Volcanic activity of Mt Kusatsu-Shirane suggested by the variations in fumarolic gas composition and crater lake water chemistry

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Introduction

In the early of 2014, a swarm of volcanic earthquake has started at Mt Kusatsu-Shirane (Japan Meteorological Agency, JMA, 2015). The daily number of earthquake reached to 149 as maximum on 24th July 2014, followed by a sharp decrease until September of 2014. JMA also detected a change of geomagnetic force induced by the de-magnetization of crust beneath the summit crater on the mountain. We carried out a geochemical observation at the geothermal area and the crater lake.

Results and Discussions

After the swarm of volcanic earthquake on July, the concentration of some chemical components in the lake water of Yugama crater increased, for example, Cl^- and H^+ concentration increased, respectively, 81 and 67%, in Oct 2015 relative to Aug 2014, suggesting the input of HCl. A similar change has been observed in 1990 at the same crater lake. The change is consistent to the invasion of ground water into the solidifying magma as proposed by Ohba et al (2008). The Cl in the solidifying magma could be extracted to fluid as HCl under the super critical condition of H_2O (Giggenbach, 1996).

The CO_2/H_2O ratio of fumarolic gases at the geothermal area on the mountain was 0.044 in July 2014, which decreased to 0.021 in Oct 2015. One possible explanation to the change of CO_2/H_2O ratio is the change of degassing pressure of magma. Even if the H_2O and CO_2 content in magma is constant, the pressure of degassing affects the CO_2/H_2O ratio of fluid degassed from magma. Due to the low solubility of CO_2 relative to H_2O, the high degassing pressure increases the fluid CO_2/H_2O ratio. The magma of Mt Kusatsu-Shirane might be pressurized by the sealing zone (Fournier, 1999) until the early of 2014. If the sealing zone breaks, the CO_2 enriched fluid can be liberated. The swarm of earthquakes is generated by the CO_2 enriched magmatic fluid injected to the shallow hydrothermal system beneath the crater lake. The HCl enriched fluid arrived at the lake with slight delay after the injection of CO_2 enriched fluid.

Keywords: Mt Kusatsu-Shirane, Hydrothermal system, Crater lake

Hydrothermal system beneath the Jigokudani valley, Tateyama volcano

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The mechanism of phreatic eruption has not been well understood yet, although we observed phreatic eruptions many times. Phreatic eruption is known to occur in the hydrothermal system developed within a volcanic edifice because the ejecta of phreatic eruptions often contain the hydrothermally altered minerals originated from the hydrothermal system. Therefore, an understanding of the hydrothermal system is essential to clarify the mechanism of phreatic eruption.
The Jigokudani valley, Tateyama volcano located in the Hida Mountains, has an active solfatara field, and was formed by repeated phreatic eruptions some 40,000 years ago. Recently the Jigokudani valley showed the increased volcanic activity, for example, a sulfur outflow and temporal changes in the composition of fumarolic gases. These situations make us expect the presence of a well-developed hydrothermal system which is in preliminary stage of a phreatic eruption.
The objective of this study is to reveal the hydrothermal system beneath the Jigokudani valley by resistivity exploration and hot spring water analysis. In general, hydrothermal fluids or hydrothermally altered minerals are electrically conductive, whereas gases or rocks are resistive. Therefore, a resistivity imaging by using an audio-frequency magnetotelluric (AMT) method is suitable for structural investigation of the hydrothermal system. We estimated where the hydrothermal system developed by AMT survey. In addition, we discussed what has happened in the hydrothermal system by hot spring water analysis. We compared the inferred resistivity structure with the results of hot spring water analysis, which enabled us to estimate more realistic hydrothermal system.
The 3D resistivity structure showed that the Jigokudani valley has a cap structure that is composed of upper hydrothermally altered layer (called cap rock), which shows electrically conductive and rock) and hydrothermally low-permeable, and lower gas reservoir which shows relatively high resistivity. A highly conductive layer is found in a depth of around 500 m and it seems to extend eastward as the depth becomes large. These features were interpreted as the hydrothermally altered pyroclastic flow deposit and a fluid path from the deep magma, respectively.
We measured an electrical conductivity, temperature and pH of hot spring water on the spot. The ion concentration and isotope ratio of hot spring water samples were analyzed at 27 locations. The hot spring water in the Jigokudani valley was classified into three types based on Cl^-/SO_4^{2-} concentration ratio. Considering both the chemical composition and the isotope ratio, three types of hot spring water were derived from condensation of volcanic gases, a mixing of meteoric water and vapor phase separated at a shallow depth and the surface water supplied with volcanic gases consisting of mainly H_2S.
An integrated view of the resistivity structure and geochemical analysis suggests that the hydrothermal system develops in the depth to 500 m and a common parental fluid of all hot springs is there. In addition, a gas reservoir estimated from the resistivity survey corresponds to the vapor phase inferred from the geochemical analysis. The concentration of Cl^- in the hot spring water derived from the vapor phase is a measure of the temperature condition beneath the cap rock, which implies that the monitoring of Cl^- could be useful to know the physical state of the cap

