geothermal development promotional surveys (so-called "C" surveys) for the Wasabizawa area between 1993 and 1997, and for the adjacent Akinomiya area between 1996 and 2000 (Figure 1). These areas are located just southwest of the Uenotai geothermal field which has been producing 28.8 MWe of electricity since 1994. Originally, the Wasabizawa survey was undertaken by Dowa Mining Company (at that time the operator of the Uenotai power station; Inoue et al. (2000), Suzuki et al. (2000)) and the Akinomiya survey was performed by JMC Inc. (Kurozumi et al. (2000)). The Akinomiya area was transferred to MMC in 2004 and the Wasabizawa prospect was transferred to J-Power and MMC in 2008.

Over time, it became evident that Wasabizawa and Akinomiya represent two parts of a single larger geothermal field. As a result, in 2008 J-Power and MMC entered into an agreement to carry out joint studies to examine the feasibility of developing an electrical power project using geofluids from the Wasabizawa-Akinomiya geothermal reservoir. Two exploratory wells (GW-1 and 2) were drilled in 2009 and a production test was carried out in 2010. In parallel with the feasibility study, J-Power, MMC and Mitsubishi Gas Chemical Company, Inc. (MGC) jointly established the Yuzawa Geothermal Power Corporation (YGP) in April 2010 to manage the resource and to accelerate geothermal exploration for both areas in a unified manner. Since then, YGP has led the project and carried out the environmental impact assessment (EIA) procedure required for constructing the new geothermal power station. YGP originally planned a 42 MWe double-flash plant, and the construction works including drilling of new production and injection wells commenced in May 2015. During the construction, YGP decided to increase power output to 46.199MWe, after detailed design of a generating facility that uses the same amount of steam and brine flow rates as the original planned 42 MWe power plant.

This paper presents a newly developed conceptual model based on the available data, which provides technical basis for the planned power station. The "Wasabizawa" geothermal field in this paper represents the above mentioned unified area of the NEDO's two survey areas. The field is located in mountainous area with surface elevation varying between +600m ASL and +900m ASL ("above sea level"). The south-eastern part of the field involving a part of NEDO survey areas is part of the Kurikoma Quasi-National Park, in which geothermal development has been prohibited.

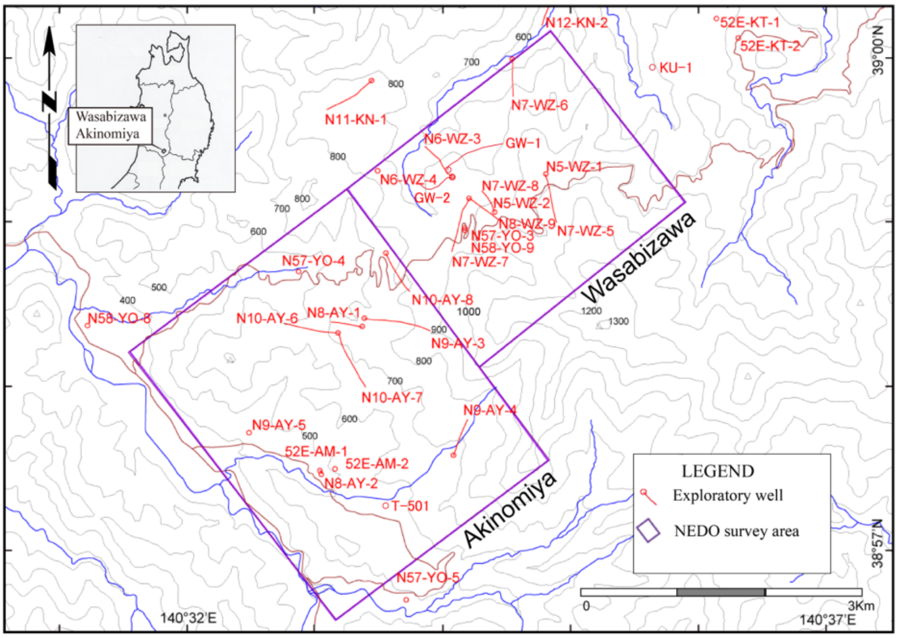

Figure 1: Exploratory well locations in the Wasabizawa geothermal field. Black: ground surface elevation contours (0.1 kilometer ASL separation). Blue: river or channel. Brown: road.

