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Significance of Electromagnetic Surveys at Active Volcanoes: Toward Evaluation of the Imminence of Wet Eruptions

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The detection capability of various anomalous phenomena preceding volcanic eruptions has considerably progressed as the geophysical monitoring network has become denser and multi-disciplinary. However, current eruption forecasting techniques still have much scope for improvement from a practical perspective, since they largely depend on empirical techniques. In the past decade, three-dimensional modeling in the electromagnetic sounding methods such as magnetotellurics (MT) has become a practical choice, and its recent application to active volcanic fields has revealed some common features among volcanoes. Information about the resistivity structure, especially in "wet" volcanic fields, is useful for the provisional screening of eruption potential from the viewpoint of subsurface structure, and, thus, may contribute to the evaluation of eruption imminence in a broad sense. In this study, for evaluation purposes, we present the roles and possible further applications of the subsurface resistivity structure studies, via demonstrating the preliminary results and interpretations of the MT survey that we performed at Kuttara Volcanic Group, northern Japan.

Keywords: Kuttara volcano, magnetotellurics, wet eruptions, unrest phenomena

1. Introduction

Over a century has passed since modern geophysical instrumentation and chemical analyses were implemented in volcano monitoring. Substantial progress has been achieved in classification, investigation, and modeling of volcanic phenomena preceding and during an eruption. As a result, some empirical-based eruption prediction, especially as pertains to commencement timing, has been partially successful, as in the cases of Mt. Usu [1] and Miyakejima [2], both of which erupted in 2000. Even individual explosions can be predicted by detection of heightened seismicity and shallow ground inflation at some well-monitored volcanoes that exhibit vulcanian-type activity, like Sakurajima (e.g., [3]).

However, the current technique of eruption prediction largely relies on the detection of precursory events, such as seismic swarms and/or rapid ground inflation, and thus, even determining when initiation occurs is difficult to do for the eruptions that are devoid of remarkable forerunning anomalies or devoid of acceleration in their occurrence rates or amplitudes. Meanwhile, significant anomalous events do not always result in immediate eruptions, which are sometimes termed failed eruptions. In addition, such a precursor-based approach has essential difficulty in improving the accuracy of timing of an eruption, as it is not assured that the same sequence that took place in the past episodes will be repeated. Once an eruption begins, what follows is even more difficult to forecast.

Let us first review the eruptions in recent years in Japan to clarify the current state of eruption prediction. In some instances, eruption was thought to occur beforehand by the detection of so-called unrest phenomena, such as shallow micro-earthquakes and localized ground inflation, resulting in actual phreatic eruptions (Mt. Hakone in 2015 [4]; Iwo-yama in Kirishima Volcanic Complex in 2018 [5]). At Mt. Aso during the eruptive period of 2014−2015, heightened episodes of magmatic and phreatomagmatic events [6] were roughly predicted by means of multiple monitoring data, such as the occurrence rate of a particular tremor, ground inflation, or changes in the geomagnetic field. On the other hand, there were some unsuccessful events. In the case of the 2011 eruption of Shinmoe-dake in Kirishima Volcanic Complex, continuous ground deformation (suspected to be deep inflation) was observed at a distant site from the erupted crater since approximately one year prior to the medium-scale magmatic eruption [7]. No acceleration was observed in the deformation rate until it became remarkable co-eruptive deflation. At Mt. Ontake in 2014, a disastrous phreatic explosion took place during a two-week period of elevated micro-seismicity, which was difficult to distinguish from background activity. Neither remarkable acceleration in seismic amplitude nor deformation was observed until ten minutes before the eruption [8]. Intermittent unrest episodes had been well-monitored by multi-disciplinary observations over an even longer period (over 10 years) at Kuchinoerabu-jima, an island volcano in southwestern Japan, which erupted in 2014 [9]. The eruption was envisaged to occur in the long term. However, the timing of the eruption was not predicted, mainly because of a lack of remarkable enhancement in the unrest phenomena. In contrast, no precursory unrest phenomena at all were detected by the monitoring network in the case of the 2018 phreatic eruption at Mt. Moto-Shirane, one of the previous eruption sites of Kusatsu-Shirane Volcano but was not expected to undergo imminent activity at that time [10].

