

## Geostatistical analysis of VLF-MT resistivity data at the Tatun Volcano Group, Taiwan

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Tatun Volcano Group (TVG) is composed of over twenty volcanoes, which were formed within faults at the northern tip of Taiwan. Its active heat discharge from fumaroles and springs also suggests a large amount of volcanic fluids released from a potentially-existing magma beneath Chishinshan volcano (e.g., Yang et al., 1999; Ohba et al., 2010; Konstantinou et al., 2007). Komori et al. (2014) conducted AMT surveys for a better understanding of this magma degassing, and found low resistivity anomalies associated with the hydrothermal activity of the TVG.

In the TVG, we also conducted VLF-MT, which uses an electromagnetic wave with a singular frequency such as 22.1 kHz. Generally, its high simplicity of use enables a huge numbers of measurements at low cost, compared to AMT surveys. Therefore, VLF-MT could easily and extensively trace a surface distribution of hydrothermal fluids discharged from a deeper part, although its sounding depths are only a few tens to hundreds meters. However, it is quite often that there are many missing data points, mainly due to inaccessibility and high-level noises. Consequently, a sparse distribution of the surface resistivity is obtained, which might result in wrong spatial features of the resistivity at the survey areas.

Geostatistics is potentially a good tool to solve the above problem. It was theoretically developed by Krige (1951) to evaluate a quality of mines by estimating data values at unsampled points from a viewpoint of statistics. To date, it has been widely used for explorations of oils and geothermal/groundwater resources, by applying to data such as temperature, crack density, porosity, permeability, and chemical composition (e.g., Koike and Ichikawa, 2006; Anderson and Fairley, 2008). Because this method is mathematically based on statistics, it would enable a fair inference with regard to a spatial property of the obtained data.

The present study applied the Geostatistics to over 300 VLF-MT resistivity data of the TVG, which were conducted in 2009-2010 by Kagiya et al. (2010, JPGU meeting) and in 2012-2013 by Komori et al. (2014, CA meeting). The numerical code GSLIB (Deutsch and Journel, 1998) was used for our geostatistic works. The data were first processed to make an experimental semivariogram. It was used to estimate a model variogram by assuming values of nugget, sill, and range, on the basis of the criteria put by Kitanidis (1997). The modeled variogram was input to Simulated Annealing (SA) process to estimate a statistically-plausible spatial distribution of the surface resistivity. In the presentation, we will show preliminary results by the above processes, and examine its relation to structural features and hydrothermal activity of the TVG.

Keywords: Tatun Volcano Group, hydrothermal activity, VLF-MT, geostatistics, simulated annealing

## Hydrothermal system beneath the Jigokudani valley, Tateyama volcano, inferred from AMT surveys and hot spring chemistry

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We carried out AMT surveys and the analyses of hot spring water in the Jigokudani valley (JV), Tateyama volcano, Japan. The JV was formed by repeated phreatic eruptions some 40,000 years ago, and has laminated lacustrine sediments that are located at the base of an extinct crater lake. Currently, the JV is an active solfatar field dotted with hot springs and fumaroles, and has experienced several anomalous events indicating the increase in volcanic activity. The objective of this study is to clarify the characteristic of electrical resistivity structure where multiple phreatic eruption events occurred, and to investigate the spatial relationship between subsurface structure and recent volcanic activity. We collected the AMT data at 25 locations in and around the JV, and estimated a 3D resistivity structure using the inversion code of Siripunvaraporn and Egbert (2009). Electrical conductivity, temperature and pH were measured in 50 hot springs, and chemical analyses were performed on representative 12 samples of those springs. Hot springs in the JV showed features of strong acid Cl-SO<sub>4</sub>-type, and turned out to be derived from magmatic hydrothermal fluids because of the high ratio of Cl/SO<sub>4</sub> concentration. A highly conductive region with thickness of approximately 50m was detected beneath the most active geothermal field, and was interpreted as representing clayey sediments. A slightly resistive portion was present beneath this layer and hot spring water of this area showed high ionic concentrations, which suggests that there are high temperature gases of magmatic origin. A deep feature of 3D resistivity structure suggests that such magmatic gases are provided from east of the JV, which is consistent with the location of seismically inferred magma reservoir.