2. RESERVOIR EXPLORATION AND CHARACTERIZATION

2.1 Geological and Geophysical Structure

Figure 2 shows a SW-NE section of geological structure of the field which passes through wells AY-5, AY-1, AY-8, WZ-7, WZ-1 and KU-1. The subsurface stratigraphy consists of a sequence of volcanic rocks overlying naturally-fractured granitic basement rocks. The geothermal reservoir is hosted by the naturally-fractured granitic rocks. Figure 3 shows results of (a) gravity survey and (b) MT and CSAMT surveys with inferred fault zones and inferred temperature distribution at -500 m ASL. Several linear trends of change in depth of geophysical (gravity and resistivity) basement are delineated in these maps, and fault systems striking along NW-SE, NE-SW and E-W trends are identified by these geophysical surveys.

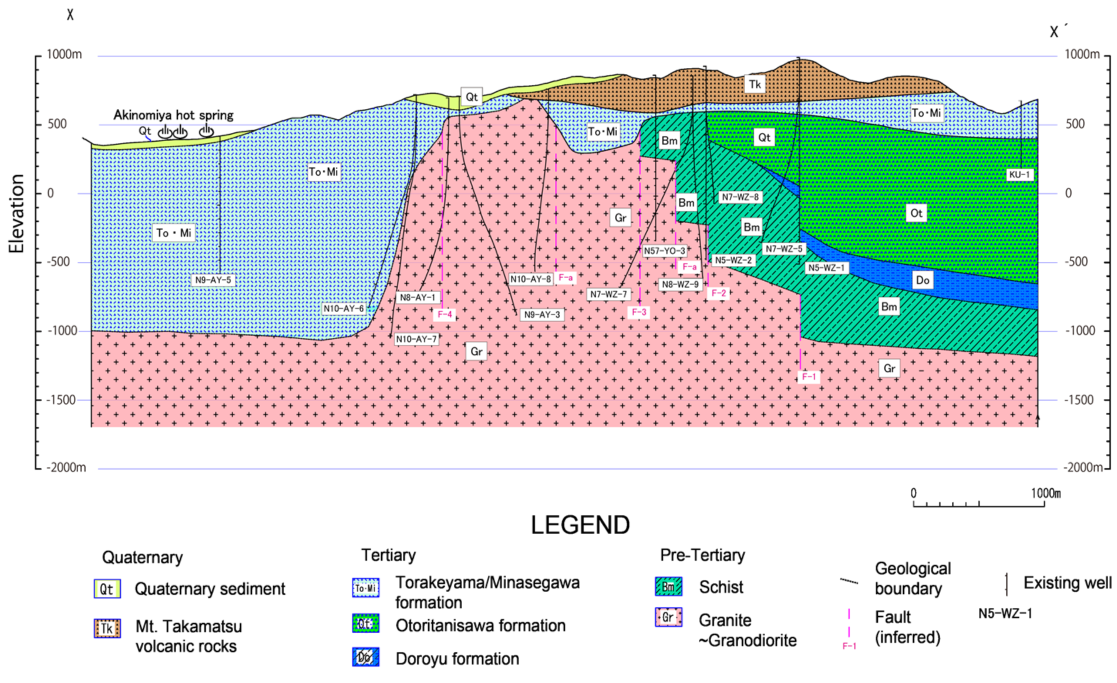

Figure 2: SW-NE section of geological structure of the field.