These examples suggest that multi-disciplinary monitoring, proximal to expected eruption sites, is potentially useful in sensing future eruptions, but is not always capable of evaluating their imminence. Other recent examples of remarkable unrest episodes, such as intermittent swarms of shallow micro-earthquakes and ground inflation at Mt. Tokachidake [11], Mt. Azuma [12], and Yugama crater in Kusatu-Shirane [10], all of which have not yet resulted in actual eruptions so far, recall the need for a technique to evaluate the severity of such unrest phenomena or their imminence to an eruption.

Japan, home to 111 active volcanoes (as of 2018), has experienced numerous calamities due to volcanic eruptions. Today, one of the social functions of volcanology is promoting practical research and development to minimize volcanic disasters by extension of existing knowledge and technology. To this end, accuracy improvement and/or sophistication in the eruption prediction technique is desired. However, simulation-based forecasting using the laws of physics and chemistry, in combination with real-time monitoring data similar to that obtained for weather forecasting, is still lacking. Nonetheless, it would be beneficial if we could evaluate and quantify the severity of volcanic activity preceding an eruption in any objective framework, based on monitoring prior data and eruption history. The volcanic alert level (VAL) issued by the Japan Meteorological Agency (JMA) has a similar function. However, VAL is not evaluated solely based on volcanic activity. The Japanese VAL varies from 1 to 5 at any given moment in time, including pre-eruptive, eruptive, and post-eruptive periods. Naturally, VAL in an eruptive period is much more focused on the ongoing hazard rather than any future prospect that might be more important in non-eruptive periods. In the evaluation of VAL, social impacts should be considered, while the evaluation of severity and/or imminence of the observed phenomena itself, particularly in non-eruptive periods, often can be a predetermined matters of concern. We consider that knowledge of the internal structure of a volcano as a possible eruption site is beneficial for determining this aspect. This is analogous to diagnosing the medical severity from the symptoms of a patient, for which the background information regarding anatomy is highly advantageous.

Nonetheless, on one hand, geological and/or petrological data sometimes requires complicated internal structure for a specific volcano, based on the evidence from materials, geophysicists are often compelled to sacrifice an unguaranteed reality and assume simplistic subsurface, such as a homogeneous half space, in modeling volcanic phenomena. One of the reasons for this situation is the intrinsic difficulty in rigorously constraining the subsurface structure solely from the usually sparse deployment of continuous monitoring stations, or from campaign-based monitoring, which is often sporadic in time. Temporary but intensive geophysical surveys for individual volcanoes are useful to meet this gap and compromise the problem.

The "Integrated Program for Next Generation Volcano Research and Human Resource Development" of the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) has conducted the surveys of subsurface structure for the domestic active volcanoes that are under unrest conditions or are potentially hazardous when they erupt. In the followings, we present the roles and some possible applications of the studies on the resistivity structure in developing the evaluation method of eruption imminence, demonstrating the preliminary results of the MT survey, which we performed at Kuttara Volcanic Group (KVG), northern Japan.

2. Roles of the studies on the resistivity structure as an evaluation tool for the potential of wet eruptions

Volcanic eruptions can be classified into two categories: "dry" and "wet" eruptions. In "dry" eruptions, magma behavior plays an essential role in the eruption itself and/or in the preceding preparation processes (that is, processes leading up to the eruption). These are often termed magmatic eruptions. In "wet" eruptions, the groundwater and/or hydrothermal systems present in shallow regions play the key role. Wet eruptions are the primary topic of the following discussion. We use "wet eruptions" as a general term in the present paper to describe hydrothermal eruptions, phreatic eruptions, phreatomagmatic eruptions, and magmatic-hydrothermal eruptions, which are based on the definitions reviewed in Browne and Lawless (2001) [13].

Dry eruptions involve an area of research called conduit flow models in which the dynamics of erupting magma is mathematically investigated by solving a set of differential equations to model a simple system, such as a vertical conduit, that is connected to a deeper magma reservoir. The relationship between eruption style/intensity and magma chemistry, water content, temperature, and depth, is often a common focus (e.g., [14, 15, 16]). In such models, whether they are deterministic or probabilistic, steady or unsteady, fluid flow is perfectly confined in the conduit and one-dimensional in vertical direction, except some models that incorporate lateral gas escape in a parameterized manner. In addition, these models generally consider the interchange of heat between the conduit and host rock negligible. Even so, readers may envision that refining the currently available unsteady (i.e. time-varying) models, such as that proposed by Kozono and Koyaguchi (2012) [17], in combination with monitoring data, is a straight way to make numerical forecasting of an eruption possible. However, such conduit flow models are not very suitable for the practical application to the imminence evaluation of wet eruptions for the following reasons.