structure.

Keywords: hydrothermal system, phreatic eruption, AMT, hot spring water analysis, cap structure

The effect of the change of geothermal system for the scaling on surface facilities

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Geothermal usage such as geothermal power generation, hot spring, space heating based on the volcanic hydrothermal activity is progressing in worldwide. In using geothermal energy, the scale precipitation from fluid composition on surface facilities such as pipeline, heat exchanger become serious problem to maintain the system.
Therefore it is necessary to predict the kind and precipitaion rate of the scale in usage temperature region.
And during long term, the situation of scaling chnge with geochemical composition.
For example, the Kakkonda geothermal area, Iwate prefecture, north-eastern of Japan, there is 80MW geothermal power plant using high temperature fluid from the reservoir at the boundary between Quaternary Kakkonda granite and Pre-Tertiary formations about 3km depth. And metal sulfide minerals deposited at production wellhead and pipeline from fluid. From one of prodution well, in early stage, the fluid pH is about 4. At this well, scale precipitated including amorphous silica, chalcocite (Cu_2S), bornite (Cu_5FeS_4), loellingite ($FeAs_2$) and native antimony (Sb). On progress of production the fluids from deep reservoir suffered by the fluid of shallow reservoir and meteoritic water. The pH change to about 6 and SiO_2 decreased and the scale changed to tetrahedrite ($Cu_{10}[Fe,Zn]_2[As,Sb]_4S_{13}$) and sulfur increased.
And in the case of two-year circulation test in the Hijiori EGS system in Yamagata Prefecture, Japan, amorphous silica and calcium carbonate scale tended to precipitate in the flow line, with the ratio of silica and calcium carbonate depending on fluid temperature and chemical composition. In the case of well HDR-2, with reservoir temperature decreasing, scale changed from amorphous silica to calciumu carbonate. The scale change was contorlled the disolution and precipitation of anhydrite in reservoir. At reservoir has high temperature, anhydrite precipitated in reservoir but after coolong reservoir, the high Ca fluid flow up surface facilie and cause to precipitae calcium carbonate.

Keywords: Geothermal energy, scale, geochemistry of fluid

Numerical model of temporal changes in magnetic total field and ground deformation due to hydrothermal system in volcanoes (1). - A case study on Tokachi-dake volcano, Japan -