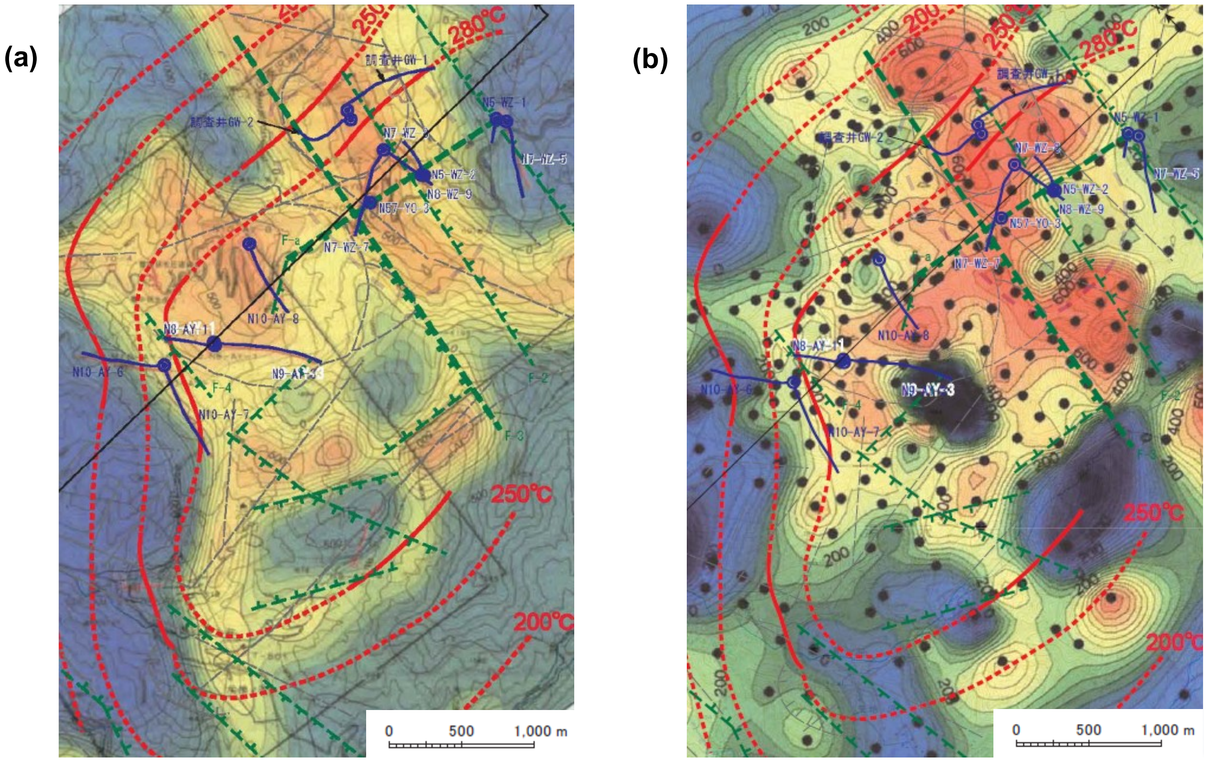

Figure 3: Results of geophysical surveys. (a) Gravity basement structure from 3-D gravity modeling with inferred fault zones (green dashed line with dip direction marks) and inferred temperature distribution at -500 m ASL (red lines). Warmer colors represent shallower depth of the gravity basement with contour separation of 100 meter ASL. (b) Resistivity basement structure from MT and CSAMT surveys with survey points (black dots), inferred fault zones from gravity survey (green dashed line) and inferred temperature distribution at -500 m ASL (red lines). Warmer colors represent shallower depth of the resistivity basement with contour separation of 50 meter ASL.

2.2 Temperature and Pressure

Stable temperature profiles in representative wells are shown in Figure 4, which exhibit conduction-dominated behavior in a low-permeability shallow caprock layer through which heat flows from the underlying convective reservoir upward into the shallow groundwater system. The caprock appears to extend down to depths corresponding to between +200 m ASL and -200 m ASL depending on the horizontal location, below which the convection-dominated reservoir is found at temperatures between 280°C and 290°C. Typical vertical temperature gradient in the low permeability caprock layer is approximately 35 °C / 100 m, and large conductive upward heat flow is exhibited.

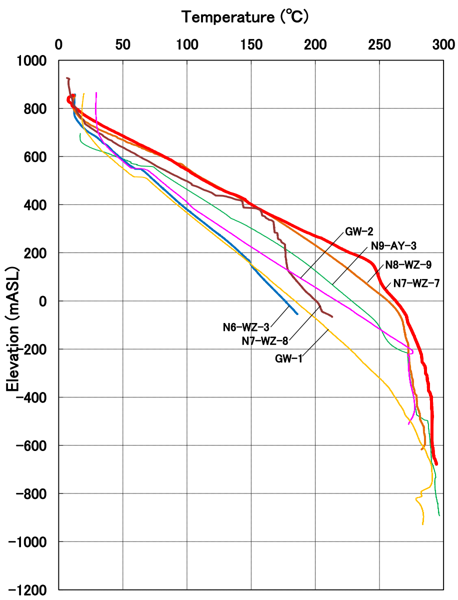

Figure 4: Stable temperature profiles in representative wells in the Wasabizawa geothermal field.

Figure 5 shows the inferred temperature distribution at -500m ASL, based on all the available temperature profile data in various wells. Inferred temperature distribution in the area delineates the horizontal reservoir extension, and the region between the 250°C and 280°C contours probably represents the outer boundary of the permeable reservoir. The regional heat source of the field is postulated to be deep seated residual magma of Mt. Yamabushi and Mt. Takamatsu located to the south-east of the field. Geological age of the Mt. Takamatsu volcanic rocks (see Figure 2) was measured to be 0.23 Ma by thermoluminescence dating (Takashima et al. (1999)).

