PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Time-lapse Gravity and Self-potential Measurements for Reservoir Monitoring in the Wasabizawa Geothermal Field, Japan

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Keywords: Geophysical Monitoring, Gravity, Self-potential, Wasabizawa

ABSTRACT

Time-lapse geophysical exploration in geothermal resource development areas is an effective method for monitoring reservoir behavior and often provides useful information for reservoir simulation to improve the reliability of its prediction. The Wasabizawa geothermal power plant in Akita prefecture, Japan has been in operation since May 2019 with a generation capacity of approximately 46 MW. We have been performing repeated gravity and self-potential (SP) measurements, as well as GNSS surveys, around the power plant both before and after the start of the operation. The time-lapse gravity measurements revealed apparent changes in gravity at the ground surface around the production area. On the other hand, no significant gravity changes have been observed around the reinjection area. The SP profile along the line connecting the production and reinjection areas shows a convex change around the production area, which may correspond to the upward flow of hydrothermal fluid. We have also conducted reservoir simulations and attempted the history matching between the observations and the simulations.

1. INTRODUCTION

In geothermal resource development, monitoring the temporal variation of the reservoir condition is important for evaluating the sustainability of power generation. Geophysical monitoring techniques generally provide extensive yet indirect data regarding the reservoir behavior, and the combination of these data with the well-based monitoring allows for more advanced understanding of the reservoir. Gravity monitoring is used to reveal temporal density changes in the reservoir, and has been carried out in many geothermal fields and observed the geothermal fluid movement caused by production and reinjection (e.g., San Andres and Pedersen (1993); Sugihara and Ishido (2008)). SP has been proposed to be sensitive to underground fluid flow, and in several previous studies, SP monitoring has been conducted to investigate reservoir fluctuations (Yasukawa et al., 2005). It is anticipated that these geophysical data will provide constraints on reservoir simulations and enhance the reliability of the simulations.

Since 2017, AIST and J-Power have been engaged in the collaborative research on the geophysical monitoring, including gravity and SP, and numerical prediction of reservoir behavior associated with power plant operation in the Wasabizawa geothermal field. We have periodically measured gravity and SP profiles, as well as elevation changes by GNSS survey in order to clarify the reservoir behavior. This paper presents a summary of these monitoring results and a discussion of how to improve the reservoir model by matching the observations and the simulations.

2. WASABIZAWA GEOTHERMAL FIELD

In the Wasabizawa geothermal field, which is located in Akita prefecture, the northeastern part of Japan, two geothermal development promotion surveys supported by the New Energy Industrial Technology Organization (NEDO) were performed (NEDO, 1998; NEDO, 2001). These surveys have led to a relatively comprehensive delineation of the geothermal reservoir (Figure. 1). The Wasabizawa geothermal power plant has been in operation since May 2019 with a generation capacity of approximately 46 MW operated by Yuzawa Geothermal Power Corporation (YGP) which is jointly established by J-Power, Mitsubishi Materials Corporation (MMC), and Mitsubishi Gas Chemical Company, Inc. (MGC).

A conceptual model of the field (Nakanishi et al. (2020)) shows that the reservoir mainly exists between two relatively impermeable zones. The reservoir is isolated from nearby Akinomiya hot spring area to the southwest by a relatively impermeable zone. It is likely that the reservoir is also isolated from nearby Kawarage fumarole to the east. The reservoir is hosted by naturally fractured granitic rocks and topped by an impermeable caprock layer. The principal heat source for the geothermal system is believed to underlie the area around the Mt. Takamatsu and Mt. Yamabushi on the southeast side of the field. The power plant facilities were constructed along the prefectural road, with the production area on the northeastern side and the reinjection area on the southwest side.