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Localized temporal changes in the magnetic total field and ground deformation are often observed at volcanoes that have hydrothermal system within. At Tokcahi-dake volcano, one of such volcanoes in central Hokkaido, Japan, continuous magnetic field changes accompanying ground inflation at a shallow depth have been observed. At this volcano, small phreatic explosions took place commonly among major magmatic/phreatomagmatic eruptions in recorded history (JMA, 2013). Repeated magnetic total field surveys since 2008 revealed demagnetization beneath 62-2 crater between 2008 and 2009 (Hashimoto et al., 2010). Besides, the baseline changes by GPS suggested a localized inflation beneath the crater after 2007 (JMA, 2015). Assuming the thermomagnetic effect, Hashimoto et al. (2010) proposed a possible mechanism for such changes. They suspected that steam ascending along the conduit experienced phase change at a shallow depth, releasing latent heat and flowing back as liquid to form a hydrothermal reservoir. They also suggested that increase in heat supply from depth is not essential for the demagnetization in case that heat discharge rate from the crater has been reduced for some reasons. In this study, we verify such a conceptual model by using a numerical simulation of hydrothermal system.
In general, phreatic explosions need substantial amount of water, cap-rock structure that confines pressure, heat supply and increase in pressure for a hydrothermal reservoir to flush through an abrupt phase change. However, it remains an open question whether such structure and processes bring about observable magnetic changes and/or ground deformation preceding to a phreatic eruption. We addressed the following working hypothesis to model Tokachi-dake as a case study. (1) There is a cap-rock structure with a narrow crack below 62-2 crater. (2) Gases through the crack are discharged as plumes from the crater. (3) Decreasing permeability of the crack causes increase in temperature and pressure around the cap-rock structure. We tried to examine the hypothesis using the numerical code “STAR” with the equation-of-state “HOTH2O” (Pritchett, 1995). It enabled us to calculate the heat and mass flow rate of H_2O (gas, liquid and two-phase) in porous media. The calculation region was set as approximately the cross-section passing the summit of Tokachi-dake, 62-2 crater and hot spring located on halfway up the mountain. Firstly, we estimated the background permeability of rock constituting the volcano, which gives a plausible water table. As boundary conditions, constant temperature and pressure conditions were applied to the ground surface and downstream vertical boundary, thermally-insulating and impermeable conditions were applied to the bottom and upstream vertical boundaries. A constant rate of precipitation was injected from the ground surface. A constant heat flow was supplied from the bottom. Subsequently, we reproduced the fumarolic discharge from the crater and the hot spring located in the middle of the slope by providing thermal water from the bottom just beneath the crater. We also introduced a high permeability column as a vertical conduit connected from the volcanic input at the bottom to the crater, as well as a horizontal channel connected to the hot spring. In addition, the low permeability cap-rock with a narrow crack was introduced below the crater. Finally, we changed the crack permeability to observe changes in temperature and pressure of the system. We confirmed that the decrease of the crack permeability caused the increase in temperature and pressure around the cap-rock structure. These results suggested that the working hypothesis was at least self-consistent. In the next step, we will quantitatively investigate the system's responses by comparing the changes in temperature and pressure beneath the crater from the numerical simulation

to the observed temporal change in the magnetic total field and ground deformation.

Keywords: numerical simulation, hydrothermal system, phreatic explosion, magnetic total field, ground deformation

Mass budgets of hydrothermal water beneath hot crater lakes at Kusatsu-Shirane volcano evaluated by ground deformation and changes in thermal activities

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Kusatsu-Shirane volcano is one of the most active volcanoes in Japan in terms of persistent heat-release of approximately 150 MW. Mt. Shirane which is one of the pyroclastic cone contains a hot crater lake, locally referred to as Yugama, showing interesting variations of water temperature and chemical concentrations. We detected intense earthquake swarms located at shallow depth around the Shirane pyroclastic cone between March and August 2014. The seismic activity was accompanied by a ground deformation, increase in water temperature of Yugama crater lake, changes in geomagnetic field and chemical concentration of volcanic gas emitting around the cone.
Volcanic Fluid Research Center, Tokyo Institute of Technology have deployed three continuous bore-hole type tilt meters, enabling evaluation of changes in volume at shallow depth of the cone. In addition to them, we have monitored thermal activities on the cone. Temperatures of Yugama crater lake have been continuously recorded at an interval of 1 minute. Repeated aerial infrared surveys observe changes in ground surface temperatures around the cone. Using these data we evaluate changes in mass-budgets of hydrothermal water which cause earthquake swarms in 2014.
Records of tilt meters indicate that gradual increase in pressure occurred at shallow depth of the cone. Applying the Mogi model we find the inflation source at a depth of only 500 meters from the bottom of Yugama crater lake. A volume change of the inflation source during the period from March 2014 to November 2015 is estimated to be 110,000 cubic meters.
To evaluate changes in thermal activities on Kusatsu-Shirane volcano, repeated aerial infrared survey were carried out between 2012 and 2015. The observation of 2014 and 2015 were done in the nighttime because even slight changes in ground surface temperature can be detected. Comparing IR records obtained in 2015 and that in 2015, surface temperatures of steaming ground located at northern flank of the cone increased significantly, indicating increases in volcanic gas flux. Water temperature of Yugama crater lake rose several degree Celucius from May 2015.
We evaluate evaporation mass by use of atmospheric conditions obtained at the cone, water evaporation rate in 2014 is estimated approximately to be 5 kg/s, which is 2.5 times higher than that of the value in 2012. Rapid decreases in water level were detected by photographs of bars installed near the shore of Yugama crater lake. There results suggest increases in enthalpy of fluid emitting from the lake bottom have occurred since May 2014. We believe that increases in flux of hydrothermal fluid from depth have been maintained although the inflation detected by tilt meters has almost stopped since November 2015.