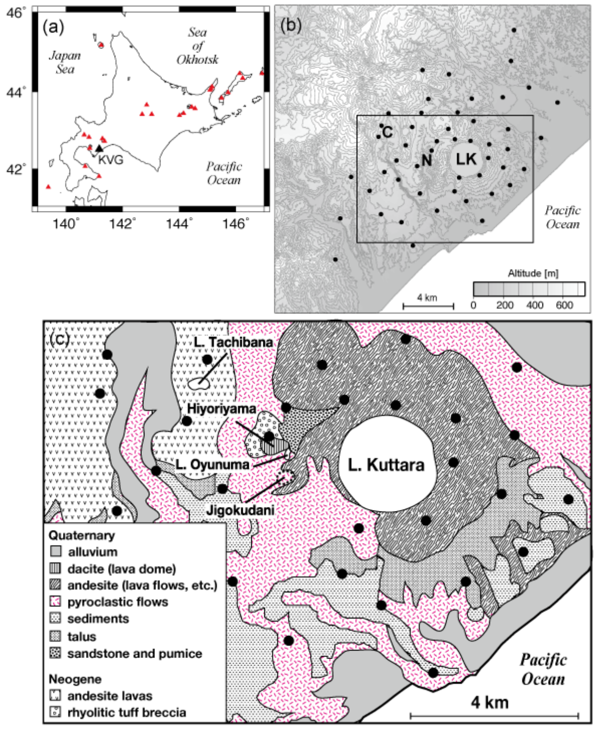

Fig. 1. (a) Location of Kuttara Volcanic Group, (b) topography with major landmarks on surface geology (c). Triangles in (a) indicate active volcanoes. Solid circles in (b) and (c) indicate the MT sites in the present study. Letters LK, N, and C in (b) represent Lake Kuttara, Noboribetsu hot spring, and Carls hot spring, respectively. Geological map (c) is simplified from 1:50,000 quadrangle series (Tokushumbetsu and Noboribetsuonsen) published by the Geological Survey of Japan, AIST.

Although wet eruptions may also be regarded as a part of magma processes in a broad sense, water (liquid or vapor) and other volatiles in the shallow subsurface play a key role as agents of heat transport, pressure changes, and chemical reactions, including hydrothermal alteration. In this respect, a different approach from those for magmatic eruptions is needed to treat such processes. Secondly, from a viewpoint of public concern, severity evaluation of volcanic unrest phenomena during a prolonged inter-eruptive period is sometimes more important rather than modeling the eruption process itself. This is partly because wet eruptions, as compared to magmatic ones, generally end only in a short time. For the background long inter-eruptive periods, the assumption of the confined adiabatic 1D flow, as adopted in conduit flow models for magmatic eruptions, is unrealistic. Moreover, most wet eruptions take place in the shallow subsurface, where inhomogeneity around the eruption site and its time evolution probably contribute significantly to the processes preceding an explosion. This is an important issue but not yet fully understood, and normally difficult to incorporate in conduit flow models with a simplified geometry.

In addition to such difficulties, another problem intrinsic to mathematical approaches is that verifying and revising a model for volcanic eruption/activity requires much time, since volcanic eruption repeats much less frequently than, for example, daily meteorological phenomena in weather forecasting. Considerable amount of time and efforts will be needed to overcome all these problems. In the meantime, surveying the internal structure of a volcano by the electromagnetic (EM) method is a practically effective approach, aiming for the evaluation of the imminence of wet eruptions, as explained below.

Although wet eruptions may have considerable variability depending on the degree of magmatic contribution, they are generally thought to occur as a result of over-pressurization of a hydrothermal reservoir. This is preceded by an imbalance of the system due to episodic oversupply of fluid/heat from depth, due to depleted fluid escape to the ground surface or in a lateral direction, or due to abrupt decompression of the reservoir by destruction of a seal layer that surrounds it, leading to a phase change for water. We consider such a critical imbalance takes place in a hydrothermal system that has developed at a shallow depth during prolonged inter-eruptive periods with intermittent unrest events. Such a mature hydrothermal system can be characterized by the inhomogeneous subsurface structure composed of ground water, hydrothermal reservoirs, and less permeable altered clay layers. Thus, it is useful to know their locations and geometries in advance in some way.