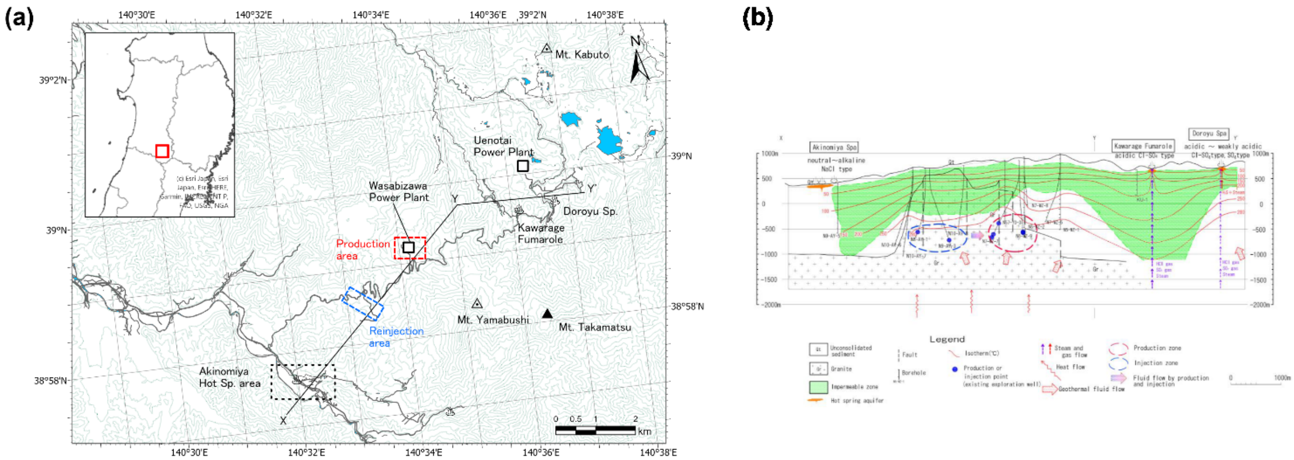

Figure 1: (a) Location of the Wasabizawa geothermal field. The original basemap was provided by Geospatial Information Authority of Japan. (b) Conceptual model of the field from southwest (left) to northeast (right) (Nakanishi et al., 2020). The letters X, Y and Y' in the figure roughly correspond to the same letters in Figure 1a. The green shaded area corresponds to a caprock, the reservoir exists isolated from the Akinomiya spa area and the Kawarage fumarole. Planned production and reinjection zones are shown by the red and blue dashed circles respectively.

3. GRAVITY AND SELF-POTENTIAL MONITORING

3.1 Hybrid Gravity Monitoring

In the field, we have carried out hybrid gravity monitoring using an absolute gravimeter and relative gravimeters in combination. The survey area covered the production and reinjection zones, with a total of 27 gravity stations for the relative survey. In addition, one gravity reference point was established at a distance from the production/reinjection area, which would not be affected by the reservoir perturbation (Figure 2). The gravity monitoring survey was started in July 2017, and the relative survey has been conducted 1 – 3 times per year. Moreover, GNSS surveys have been performed to confirm elevation changes at each gravity station, with a focus on stations in proximity to the production/reinjection zones.

Absolute gravity values at the reference point were measured by Micro-g LaCoste FG-5 (#217), and tidal and barometric corrections on the measurement data were performed using the manufacturers' processing software (g9). For the relative gravity surveys, we used two gravimeters of Scintrex CG-5 (#0352, #1329) until 2020, and have been using a Scintrex CG-6 gravimeter (#0228) since 2021. The scale factor for each gravimeter was determined regularly, and its effect on the monitoring results was calibrated. The loading effect of the earth tide on the data was removed theoretically using Nakai (1979) for the solid earth tide and GOTIC-2 (Matsumoto et al. 2001) for the ocean tide. The barometric correction was facilitated by leveraging the pressure observations from the Automated Meteorological Data Acquisition System (AMeDAS), which is operated by the Japan Meteorological Agency and is situated in close proximity to the site. Furthermore, non-linear drift terms in the data were estimated and removed for each gravimeter according to the procedure in Murata (2019).

3.2 Self-potential Monitoring

The SP profile survey was started in October 2019, and prior to the commencement of power plant operations was not obtained. Survey lines were established along prefectural or forest roads in the field, and the longest line of approximately 7.5 km follows the road connecting the production and the reinjection areas (Figure 2). Annual measurements of the SP profile have been obtained along almost the same survey lines. Ag-AgCl non-polarizable electrodes were used, and the electrode separation was approximately 50 m. The maximum length of electric cable extension was constrained to 2 km, and three measurement points were obtained at each junction of individual cable sections to avoid error accumulation. However, it should be noted that the survey lines were not looped and therefore the evaluation of closure error for each measurement was difficult. When comparing the SP profiles from different measurement years, the average value at the points where the altitude is lower than 550 m A.S.L. and the influence of reservoir perturbation seems to be small, was used as a reference.