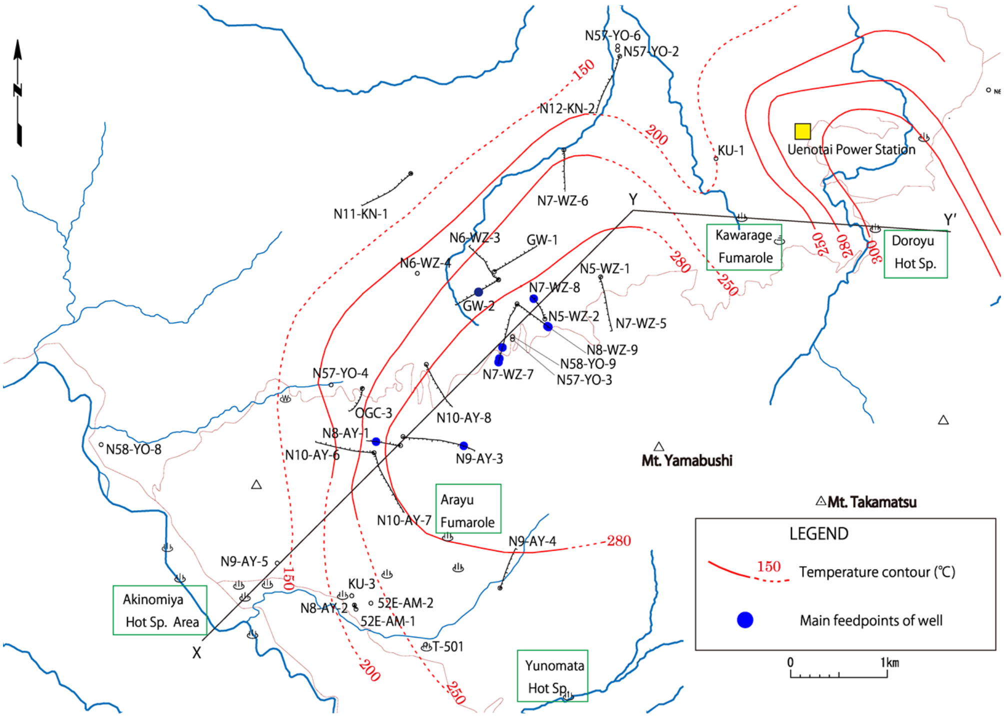

Figure 5: Inferred temperature distribution at -500 m ASL.

Correlation of pressure with equivalent feedpoint elevation is shown in Figure 6. The figure shows that almost all wells in the area are in good pressure communication with each other, except two wells (YO-8 and AY-5) located to the west near Akinomiya hot spring area: the feedpoint pressures of these two wells are about 1 MPa lower than those of other wells relative to the same elevation. Comparing saturation temperature profile corresponding to the reservoir pressure with stable temperature profiles in wells, it is likely that a two-phase region (steam cap) exists just below the cap rock in eastern part of the field where elevation of reservoir top is relatively high.

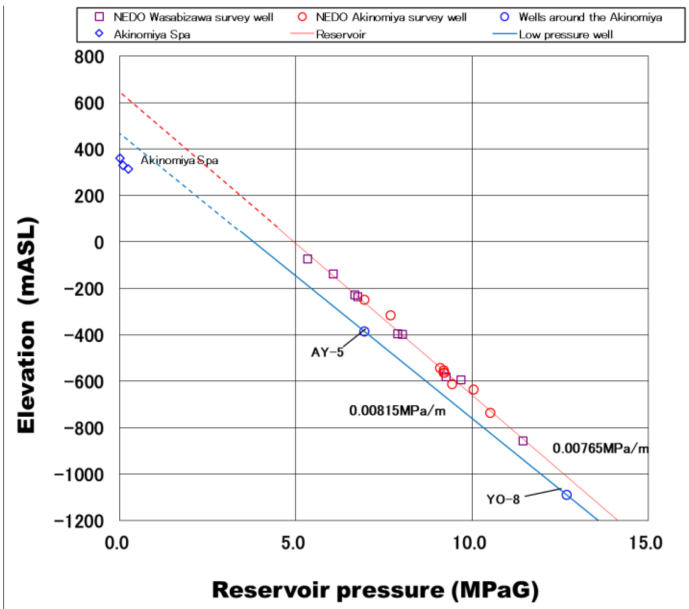

Figure 6: Measured downhole feedpoint pressures in wells as function of feedpoint elevation. Straight lines show least-squares fits to high pressure and low pressure wells respectively. The Akinomiya hot spring area has natural ground surface springs and shallow wells, and data of representative springs are shown in the figure.