The electrical resistivity structure can be a good indicator in screening such a potentially explosible system for the following reasons. Firstly, the resistivity is suitable for imaging the shallow inhomogeneity in volcanic fields, as it ranges over many orders of magnitude depending on the rock species and states. In principle, the most reliable information on hydraulic characteristics, such as the permeability or porosity, is brought by the direct measurements based on drilling, which would incur huge costs because of the vast areas involved. In contrast, the resistivity can be surveyed on the ground surface by means of some EM soundings, such as the magnetotellurics (MT), the time-domain electromagnetics (TDEM) and the electrical resistivity tomography (ERT). Among them, the ERT, which is often deployed as a densely-arrayed electrodes, is capable of finest imaging of the near-surface down to about 50 m (e.g., [18, 19]). The MT, as compared to the ERT, is less sensitive to the very surface, but has an advantage in an extended sounding depth to image a hydrothermal system. Next, the resistivity and the hydraulic characteristics are related, even though the resistivity is affected by many factors. As resistivity modeling based on three-dimensional inversion has nowadays become a practical choice, the EM survey on active volcanoes is one of the useful tools for narrowing down the potential sites for future wet eruptions, providing basic information for the imminence evaluation in a broad sense. As stated later, such a three-dimensional structure model can also be used for the mathematical simulation studies leading to the imminence evaluation of wet eruptions.

Unfortunately, detailed surveys for locating and imaging such a shallow hydrothermal system have been conducted in few volcanoes, eliciting an immediate cause for concern, particularly for volcanoes at touristic venues. In the following section, we summarize the MT survey, which we carried out under the above-mentioned concept as a part of the MEXT project at Kuttara Volcanic Group (KVG).

3. The Magnetotelluric Survey in KVG

We conducted a board-band MT survey at KVG including the Noboribetsu area, where the social impact of the eruption is expected to be large, since tourism facility is close to the assumed eruption sites. Some studies on the subsurface resistivity structure that have already been performed in this region in the past [20, 21, 22] were based on the controlled-source methods, such as the controlled-source audio-frequency MT and the TDEM, in which the relatively shallow structure up to ca. 1 km was targeted for imaging in the Noboribetsu geothermal area, and a relatively long EW cross-section piercing Lake Kuttara was profiled up to the depth of ca. 1 km. The present study aimed to image the structure of the overall KVG in 3D at increased depths (**Fig. 1**) based on a natural-source broadband MT. In the following subsection, we present the geological and geophysical background of the target area and general description of our MT survey, as well as the provisional modeling results by Hayakawa (2018) [23]. The 3D resistivity structure shown below is a preliminary model and, may be revised in the future. A more detailed discussion of the robustness of the model will be considered in future studies.

3.1. Geological and Geophysical Background of the Target Area

Kuttara Volcanic Group is a basaltic to andesitic volcanic complex in southwestern Hokkaido, northern Japan. According to the geological studies of Yamagata (1994) [24] and Moriizumi (1988) [25], Kuttara experienced multiple explosive eruptions of silicic magmas from ca. 80 to 45 ka. A stratovolcano comprising lava flows and scoria falls of felsic magmas has formed by ca. 45 ka, followed by an explosive eruption at ca. 40 ka and formation of Kuttara Caldera (now called as Lake Kuttara) with a diameter of about 3 km. The cumulative amount of magma that erupted before 40 ka is 100 km^3 in dense-rock equivalent [25]. Although the magmatic activity in this area has been relatively low from 40 ka to the present, mostly phreatic style eruptions have begun at the Noboribetsu area, which is sometimes called specifically as Noboribetsu Volcano [24, 25, 26]. Goto et al. (2013) [27] conducted trench surveys in the Noboribetsu area and identified at least twelve phreatic explosions over the past 8500 years, of which the latest one at ca. 200 ya. Lake Tachibana, Lake Oyunuma, and Jigokudani Valley are the explosion craters due to these eruptions, whereas Mt. Hiyoriyama is a dacitic cryptdome just beside Lake Oyunuma. Moriizumi (1998) [25] called this volcanic area the KVG, based on the geological knowledge that it comprises multiple volcanoes and eruption sites with different ages. Following this nomenclature, we term the overall target area of this study the KVG, whereas we use Kuttara Volcano when we need to specify the individual stratovolcano which has Lake Kuttara on its summit.