Keywords: Resistivity structure, AMT, Tateyama volcano, Phreatic eruption, Hydrothermal system, Clay cap

## Hydrothermal system around the active crater of Aso volcano inferred from a three-dimensional resistivity structure

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This paper presents a three-dimensional (3-D) electrical resistivity model around the active crater of Aso volcano using the audio-frequency magnetotelluric (AMT) data obtained during 2004-2005. The AMT data were collected at 43 locations on an approximately 300-m grid in and around the Nakadake crater, the summit of the central cone complex, and were already interpreted by two-dimensional models (Kanda et al., 2008).

Over the past 80 years, all of the volcanic events within Aso volcano have originated from the 1st crater of Nakadake. The volcanic activity of Aso has showed a cyclic activity pattern: a crater lake is formed at a quiet period and a Strombolian eruption occurs at an active period. From November 2014, Strombolian eruptions have been observed at the 1st crater, which is considered to be a part of a similar activity cycle. This cyclicality of the volcanic activity implies that a specific structure that acts to accumulate the energy required to trigger eruptions develops at approximately the same location beneath the 1st crater. The objective of this study is to reveal such specific subsurface structure.

As a result of 3-D inversion using the code of Siripunvaraporn and Egbert (2009), we have obtained the following features in the 3-D resistivity model. A highly conductive zone is present at depths between 100 and 300 m beneath the 1st crater, but unexpectedly the resistivity of the shallow subsurface around the Nakadake crater is not low in general. The low resistivity zone widely distributed at a depth around sea-level which was found in the previous studies is seen only beneath the northern half of the Nakadake crater including the 1st crater. We will discuss these features in connection with the variation sources inferred from other geophysical studies.

Keywords: Aso volcano, resistivity structure, active crater, audio-frequency magnetotellurics, hydrothermal system

## Time variation in the chemical and isotopic composition of fumarolic gases at Hakone volcano, Japan

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The driving force of eruption is the degassing of magma or the explosion of hydrothermal reservoir. The volcanic gas contains the component originating in the degassing magma or the hydrothermal reservoir. Therefore, the volcanic gas is essentially important object for the understanding of eruption and the eruptive prediction.

Although no historical eruption was recorded at Mt Hakone, the swarm of volcanic earthquakes has been observed several times. For example, in 2001 the swarm of volcanic earthquakes was observed with the deformation of volcanic body suggesting a pressure source the depth of which was estimated to be 7km (Daita et al, 2009). In parallel to the swarm of earthquakes, the steam pressure in the borehole located in the geothermal area of Owakudani significantly increased.

### Sampling and analysis of fumarolic gas

The Owakudani geothermal area is developed on Mt Kamiyama, one of the central cones of Hakone caldera. The fumarolic gases have been sampled and analyzed at two outlets in Owakudani geothermal area almost every month since May 2013 to Jan 2015. One fumarolic gas (T) is located near the parking for sightseeing people of Owakudani geothermal area. Another fumarolic gas (S) is located on the north flank of Mt Kamiyama, 500m far from the fumarole T. The temperature of gas at the outlets was about 96C, which is close to the boiling temperature of the altitude of the fumaroles. The fumarole T associates the discharge of hot spring water. The fumarolic gas was sampled in the evacuated glass bottle containing 20ml of 5M KOH solution. For the determination of SO<sub>2</sub>/H<sub>2</sub>S ratio, KIO<sub>3</sub>-KI solution was reacted with fumarolic gas at the sampling site. For the sampling of condensed water of gas, a double glass tube was used for cooler. The solution in the evacuated glass bottle was analyzed along the method by Ozawa (1968) to determine the amount of H<sub>2</sub>O, CO<sub>2</sub>, total S (=H<sub>2</sub>S + SO<sub>2</sub>) and R-gas. The R-gas was analyzed by GC with Ar and He carrier gases to determine the relative concentration of He, H<sub>2</sub>, O<sub>2</sub>, N<sub>2</sub>, CH<sub>4</sub> and Ar. The isotopic ratio of condensed water was determined by use of an IR-laser cavity ring down analyzer (Picarro). The isotopic ratio of H<sub>2</sub> in R-gas was determined by use of the continuous flow system combining a mass spectrometer (Thermo Fischer Scientific Delta V).