Keywords: ground deformation, mass budget, tilt meter, hot crater lake, fumarole, Kusatsu-Shirane volcano

Physical structure in pillars of granite porphyry surrounded by columnar joints

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Columnar joints are developed in granite porphyry of the Miocene Kumano Acidic Rocks in the Kii peninsula, Japan. We conducted a hammer rebound test on polygonal surfaces normal to the columnar joint axis, measured physical properties (bulk density, porosity, P-wave velocities and X-CT value) and analyzed mineralogy. We found that those columns have a concentric structure around the longitudinal axis of a column. (1) The central portion of a column has porosities 1% higher than those of the other portions, while the margin of the column has more number of large pores. (2) The two parts have lower rebound value and slower P-wave velocity in the direction of the columnar axis than the intermediate part does. P-wave velocity was the fastest in that direction. (3) The ratio of smectite and chlorite was larger near the margin than the other portions. These results suggest that the structure shown by the physical properties in a column of granite porphyry is related to vesiculation of melt and also affected by following hydrothermal alternation.

Keywords: columnar joint, hydrothermal alteration, internal structure

Classification of Suijoki-hunka (steam eruption)

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The Japanese word "Suijoki hunka" and its English equivalents are usually defined by the phenomena including transformation from groundwater into steam, whereas the actual eruption is determined as Suijoki hunka based on absence of juvenile material from volcanic ash. The inequality sometimes hinders understanding of the eruption mechanism and prediction of subsequent volcanic activity. This paper represents a new classification of non-juvenile eruptions based on the reviews on three literatures: Sterns and MacDonald (1944), Mastin (1995), and Browne and Lawless (2001). Subaerial eruptions are classified according to relevance to phase transition of external water. Eruptions unrelated to phase change of external H_2O consist of magmatic eruption and gas eruption that is a kind of non-juvenile eruptions. Gas eruption is an explosive eruption derived from pressurized volcanic gas accumulated underground. Eruptions relevant to the phase change (hydro-eruptions or hydro-explosion) are further subdivided into five types: phreatic, phreatomagmatic, hydrothermal, magmatic-hydrothermal, and mixing eruptions. Phreatic eruption occurs when a cold aquifer is heated by newly injected hot magma to explode, and if the explosion involves the hot magma, the eruption is phreatomagmatic. Hydrothermal eruptions and magmatic-hydrothermal eruptions occur in geothermal fields and volcanoes underlain by underground hydrothermal systems. Hot hydrothermal fluid can explode itself by sudden phase change from water to steam without external heat influx (hydrothermal eruption). When the hot hydrothermal fluid is injected by hot magma that supplies additional thermal energy for explosion, the eruption is magmatic-hydrothermal. Mixing between groundwater and hot rock such as solidified new lava results in an explosive eruption that is a mixing eruption. As thermal regimes within volcanic edifices determine the eruption types, three types of regimes are assumed here. A volcano with a low temperature regime (type P hereinafter) contains a cold aquifer that can be the source of phreatic and phreatomagmatic eruptions when a batch of new magma injects. In a volcano with a high temperature regime (type G), hydro-eruption hardly occurs because liquid water can not exist in the heated volcanic edifice. Magmatic and gas eruptions are common to type G volcanoes. A volcano with an intermediate thermal regime (type H) includes a sub-volcanic hydrothermal system containing hot water (often boiling water and steam). The hydrothermal fluid in the type H volcano is the source of hydrothermal and magmatic-hydrothermal eruptions. It is noteworthy that hydrothermal eruption can occur without injection of or heating by new magma as the hot hydrothermal fluid can explode itself by releasing thermal energy of the fluid when it is decompressed. These thermal regimes can easily change each other in response to change of magmatic activity; types H and P change into type G when magmatic activity intensifies. To evaluate subsequent volcanic activity when a non-juvenile eruption occurs, it is crucial to realize the internal thermal condition of the volcano beforehand by means of geophysical, geochemical, and geological investigations.