Major geothermal activity is currently seen at Lake Oyunuma, Jigokudani Valley, and Hiyoriyama cryptdome. Temporarily and spatially sporadic temperature anomalies, geysers, vigorous steam emissions, and effusion of muddy water have been reported in the Jigokudani area by eyewitness over the past 150 years. On the other hand, Lake Kuttara is covered with ice in winters. Though it is not an active crater lake, slight advective heat transfer by relatively warm water is suggested, based on the limnological study on the temperature profile of the lake [28].

Next, we summarize the current volcanic activity of the KVG. Weak plumes (110−140 °C; maximum height of ca. 50 m) are present near the top of Hiyoriyama cryptdome [29]. The gas is dominated by water vapor (ca. 98 vol.%) and contains CO_2 and H_2S as other major species (unpublished data by Hokkaido University, based on the aerial measurements from an unmanned helicopter). The power supply to Lake Oyunuma, where the dominant hydrothermal activity is observed, is estimated to be ca. 45 MW by Fukutomi et al. (1968) [30] as the sum of sensible heat transfer via hot-spring water and evaporative heat loss from the lake surface. Some seismicity does exist around Hiyoriyama cryptdome, but volcanic earthquakes are sparse (~10 per year). In February 2016, small-scale and short-lived but unusual seismic swarms took place [29]. Although an extension has been observed in some GNSS baselines since mid-2017 [31], no remarkable ground deformation sourced at shallow depths has been reported so far. The KVG is classified as an active volcano and is continuously monitored by JMA.

3.2. Data Acquisition, Processing, and Provisional Modeling

We performed MT data acquisition at KVG in July to August in 2017 at 49 sites, as shown in **Fig. 2**. The ADU-07e system with MFS-06e (horizontal) and MFS-07e (vertical) induction coils, manufactured by Metronix Geophysics, was used for the measurements. For telluric sensors, non-polarizable Pb-$PbCl_2$ electrodes were used. The typical length of the electric field measurements in the survey was approximately 50 m. Three components of the geomagnetic field (H_x: northward, H_y: eastward, H_z: downward) and two horizontal components of the electric field (E_x and E_y) were sampled at 32 and 1024 Hz, respectively, in which the former was recorded continuously over the measurement period, while the latter was sampled for four hours, from 1:00-5:00 JST each day, when the signal-to-noise ratio was relatively high. The duration of the measurement was three to five days for each site.

The bounded-influence remote reference processing (BIRRP) program by Chave and Tomson (2004) [32] was applied to the time-series records for conversion into the impedance in the frequency domain approximately from 0.0002 to 400 Hz, with the aid of remote reference processing [31]. To reduce the noise of local origins, the reference data at a distant continuous recording station (about 650 km away from the target area) provided by GERD Co. Ltd. was used.

Based on this data, Hayakawa (2018) [23] modeled the resistivity structure by using a 3D inversion

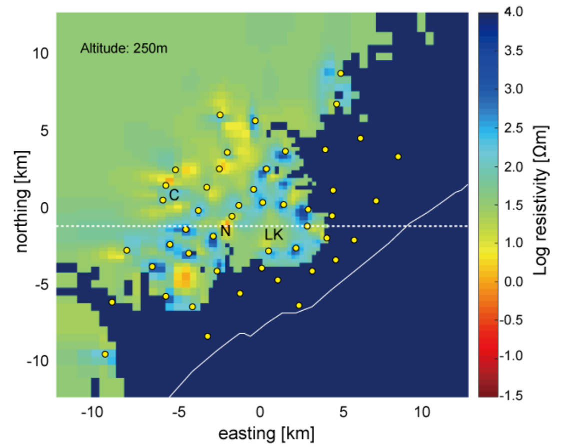

Fig. 2. 3D resistivity model by Hayakawa (2018) [23]. A plan view at altitude 250 m. The circles and the white line indicate the MT sites and the coastline, respectively. The dashed line corresponds to the location of the cross-section of **Fig. 5**. Note that the resistivity of air (10^6 Ωm) is shown in the southeastern side of the panel because the topography is lower than the sliced altitude. LK, N, and C represent Lake Kuttara, Noboribetsu hot spring, and Carls hot spring, respectively.