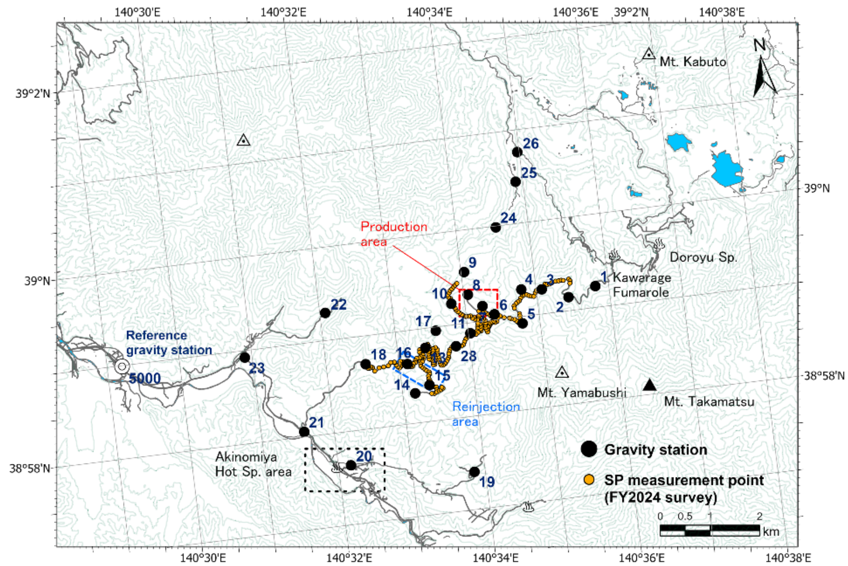

Figure 2: Distribution of gravity and SP measurements points. Filled black circles correspond to relative gravity measurement stations, a double circle to a reference point and filled orange circles to points for SP measurement in 2024. The number nest to each gravity station corresponds to the station number (No. 1-11, 13-26, 28, 5000 (reference station)).

4. RESULTS AND QUALITATIVE INTERPRETATION

4.1 Time-series Gravity Changes

The absolute gravity measurements indicate that the gravity values at the reference station have generally fluctuated within ±5 μGal throughout the monitoring period. As there were some missing measurements due to trouble of the gravimeter, in this study, we have assumed that the absolute value at the reference remains constant. In addition, we calculate the changes in baseline length between each gravity station and the nearest GPS-based Control Station, operated by the Geospatial Information Authority of Japan, from the GNSS surveys. This analysis yielded no systematic changes attributable to the reservoir perturbation. However, a decline in elevation of approximately 7 cm at station No. 21, located far from the plant, was observed after 2020, which may be attributed to nearby road construction. Consequently, the influence of elevation changes at the stations was not considered during the calculation of gravity values at each station.

The baseline data for this study was derived from the mean gravity values obtained from five relative measurements conducted prior to the commencement of power plant operations in 2019. The time-series changes were then determined by examining the differences between each relative measurement and the baseline. The results indicate that decreases in gravity have predominantly observed on the southeast side of the production area since the start of operation (Figure 3). These gravity decreases may suggest the progression of vaporization within the reservoir due to pressure decrease by fluid production. At the station No. 21, an increase of more than 20 μGal was observed in 2024 compared to the baseline, which attributes to the previously mentioned elevation change. The time-series gravity changes at respective three stations surrounding the production and reinjection areas are shown in Figure 4. This figure suggests that at the station No. 5, which is located at the southeast of the production area, the gravity had decreased up to nearly 20 μGal for three or four years since the beginning of operation and has become stable state in recent years. At the other stations near the production/reinjection area, there is also tendency for gravity to decrease initially after the operation started, and then to gradually increase or stabilize. However, the gravity changes at these stations are generally within 10 μGal throughout the monitoring period. As the measurements include the fluctuation due to measurement errors and natural perturbations caused by precipitation and groundwater table, whether such the small gravity changes result from the operation of the power plant remains to be investigated.