In Figure 5, temperature decreases sharply to the south-west of the reservoir. Stable pressures in wells N58-YO-8 and N9-AY-5, located west of the field, are almost 1 MPa lower than those of the other wells at comparable elevations as mentioned above, and no pressure interference was observed in well AY-5 during the field-wide flow tests. These facts suggest that a nearly impermeable barrier exists between these two wells and the others, and thus the reservoir is isolated from nearby Akinomiya hot spring area by a relatively impermeable zone.

2.3 Geochemistry

Figure 7 shows a ternary plot of major anions (Cl, SO_4 and HCO_3) in hot spring water and well discharge water samples (locations of hot springs are shown in Figure 5). Well discharge water is neutral NaCl type brine, and almost all well waters plot close to the Cl corner, while brines of WZ-5 and 6 located to the east have minor concentration of SO_4. The Akinomiya hot spring waters show also NaCl type water with minor concentration of HCO_3. Three samples from the Doroyu hot spring located in the east of the field and one sample from Arayu hot spring plot close to the SO_4 corner, and are classified as SO_4 type "steam-heated water". Volcanic gases including SO_2 and HCl, and strong acidic Cl-SO_4 type hot springs caused by gas dissolution in the shallow ground water discharge at the Kawarage fumarole area in the north-east where temperatures are relatively low (Figure 5). One sample from Doroyu hot spring also shows acidic Cl-SO_4 type water (Figure 7). It is likely that the reservoir is also isolated from nearby Kawarage fumarole and Doroyu hot spring located to the east, based on the inferred temperature distribution and chemical composition of these hot springs. Thus, the Wasabizawa reservoir appears to be hydrologically disjoint from the nearby geothermal resource supplying the power station at Uenotai.

Figure 8 shows isotope compositions of waters of the area including calculated reservoir water from analyses of steam and water discharged from wells. The figure shows that the δD of the Akinomiya hot spring waters is apparently higher than those of the reservoir water. The fact implies that the source of Akinomiya hot spring water is different from that of reservoir brine, even though both waters indicate similar NaCl type water. This isotope analysis also supports the above-mentioned model that the reservoir is isolated from nearby Akinomiya hot spring area by a relatively impermeable zone. A range of isotope components of reservoir water at the Uenotai power station is also shown in Figure 8, and the range of δD is apparently different from that for the Wasabizawa reservoir. The figure also shows that Cl-SO_4 type waters from Kawarage fumarole and Doroyu hot spring areas are affected by mixing with volcanic gas.

Figure 9 shows variations in δD content with chloride concentration. The difference of δD between the reservoir waters and the Akinomiya hot spring waters is apparent in the figure. Reservoir fluid is neutral NaCl type brine with chloride concentration between 400 mg/L (WZ-5 and 6) and 2,400 mg/L (AY-1). The variation of chloride concentration among wells is rather high. The low Cl concentration of water may be due to dilution by steam condensate and/or possible recharge water from the eastern part.