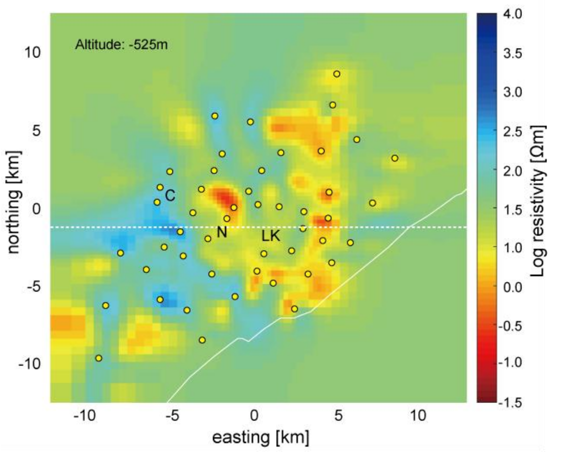

Fig. 3. 3D resistivity model by Hayakawa (2018) [23]. A plan view at an altitude of −525 m.

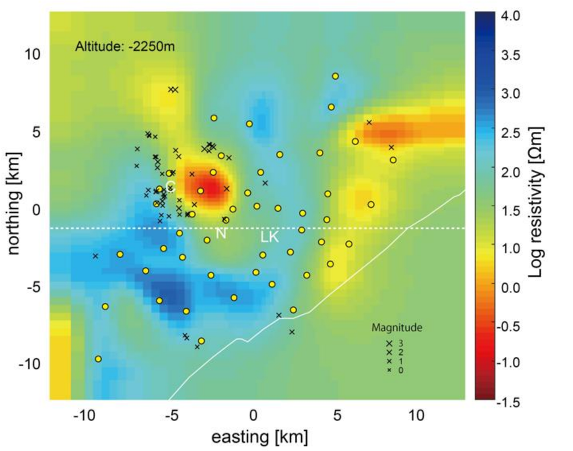

Fig. 4. 3D resistivity model by Hayakawa (2018) [23]. A plan view at an altitude of −2250 m. Routinely determined earthquake epicenters (black crosses) by JMA from 1997 to 2019 are overlaid (depth less than 10 km, magnitude greater than 0.8).

code ModEM [34]. The model space (674×674×244 km: NS, EW, UD) was gridded in rectangular coordinates, with the smallest horizontal mesh size as 250 m for the central target area, increasing in size toward the model borders, resulting in a mesh of 84×84×93 blocks in total. Topography was incorporated on the basis of the 10−m mesh DEM by the Geospatial Information Authority of Japan and the 500−m mesh bathymetry model by the Japan Coast Guard. For the blocks corresponding to air and sea, 10^6 Ωm and 0.3 Ωm were given, respectively, as fixed values. Responses at twelve periods between 0.00521 and 512 s were selected as the input data of the inversion, in which those with phases out of the ranges of 0 to 90˚ for Z_{xy}, or −90 to −180˚ for Z_{yx} (indicative of noise contamination) were avoided. Error floors of 5 and 10% for the off-diagonal and diagonal components of the impedance, respectively, and 10% for the tippers were given to avoid too much weighting for these data in the inversion process. Two-step inversion was applied, in which only the tippers were inverted at first (RMS misfit 5.8 after 20 iterations). In the first step inversion, we started from the uniform resistivity structure with 35 Ωm, which gave the smallest initial RMS misfit. Subsequently, only the impedances were inverted (RMS misfit 2.3 after 154 iterations). We summarized the key features of the modeling results as follows.

(1) The near-surface resistivity distribution, as shown in **Fig. 2**, is in good agreement with the surface geology (**Fig. 1**). For instance, the Noboribetsu and Carls (frequently spelled Karurusu in Japanese literatures) hot spring areas showed low resistivities around 10 Ωm, which were indicative of hydrothermal alteration. Meanwhile, the resistivity was relatively high (100 to 1000 Ωm) on northern and eastern to southern flanks of Kuttara Volcano, where volcanic deposits such as andesite lava flows covered the surface as shown in the geological map in panel (c) of **Fig. 1**.