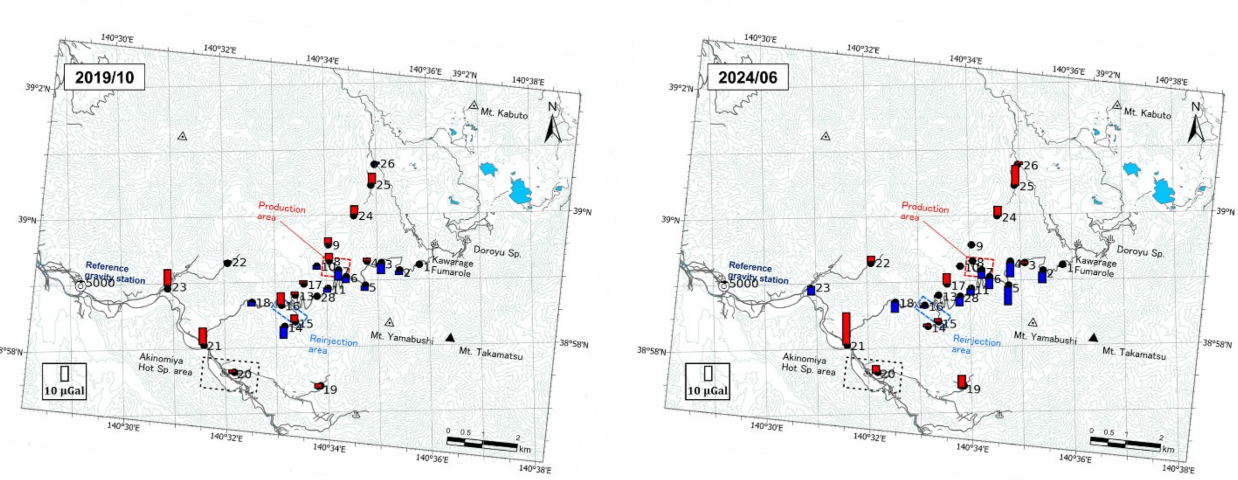

Figure 3: Distribution of gravity changes from the baseline data (left: survey in Oct. 2019, right: survey in June 2024). For each station, the difference in gravity from the baseline data is shown by the height of the bar, with red bars meaning an gravity increase and blue ones to a decrease.

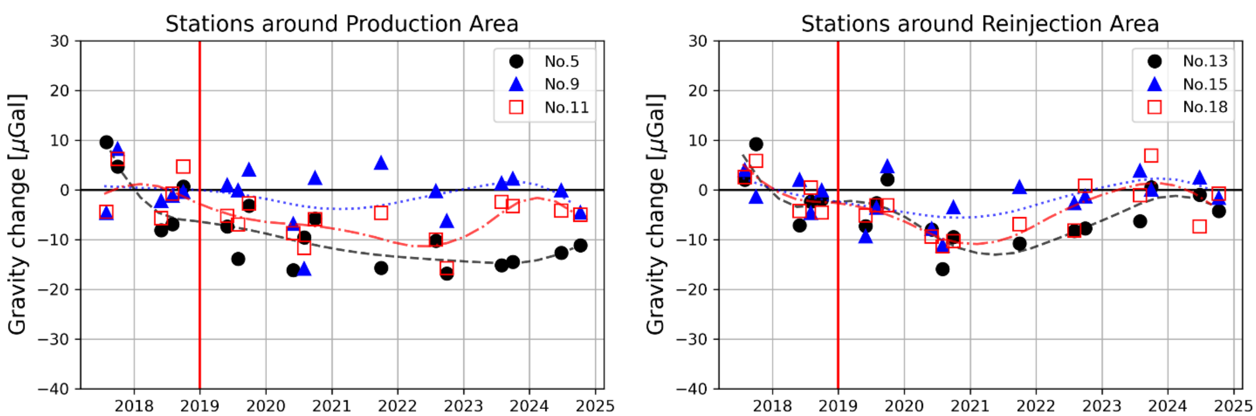

Figure 4: Time-series gravity changes for each measurement point around the production/reinjection areas. Each marker corresponds to the gravity difference between each observation and the baseline, and the dashed curves are obtained by smoothing the observation results with the 3-order B-spline. The red vertical line represents the start of the power plant operation in 2019.