### Result and Discussion

The both fumarolic gases, T and S was composed by mainly H<sub>2</sub>O vapor the relative concentration is about 98%. The secondary dominant component was CO<sub>2</sub>, the concentration was 1 to 2%. The T and S fumarolic gases contained H<sub>2</sub>S of 0.2 to 0.4% and 0.04 to 0.05%, respectively. The CO<sub>2</sub>/H<sub>2</sub>O ratio of T decreased in May 2013 until Oct 2013, then stable until Sep 2014. In Oct 2014, a small increase was observed in the ratio. A similar change was observed in the S fumarole. In Oct 2014, about 50 of earthquakes occurred at Mt Hakone, the number of which was higher than the preceding months. The increase of CO<sub>2</sub>/H<sub>2</sub>O ratio in Oct 2014 looks to be correlated with the occurrence of earthquakes. The change in CO<sub>2</sub>/H<sub>2</sub>S was almost similar the change in CO<sub>2</sub>/H<sub>2</sub>O ratio for both T and S fumaroles. An interesting change was found in the He/H<sub>2</sub>O ratio of T fumarole. The ratio increased in Sep 2014, which is one month before the increase in CO<sub>2</sub>/H<sub>2</sub>O ratio. The increased He/H<sub>2</sub>O ratio decreased in Oct 2014, which looks like a precursor of the change in CO<sub>2</sub>/H<sub>2</sub>O ratio and also the swarm of earthquakes. For the estimation of hydrothermal reservoir temperature, the apparent equilibrium temperature (AET) was calculated between H<sub>2</sub>O and H<sub>2</sub> assuming the exchange of D between those species. The AET was high as 140C in May 2013 at T fumarole. The AET decreased quickly down to 100C. A small increase was observed in Dec 2013 and Aug 2014. The AET of S fumarole was almost stable, showing a gradual increase from 92C in May 2013 to 104C in Aug 2014. The AET seems to be useful for the estimation of reservoir temperature.

Keywords: Hakone, Volcanic gas, Chemical composition, Volcanic earthquake, CO<sub>2</sub>, He

## Volcanic plume measurements of Ontake volcano by unmanned aerial vehicle (UAV)

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On Sept. 27, 2014, a phreatic eruption occurred at Ontake volcano, central Japan, caused unprecedented disaster and took the lives of many tourists. The explosion plume rose up to nearly ten thousand meters and ash fall was observed as far as about 100 km east in Yamanashi Prefecture (JMA, Sept., 2014). The plume activity gradually decreased but the volcano still vigorously emits white plume as of Feb. 2015.

We made plume observation using a multicopter UAV on Nov. 20 and 21, 2014 to carry out following four kinds of measurements; sulfur dioxide flux, in-plume multiple gas concentrations, thermal images of the crater area and collection of fine particles inside the plume. In Ontake volcano measurements, the UAV was expected to fly 4000 m roundtrip distance at the altitude of 3000 m. Thus, the respective instruments were made compact and light to fit the payload of 1kg. The SO<sub>2</sub> flux measurements was carried out by traversing below the plume with a compact UV spectrometer operated by a single-board-computer. In the multiple gas concentration measurements, H<sub>2</sub>S, SO<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub> sensors and a thermohygrometer (H<sub>2</sub>O) were loaded to the UAV and flew inside the plume. In these in-plume flights, an adhesive film was used to collect fine particles inside the plume. An infrared thermography camera mounted on the UAV was used to image Jigokudani crater area to reveal the thermal condition. On Nov. 20, takeoff and landing of the UAV was located at Imorikougen ropeway station about 3.5 km ENE due to NE plume direction. On Nov. 21, the UAV was operated from Tanohara park about 3 km SE from the crater area to approach the plume flowing in ESE direction.

Sulfur dioxide flux and SO<sub>2</sub>/H<sub>2</sub>S molar ratio obtained by the UAV plume measurements were 130-140 ton/day and about 0.09 for Nov. 20-21, 2014. No volcanic H<sub>2</sub>, CO<sub>2</sub> and H<sub>2</sub>O were clearly detected due to high mixing ratio of atmosphere. The thermal images of Jigokudani crater showed maximum temperature of 90.6 °C corresponding to the boiling point of the local altitude. Although some fine particles including crystalline minerals were found on the adhesive films, they were probably dusts from the ground.