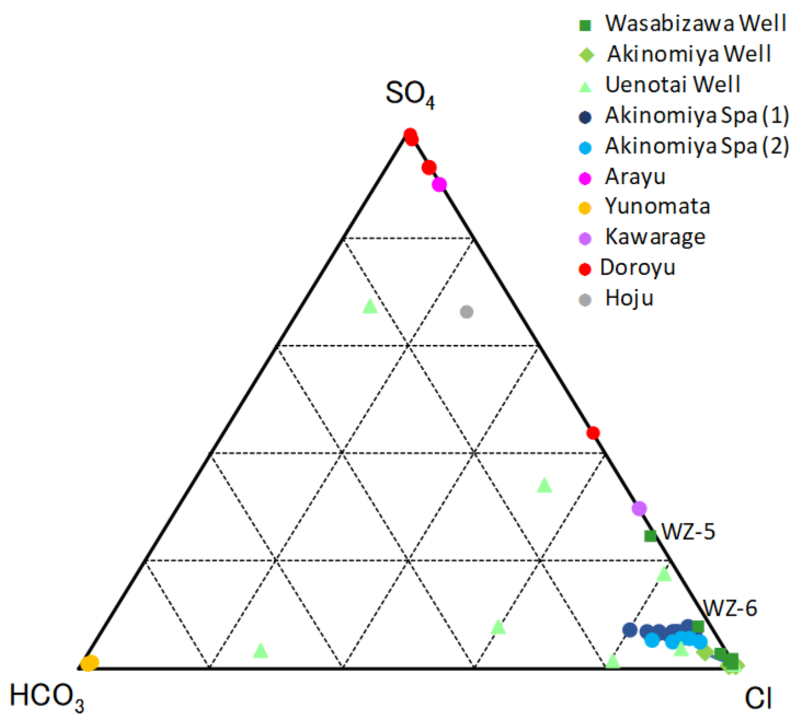

Figure 7: Ternary plot of major anions (Cl, SO_4 and HCO_3) in hot spring water and well discharge water samples. Location of hot springs are shown in Figure 5. Well discharge waters are classified by the area of NEDO surveys and the Uenotai area. The Akinomiya hot spring area involves numerous hot springs, and the water samples are divided by their location as northern (Akinomiya Spa (1)) and southern (Akinomiya Spa (2)) part of the area.

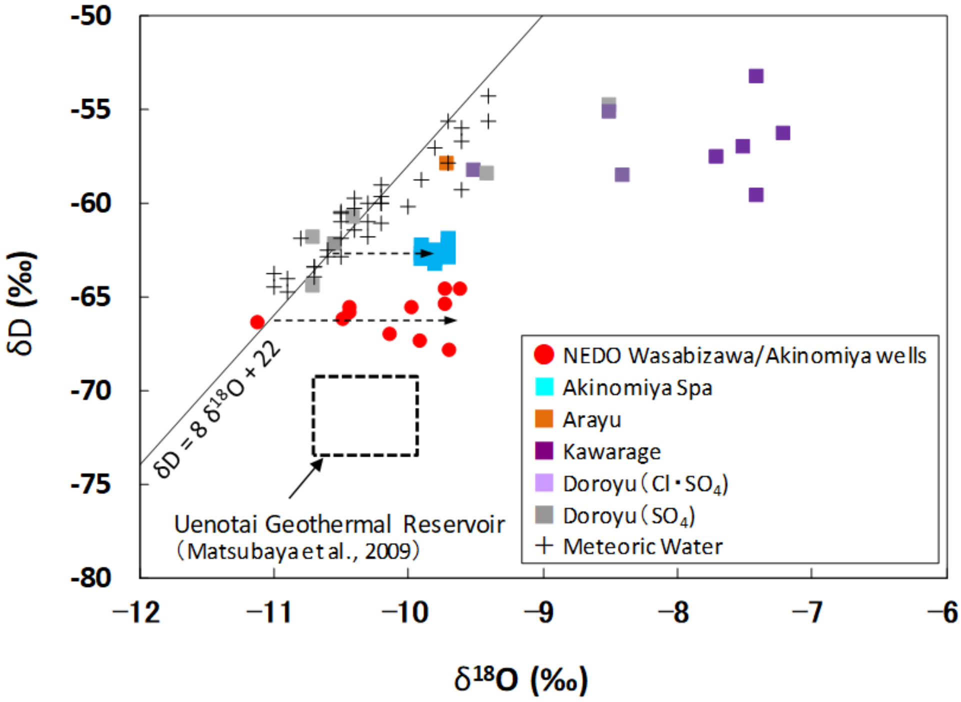

Figure 8: Isotope compositions of waters of the area. The composition of well water shows calculated reservoir water from analyses of discharged steam and water. Dashed square indicates the range of reservoir waters at the nearby Uenotai geothermal power station (after Matsubaya et al. (2009)). Black dashed lines with arrowhead show inferred oxygen shifts. The acidic Cl-SO4 type waters of Doroyu hot spring and Kawarage fumarole areas indicate an effect of mixing with volcanic gas.