4.2 Self-potential Profile

The SP profiles measured along the prefectural road were obtained with the gravity station No. 18 as the reference point, and the profiles for each measurement year are plotted in Figure 5. The SP was measured approximately every 50 m, however the measured values are smoothed using the 3-order B-spline function because of the large variance. This figure shows that the SP profiles are almost the same regardless of the year. Large negative SP anomalies of more than 100 mV are observed in the regions about 1,800 m and 3,700 m away from the reference, where the hot water transport pipes cross under the road. Several studies (Bigalke and Grabner (1997); Ishido et al. (2013)) proposed that buried electric conductors cause large negative SP anomalies in the surrounding area, and the observed negative anomalies are likely due to the pipes. In SP measurements in areas with elevation differences, streaming potential associated with shallow groundwater flow is often observed, and previous studies remove the effect from SP profiles by using a linear function of elevation (Hase et al. 2005). The SP profiles around the No. 18 station, where the production/reinjection effects on the SP may be small, suggest that the SP decreases as the elevation increases, but the groundwater effect seems to be sufficiently small compared to the other SP anomalies observed. Consequently, the global SP profile can be considered as follows: the SP gradually decreases from the reference to the production area with a maximum difference of about 100 mV around the power plant, and subsequently the SP increases towards the east and shows a convex change with a maximum value between the gravity stations No. 4 and No. 5. Many previous studies have observed similar convex profiles of SP in geothermal areas, indicating areas of rising hot water (Revil et al. (2023)). The SP profile observed in this study suggests that the zone of hot water convection is located on the southeast side of the production area, which coincides with the area where decreases are observed in the gravity monitoring.