Prior to the UAV measurements on Oct. 9, in-plume multiple gas concentration measurements were carried out using Multi-GAS analyzer onboard a helicopter and we obtained SO<sub>2</sub>/H<sub>2</sub>S molar ratio of about 0.3, indicating a significant decrease of the ratio by Nov. 20-21, 2014. Sulfur dioxide flux was over 1000 ton/day just after the eruption and was 400-500 ton/day (JMA, Oct. 2014) on Oct. 9 and decreased to 130-140 ton/day in two months after the onset of the eruption. In contrast, a total sulfur flux on Oct. 9 was about 1000 ton/day and was about 800 ton/day on Nov. 20-21 showing no significant change. The plume activity of 2014 Ontake volcano eruption is characterized by high total sulfur flux, however, low fumarolic temperature and low SO<sub>2</sub>/H<sub>2</sub>S ratio suggest that volcanic gas at Ontake volcano is not directly emitted from magma.

After 1979 Ontake volcano eruption, SO<sub>2</sub>/H<sub>2</sub>S molar ratio showed significant decrease from 5 soon after the eruption to 0.1 a year after the eruption (Ossaka et al., 1983). The decrease of SO<sub>2</sub>/H<sub>2</sub>S molar ratio after the eruption is the common characteristic of the two eruptions in 1979 and 2014. Detailed comparison of the two eruptions would be important to understand the future of ongoing Ontake volcano's activity.

Keywords: Ontake volcano, volcanic gas, UAV

## Case study of the behavior of isotope in several hot-spring and geothermal field part2

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The Oxygen and hydrogen isotope data provide information about the origin and evolution of geothermal waters and relationship with hot spring reservoir and river water.

According to Enhanced Geothermal System (EGS), stable isotope data show the water source in reservoir or injected water. Recently, several EGS project are carried out in USA, Australia and Europe. And after nuclear power plant accident at 2011, we need new EGS project and the review of previous project at Hijiori. At Hijiori EGS site, the long term circulation test was carried out from 2000 to 2002. The tracer response changed with circulation (Yanagisawa et al., 2002, 2003) and calcium carbonate and anhydrite scale precipitated in circulation system (Yanagisawa et al., 2008). This shows the geochemical condition change in Hijiori system. And to develop EGS project, we have to survey the relationship between hot spring and EGS reservoir. Then, this presentation shows the results of stable isotope change of production and injection well at Hijiori test site and discuss the reservoir condition during circulation test.

During this test, hydrogen and oxygen isotope composition of production wells (HDR-2 and HDR-3), injection well, river water and hot springs were analyzed.

The isotope ratio of the river water and hot springs plot along the meteoric water line. The isotope ratio of hydrogen and oxygen ratio of HDR-2 increased with circulation and reached value of -45 ‰ of  $\delta D$  and -4.6 ‰ of  $\delta^{18}O$  at end of May 2001, respectively. However  $\delta D$  and  $\delta^{18}O$  rapidly decreased to -54.4 ‰ and -8.6 ‰ respectively from May to June and came close to meteoric line. The isotope ratio of HDR-3 plot at higher  $\delta^{18}O$  than that of HDR-2 and the change of the isotope ratio of HDR-3 is similar as that of HDR-2.

The change of  $\delta^{18}O$  value of HDR-2 is corresponds with Cl concentration change during the circulation progress.

Keywords: hot spring, geothermal, isotope, Hijiori, EGS

## Numerical modeling for a broad geothermal system of Kuju Volcano

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The Kuju volcanic field is located in the southwestern part of Oita prefecture, Japan, and consists of some andesitic volcanoes. There are many hot springs and several geothermal power stations (Hatchobaru, Otake, Takigami etc.) in this field. In the previous studies on the Kuju volcanic field, the numerical models were mainly for the power station areas or the center of Kuju Volcano where fumarolic activity appears. Therefore, we constructed a new conceptual model that includes the center of the volcano and all of the geothermal power station areas in order to attempting to construct an integrative numerical model of a broad geothermal system that has the scale of the volcanic field to explain the existence of the hydrothermal systems, which are generated by a heat source like a magma chamber in the volcanic field. Based on this conceptual model, we constructed a numerical model that replicates the hydrothermal systems of the geothermal power station areas roughly although the numerical model is relatively simple.