Keywords: Gas eruption, Phreatic eruption, Phreatomagmatic eruption, Mixing eruption, Hydrothermal eruption, Magmatic-hydrothermal eruption

The geothermal structure in the southwestern Hokkaido

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Quaternary volcanoes, Hokkaido Komagatake and Esan in the southern part, and Karibayama in the northern part, are situated in Oshima Peninsula, southwestern Hokkaido. Even though recent volcanic activity is not seen in the central part, geothermal gradient is high. The geological structure of this region is dominated by the movement of basement blocks aligning in the north-south, and folds and fractures have developed. Many hot springs and geothermal manifestations are seen in this region where called “Yakumo-Nigorikawa geothermal zone.” The Mori geothermal power plant is operating in the Nigorikawa caldera formed about 12,000 years ago. Nigorikawa and Yakumo, Kumaishi part have been thought as promising geothermal areas, so the geothermal development research (New Energy and Industrial Technology Development Organization, 1990, 1999) have been executed in various ways.
In this study, based on the investigations in Yakumo and Kumaishi area, we discussed the feature of the geothermal structure of this “Yakumo-Nigorikawa zone”. In addition, I estimated the resistivity structure of Yakumo area by Magnetotelluric method (MT). With created resistivity model, we thought about the hot water circulation system in Yakumo area. And comparing with the feature of other areas, we discussed the feature of the geothermal structure of the southwestern Hokkaido.
The hot water in the Nigorikawa area is high chlorine density water and is subjected to the reaction of volcanic gas. The heat source is considered to be residual heat of volcanic activity in the Nigorikawa caldera. On the other hand, in Kumaishi and Yakumo area, from the result of the drilling survey, it is thought that the ground temperature is increased by the thermal conduction from deep heat source. In addition, the chemical componential analysis of the hot spring water and hot water of the well indicated that hot water in this area is thought to be high chlorine density water subjected to the reaction of volcanic gas and rainwater are mixed. These features are similar in Yakumo and Kumaishi area. But considering new resistivity models, there are no remarkable low resistivity bodies to continue over both areas. And comparing resistivity model and geological columnar section, the hot water in Yakumo-Kumaishi area is rising along the faults which run through the granite and sedimentary rocks. The heat source of geothermal system in Yakumo-Kumaishi area is thought as the residual heat of past magma activity, that is the heat source unlike other area where geothermal gradient is high.

Keywords: geothermal area, Yakumo, Kumaishi, Nigorikawa, resistivity structure, Magnetotelluric method

A Magnetotelluric Exploration for Crustal Electrical Conductivity Distribution beneath around Azuma Volcano, Northeastern Japan

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A magnetotelluric (MT) observation was carried out to explore electrical conductivity distribution in the crust beneath around Azuma Volcano, northeastern Japan. We expanded 16 MT observation sites in 20 X 20 km^2 area of which Oana-Crater lay in the center. Electromagnetic field variation during 3 days with 32 Hz sampling and during 30 hours with 1024 Hz sampling were acquired at each site. The MT response function has been calculated using procMT software (Metronix Inc.). The phase tensor attitude indicates high dimensionality around this area. To obtain three-dimensional conductivity model, we will have used WSINV3DMT (e.g. Siripunvaraporn et al., 2009), and will be discussing magma/hydrotherm transportation from deep crust in this presentation.
Acknowledgment: We thank Geothermal Energe Research Development Co. Ltd. and Nittetsu Mining Cosultant Co. Ltd. for providing the magnetotelluric remote-reference data.

Keywords: electrical conductivity

Introduction of fumarole temperature observation in the Tateyama Jigokudani valley

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A molten sulfur flows has occurred infrequently in fumarole field of Tateyama Jigokudani valley. The cause of active molten sulfur flow in Jigokudani valley is not known well. In recently, the Jigokudani valley fumarole gas properties such as component, temperature and concentration have shown large changes. So that raise of fumarole gas temperature might have dissolved sulfur deposit of ground surface, or the sulfur plumes might have ascent from the reservoir of shallow hydrothermal fluids.
This paper mainly reports the results of an investigation about time variations of the fumarole gas temperature, and distribution of surface temperature in the Tateyama Jigokudani valley. We thought the geothermal observation in the fumarole field may be an index of hydrothermal fluids activity. At the moment, the obtained data only shows the extrinsic factor change resulting from a weather. We carried out the long-term continuously observation and investigate whether the change of datum is associated with such as earthquakes and crustal movement.
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Keywords: Tateyama Jigokudani valley, fumarole gas, fumarole temperature