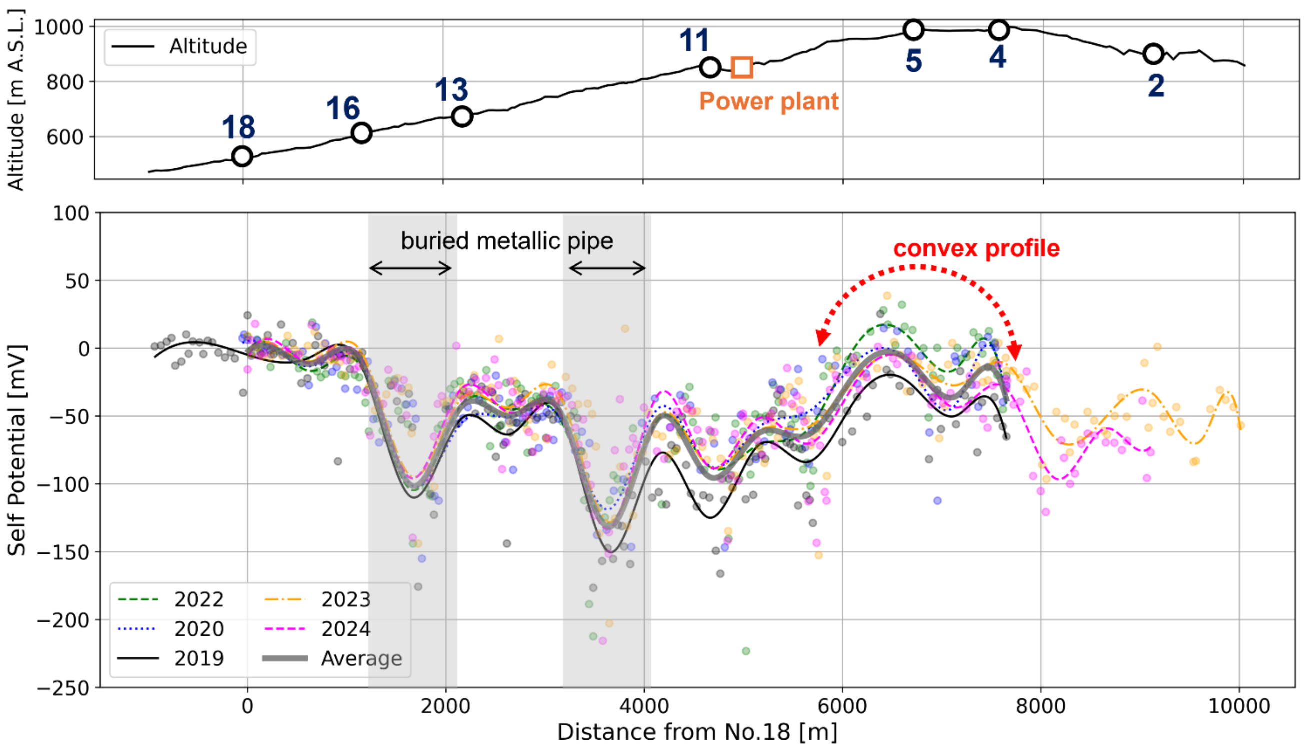

Figure 5: SP and altitude profiles along the measurement line connecting the production and reinjection area. The locations of the gravity stations were also shown in the altitude profile. Markers in the lower figure represent actual SP measurements, and the solid and dashed curves are obtained by smoothing the results with the 3-order B-spline. The large negative SP anomalies were observed in the grey shaded zone, which might result from a buried metallic pipe for hot water transportation. The convex SP change was observed in a region where the altitude was higher than the power plant.

5. HISTORY MATCHING WITH RESERVOIR SIMULATION

In the Wasabizawa geothermal field, we have also conducted reservoir simulations using STAR (Pritchett, 1995). The reservoir model (Figure 6) was adjusted to be generally consistent with observations such as reservoir temperature and pressure, and Nakanishi (2017) and Kano et al. (2024) provided detailed description of the reservoir model. In this model, the following boundary conditions were given. For the bottom boundary, a certain amount of conductive heat flux and fluid mass flux was supplied to the area considered to be close to the heat source, and only heat flux was to other areas. For the upper boundary, the boundary condition was set to be fixed-pressure type, and downward water supply based on average annual precipitation multiplied by a "deep percolation reduction factor" in this field was given. All the lateral boundaries were treated as impermeable and insulated to provide conservative estimations of future fluid production capacity. The values of heat and mass flux used in the simulation were determined by matching the 'natural state' simulation with the observations. The reservoir simulation was performed on this model, using the actual operating history data up to about 5.5 years after the start of operation. Based on the distribution of underground saturation and pressure obtained from the reservoir simulation, STAR's postprocessor calculated the time-series changes in gravity and SP at the ground surface.

5.1 Gravity Changes

The gravity changes predicted by the simulation show that the gravity decreases occurred larger on the southeast side of the production area, and small changes around the reinjection area (Figure 7a). The distribution of the calculated gravity changes is roughly consistent with the observation results. Around the production area, gravity is expected to decrease with time because the water level in the reservoir becomes lower associated with decreasing pressure due to the production. Meanwhile, around the reinjection area, the injection of a low-temperature fluid may bring out the gravity increase. In the Wasabizawa, the influence of reinjection on the gravity changes compensates for that of production, which may be one of the reasons why the area of decreased gravity is concentrated on the southeast side of the production area. On the contrary, the magnitude of gravity decreases around the production area obtained from the simulation is much larger than the observation (Figure 7b). Although the simulation results show that the gravity continues to decrease with time, from the observations the gravity decreases about three years after the beginning of the operation and then becomes the stable state. One of the major reasons for the discrepancy may be that the simulation does not take into account recharge in response to the decrease in reservoir pressure associated with the production. In addition, as the gravity changes are affected by the extent of the two-phase zone, there is room for further consideration on improving the geological model in the simulation.