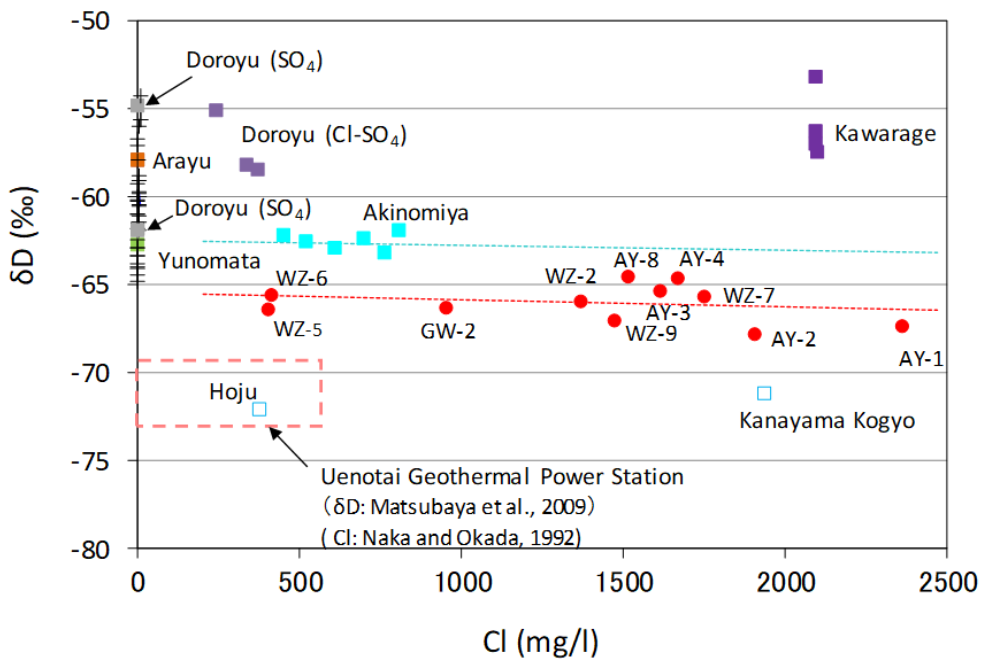

Figure 9: Variations in δD content with chloride concentration. Dashed straight lines show least-squares fits to Akinomiya hot springs (blue) and wells (red) respectively. Dashed square box (pink) indicates range of reservoir waters at the nearby Uenotai geothermal power station (after Matsubaya et al. (2009) and Naka and Okada (1992)).

3. CONCEPTUAL MODEL

Based on synthesis of all the available data, a conceptual model was developed as shown in Figure 10, which provided technical basis for planning the power station. A regional heat source of the field is postulated to be deep seated residual magma of volcanic activities of Mt. Yamabushi and Mt. Takamatsu. The geothermal reservoir is hosted by the naturally-fractured granitic rocks, and the fracture network is developed beneath relatively impermeable cap rock layer. We consider that the cap rock layer may be formed by thermal alteration, since fractures in the cap rock layer were sealed by secondary minerals like kaolinite, quartz, montmorillonite, calcite and so on, based on mineral analyses of cuttings obtained during drilling. Possible fault-controlled upwelling fluid from the deep source may flow into the reservoir, and a hydrothermal convection zone is formed in the fracture network. It is likely that a two-phase region (steam cap) exists just below the cap rock where the reservoir top is relatively shallow. Reservoir fluid is neutral NaCl type brine with chloride concentration between 400 mg/L (WZ-5 and 6) and 2,400 mg/L (AY-1). Within the hydrothermal convection zone, dilution may be occurring by steam condensate and/or possible recharge water from the eastern part.

The Wasabizawa reservoir is isolated from nearby Akinomiya hot spring area to the south-west by a relatively impermeable zone. The impermeable zone is not fully understood at present. It is likely that the reservoir is also isolated from nearby Kawarage fumarole and Doroyu hot spring located to the east, based on the inferred temperature distribution and chemical composition of these hot springs. Thus, the reservoir appears to be hydrologically disjoint from the nearby geothermal resource supplying the power station at Uenotai.

Based on the conceptual model, and considering the surface topography and location of existing exploratory wells, the location of production well pads and reinjection well pads were planned to be set about 2 km apart from each other. We set three production well pads (WA, WB (at highest elevation of +930 m ASL) and WC) and two reinjection well pads (AA and AB (at lowest elevation of +620 m ASL)). Planned production zone to the east and injection zone to the west are also shown in Figure 8, and the production and injection strategy should allow sustainable operation in the future. A numerical reservoir simulation based on the conceptual model also showed that the 46 MWe scenario will be sustainable (Nakanishi et al. (2017)).

Total of 11 production and reinjection wells, other than five existing exploration wells which will be converted to production and injection wells, were drilled targeting inferred fault zones, and an extensive heterogeneity of fracture distribution in the granitic basement rock was observed. Sasaki et al. (2018) discussed that the heterogeneity of hydraulic properties among wells are attributed to the differences in hydrothermal alteration related to the geotectonic history of the caldera. Asai et al. (2020) analyzed the permeability structure quantitatively using a number of pressure interference test undertaken during short term production and injection tests for new wells. Even though extensive heterogeneity of productivities and injectivties was observed among wells (including some dry holes), large excess total production capacity was successfully obtained relative to required flow rate for 46.199 MWe output.