Resistivity structure around the Kuju volcanic group

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Kuju volcanic group is located at a boundary of Kumamoto Prefecture and Oita Prefecture, Kyushu, Japan. Iwo-yama is active fumarolic activity area at central part of the volcanic group. Yoshikawa et al.(2005) derived the subsurface seismic velocity structure of this volcanic group and pointed out the possibility of the existence of magma chamber at 11 km depth beneath Iwo-yama. Mizutani et al.(1968) showed that volcanic fluid is supplied to surface. But it is not cleard where volcanic fluid ascends to surface. .The purpose of this study is to infer the volcanic fluid path. We carried out campaign survey using the wide-band MT (Magneto-Telluric) around Kuju volcanic group in Sep. to Oct., 2014. From the data obtained by this survey, we investigated the detailed 2D subsurface resistivity structure by the inversion method of Ogawa and Uchida (1996). In this presentation, we will show the resistivity structure along two observation lines which is passing Iwo-yama and east side of it. We found the following common features in the resultant resistivity models along these two observation lines.Near the surface, there is a low resistivity layer. This layer can be interpreted as the aquifer that consists of the underground water containing volcanic gases.There is high resistivity area beneath the volcanic group from 1km to 6km depth. This high resistivity area is surrounded by low resistivity area. The high resistivity body is related with high Vp and Vs religion that was found by Yoshikawa et al. (2005).Two low resistivity areas correspond with low Vp and Vs religion that was found by Yoshikawa et al. (2005). We are considering that high resistivity body reflects an instructive rock and that low resistivity bodies may indicates geothermal fluid.

Repeated survey of ground temperature and hot springs around Iwo-yama, Kirishima Volcanic Group

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Iwo-yama Volcano is located in the northwest of Karaguni-dake Volcano, central part of Kirishima Volcanic Group. This area had intense fumarolic activity before 1990's. After 1990's, fumarolic activity disappeared but hot spring activity has continued. However, volcanic tremors occurred frequently after 2014. And fumarolic activity appeared again at the summit of Iwo-yama in December 2015. The authors have carried out repeated measurements of electrical conductivity of hot spring waters; Western and Northeastern Flank of Iwo-yama and Ashiyu hot spring. Chemical composition was also analyzed.
Repeated measurements of electrical conductivity of spring water indicate EC of the W&NE springs are affected by rain water, but EC of Ashiyu water shows a significant change; 225 mS/m in 2008, 235-245 mS/m after the eruption of Shinmoe-dake in 2011, 256 mS/min December 2015. According to the chemical analysis, SO4 ion increased from 1060 mg/l to 1130 mg/l in Ashiyu, while the ratio of Cl/SO4 changed from 0.12 to 0.09. On the other hand, Cl/SO4 increased from 0.002 to 0.014 in the W Flank of Iwo-yama. This means SO4 ion increased in Ashiyu after the beginning of volcanic tremor in August 2014, but in W Flank of Iwo-yama, both SO4 ion and Cl ion increased.
Ground temperature at 1m depth has been observed at the central part of Ebino Heights. High temperature about 40C was detected in this area by the 1980's. But no anomalous temperature was detected. This means geothermal activity is limited within the summit area now.

Keywords: Kirishima Volcanic Group, Iwo-yama, Geothermal activity, Electrical conductivity, Volcanic actiovity

Gravity surveys in southwestern part of the Kirishima volacnic area

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Laboratory of Geothermics, Kyushu University conducted gravity surveys in the hot springs area, mainly the Maruo and Hayashida hot springs, in southwestern part of the Kirishima volcanic area in order to reveal the shallow subsurface structure of the hot springs area. And we drew a Bouguer anomaly map of this area by using the measured gravity values and the data of the gravity database (AIST, 2013).
The Bouguer anomaly map shows a gravitational steep incline, which has a strike of NE-SW direction, near the Kirishima Rehabilitation Center of Kagoshima University in the Maruo hot springs. It is explained that this steep incline indicates a fault structure. And a low Bouguer anomaly area exists at the western part of the steep incline. So it is inferred that this is a depression structure filled with some low density layers and can be a hot spring aquifer.We are grateful to Mr. Yusaku Yonekura who had progressed this study.
AIST (2013) Gravity Database of Japan, DVD.

Keywords: Kirishima volcanic area, gravity survey, hot springs, subsurface structure