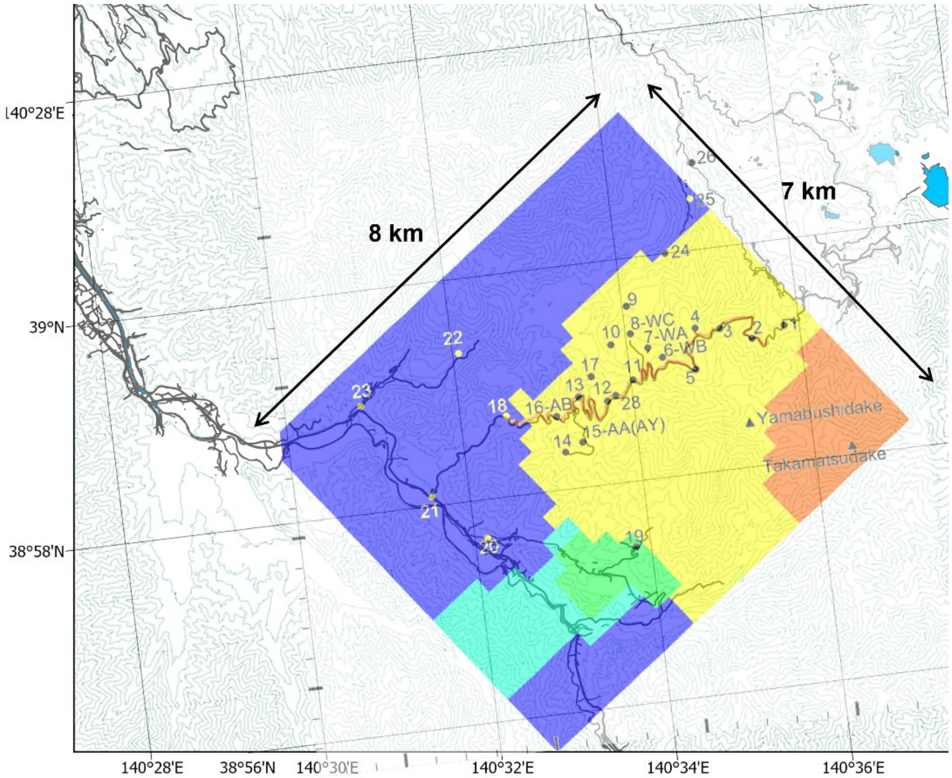

Figure 6: Rock phase distribution at the bottom of the reservoir model. Yellow and orange areas correspond to high permeability rocks as the reservoir, and in the orange area heat and mass fluid sources are obtained from the bottom. In the yellow area, only the heat source is given. Blue, cyan and green areas are impermeable. Gravity and SP changes were calculated on the stations and lines measured actually. When considering the effect of recharge, the boundary conditions in the area closed in the red frame were changed.

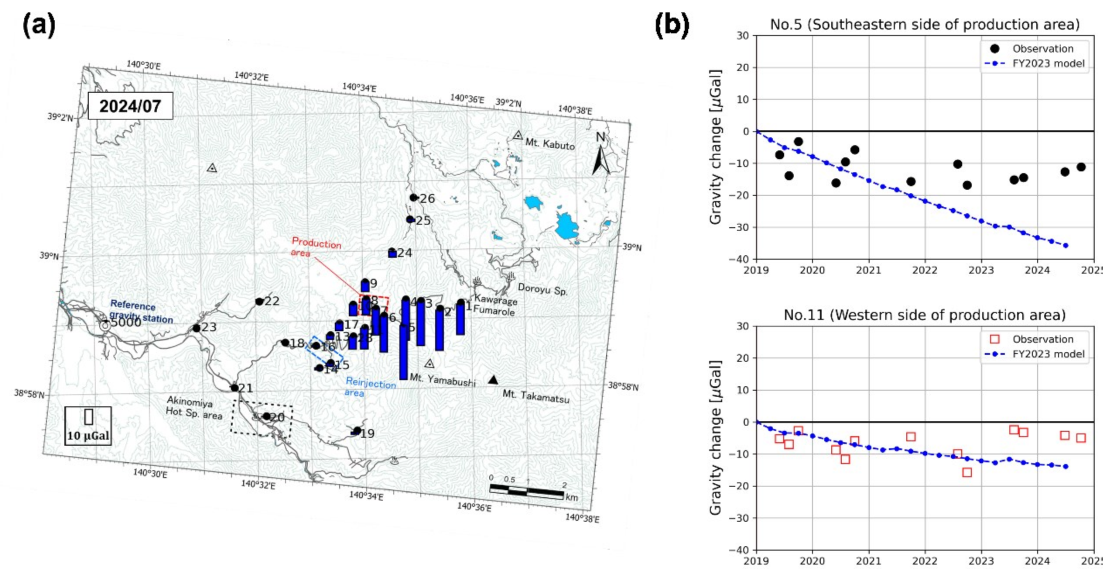

Figure 7: Gravity changes since the start of the plant operation obtained from the reservoir simulation. (a) Gravity change distribution in July 2024. (b) Comparison of gravity change at No. 5 and No. 11 stations between the simulation (the dashed lines) and the observation (black and red markers). The blue lines correspond to the simulation based on the FY2023 model (Kano et al., 2024).