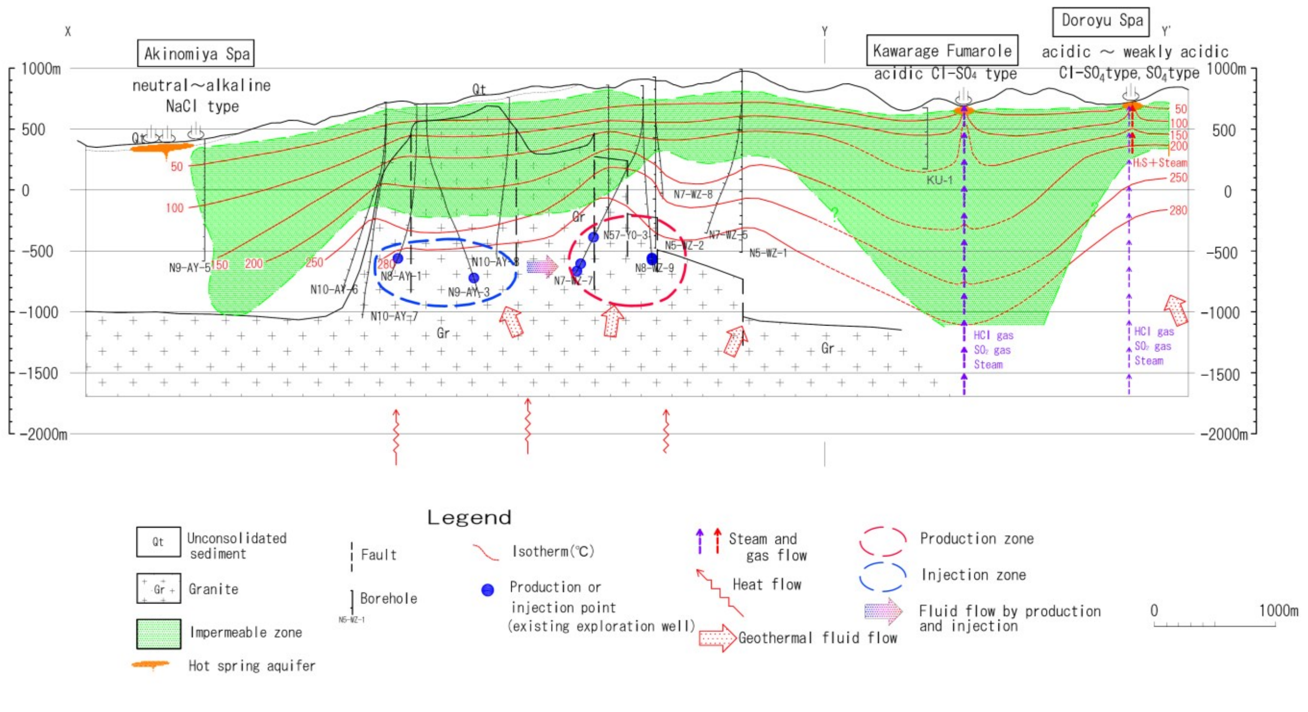

Figure 10: Conceptual model of the Wasabizawa field from south-west (left) to north-east (right). Location of the section is shown in Figure 5. Inferred temperature distribution is shown by red lines. Green shaded area shows a cap rock layer and western and eastern impermeable zones. The reservoir is hosted by the naturally-fractured granitic rocks. Conceptualized fluid flow pathways are indicated by arrows. Planned production and reinjection zones set apart from each other are also shown by red and blue thick dashed circles respectively.

4. CONCLUDING REMARKS

A conceptual model was developed for the Wasabizawa geothermal field where an extensive exploration program has been carried out. The high temperature geothermal reservoir is hosted by the naturally-fractured granitic rocks. The model is consistent with the available data, and provided technical basis for planning the power station. Commercial operation of the YGP's new "Wasabizawa Geothermal Power Station", 46.199 MWe double-flash steam plant, began in May 2019. The power station is the first new large-capacity (≥ 10 MWe) geothermal power plant constructed after 23 years of geothermal stagnation in Japan since the commissioning of the Takigami geothermal power station (27.5 MWe) in 1996.

5. ACKNOWLEDGEMENTS

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