Keywords: Kuju Volcano, broad geothermal system, hydrothermal system, numerical model

## Re-evaluation of hydrothermal activity based on magnetic measurements at Kusatsu-Shirane volcano, Japan

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Kakioka Magnetic Observatory, Japan Meteorological Agency commenced geomagnetic measurements around the summit crater lakes of Kusatsu-Shirane volcano in 1976 to monitor the thermal activity of the volcano. We re-analyzed the geomagnetic data over 36 years starting in 1978 and evaluated the long-term thermal activity beneath the crater lakes.

Changes in the geomagnetic total intensity due to thermal activity were observed in three periods: 1982-1985, 1988-1991, and 1996-2012. A thermal-demagnetization source related to phreatic eruptions during 1982-1983 was estimated to be 400 m below Mizugama crater lake during 1982-1985. The demagnetized body was also detected at a depth of 600 m below Mizugama crater lake in 1988-1991 when substantial thermomagnetic signals and numerous volcanic earthquakes were observed without an eruption. These demagnetization sources represent a hydrothermal fluid reservoir beneath the summit area. We suggest a possible mechanism of the phreatic eruptions during 1982-1983, based on our thermomagnetic model and previous geophysical and geochemical studies.

In contrast, magnetization associated with cooling of rocks beneath the crater lakes was recorded from 1996 to 2012. According to our thermomagnetic modeling of this period, the source of the magnetization was 400 to 700 m below an area immediately northeast of Yugama crater lake. In addition, we found that the cooling migrated gradually to shallower depths during this period. These suggest that the decline phase of the volcanic activity was under way at this period.

Changes in the geomagnetic total intensity after 2013 show a different tendency from those before 2013. Therefore, these suggest that the decline of volcanic activity came to an end in 2013.

Keywords: Kusatsu-Shirane volcano, geomagnetic measurement, thermomagnetic effect, phreatic eruption, hydrothermal fluid



## Evolution of a hydrothermal system of Kusatsu-Shirane volcano inferred from aerial infrared surveys in the nighttime

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Kusatsu-Shirane volcano is one of the most active volcano in terms of release of a large amount of heat as volcanic gas and hot springs. In addition to steaming grounds and fumaroles, the Shirane pyroclastic cone contains a hot crater lake, locally referred to as Yugama, which shows interesting variations of water temperature and chemical concentrations.

Intense earthquake swarms have occurred at shallow depth of the Shirane pyroclastic cone since March 2014, accompanied by a ground deformation, changes in geomagnetic field and chemical concentration of volcanic gas. A location of the pressure source is determined by network of our tilt meters at 550 m depth from Yugama crater lake. These unusual activities may be caused by an accumulation of hydrothermal hot water at shallow depth of Yugama crater lake, so we expect changes in thermal activities around the Shirane pyroclastic cone.

To detect changes in thermal activities on Kusatsu-Shirane volcano, an aerial infrared survey was carried out on 25 October 2014. The observation was done in the nighttime because even slight anomalies in ground surface temperature can be detected. Images of detailed ground temperature enable us to estimate precisely heat- and water-discharge rates from steaming ground as well as Yugama crater lake.

Steaming grounds around Yugama crater lake show no significant changes compared with the record obtained in 2012, although changes in chemical compositions of volcanic gas emitted here were observed. On the other hand, we detect an increase in water surface temperature of Yugama crater lake. 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. Such an increase in water temperature occurred in May 2014 suggested by monitoring of Yugama crater. Records of tilt meters indicate that an accumulation rate of the hydrothermal water decreased after May 2014. We consider that the reservoir of hydrothermal water fractured gently in May 2014. Consequently, an additional input of hydrothermal water started at the bottom of Yugama crater lake.

Keywords: Kusatsu-Shirane Volcano, airborne IR surveys, hot crater lake, steaming ground, hydrothermal system, heat-discharge rate