5.2 Self-potential Changes

The yearly SP profiles along the measurement line in 2023 were obtained from the simulation (Figure 8). The prediction curves are roughly consistent with the measurement results for the section from the station No. 18 to the vicinity of the production area. In this section, the SP gradually decreases with elevation, suggesting that streaming potential due to the fluid flow following the topography. On the other hand, the simulation cannot reproduce the convex SP change observed on the southeast side of the production area. The convex profile may indicate an upward hydrothermal fluid flow in the reservoir, and this inconsistency suggests the necessity of improving the reservoir model such as permeability. Regarding the time-series changes in the SP profile, the SP increase of several tens of mV is observed between the reinjection and production areas in both the observations and the simulations. One of the reasons for the increase may be the geothermal fluid flow in the reservoir from the reinjection area to the production area caused by the plant operation, which compensates for the SP decrease due to the streaming potential generated at a shallower depth according to the topography.

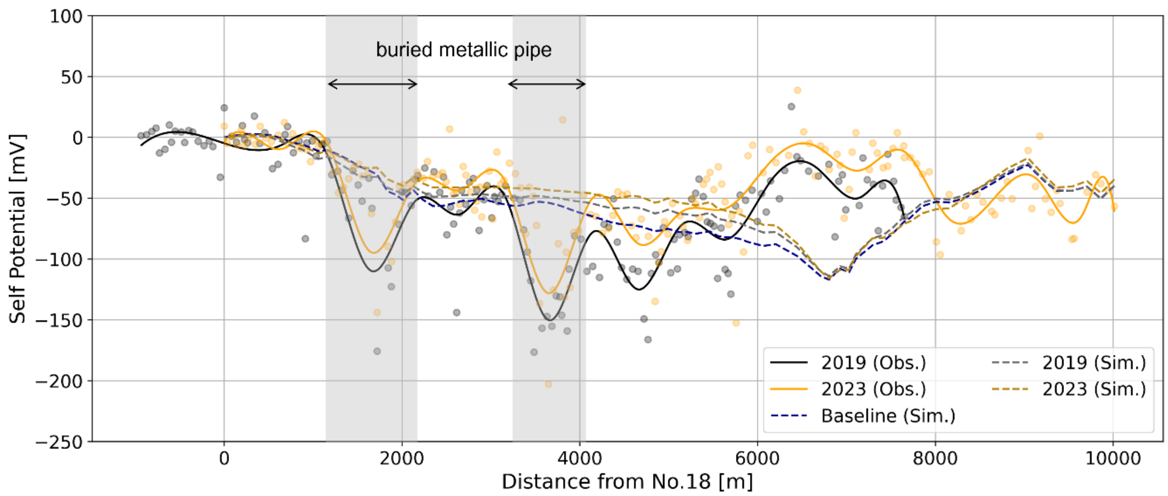

Figure 8: Comparison of the SP profile between the simulation and the observation. Solid lines correspond to the observations, and dashed lines to the simulation results. The simulations generally reproduce the tendency that the SP decreases from the reference to the power plant, however, the upward convex change observed on the southeastern side of the plant cannot be reproduced well.

6. CONCLUSION

In this study, we conducted gravity and self-potential monitoring in the Wasabizawa geothermal field. Hybrid gravity measurements have been performed since 2017, two years before the beginning of the plant operation. The time-series gravity changes reveal the decreases in gravity mainly on the southeast side of the production area, which may suggest the progress of vaporization within the reservoir. The SP profile shows the upward convex SP change in roughly the same region where the gravity decreases were observed, which may indicate the existence of upward geothermal fluid flow in the reservoir. We also performed the reservoir simulation and history-matching between the observation and the calculation. The simulated gravity change distribution roughly agreed with the observation, but the magnitude of the decreases was larger in the simulation. One of the reasons for the discrepancy may be that the simulation did not consider the fluid flow across the lateral boundaries of the model caused by the reservoir pressure changes. The simulated SP profile could not reproduce the observed convex SP change, and this inconsistency suggests the necessity of improving the reservoir model such as permeability. This study indicates that geophysical monitoring data may be useful to improve the reservoir model through history-matching between the observation and the simulation.

ACKNOWLEDGEMENT

The authors are grateful to Yuzawa Geothermal Power Corporation for their generous support on developing the model and conducting the history matching simulations.

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