(2) The overall resistivity feature in the shallow part of the EW transect across Lake Kuttara shown in **Fig. 5** is approximately consistent with the 2D model of the previous study by Goto and Johmori (2015) [22], shown in the lower panel. Looking at the resistivity beneath Lake Kuttara down to 4 km deep (region M in **Fig. 5**), no significant low-resistivity body evoking a magma reservoir with interconnected melt, which is believed to exhibit resistivity on the order of 1 Ωm (e.g., [35]), is recognized. However, considering the resistivity value of several tens Ωm, we do not rule out the existence of cooling mushy magma with a sufficiently low melt fraction or a two-phase hydrothermal reservoir.

(3) The shallow part beneath the Noboribetsu hot spring up to 1 km deep shows remarkable low resistivity of 1−10 Ωm (indicated as C1 in **Fig. 5**). This is consistent with the previous notion based on the EM survey by Goto and Johmori (2011) [20] and the trench survey by Goto et al. (2013) [27] in which they

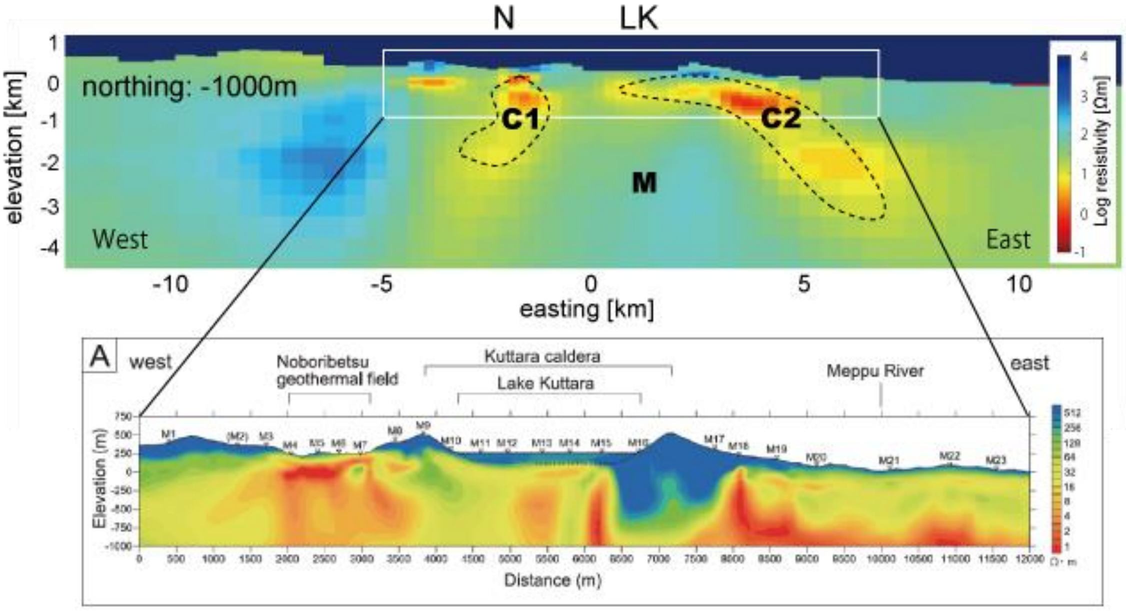

Fig. 5. Upper panel: An EW resistivity cross-section piercing Lake Kuttara and Noboribetsu spa modeled by 3D inversion in Hayakawa (2018) [23]. The white rectangle corresponds to the extent of the 2D cross-section by Goto and Johmori (2015) [22], shown in the lower panel.

pointed out the intensive alteration as a result of hydrothermal activity. One of the new findings of our MT survey is that the conductive layer extends in the NNW direction toward the deep part (**Fig. 3** and **Fig. 4**). In contrast, the resistivity is relatively high (> 100 Ωm) below the Carls hot spring area, except the surface, exhibiting a different feature from the Noboribetsu area.

(4) Low resistivity patches exhibiting 1 to 10 Ωm are also recognized at shallow depths of 0.5 to 3 km below the northeastern to southern flanks of Kuttara Volcano, which are indicated as C2 in **Fig. 5**. Regarding these conductive zones and the above-mentioned C1 as one, it looks, as a whole, like an umbrella or a mushroom cap that is centered at Lake Kuttara, below which an intermediate resistivity at tens to hundreds of Ωm is imaged (M in the upper panel of **Fig. 5**). The northern part of the conductive umbrella seems to be missing.

(5) Routinely determined earthquake epicenters by JMA, as shown in Fig. 4, are concentrated around the low resistivity anomaly extending from Noboribetsu hot spring area, although the location accuracy, especially for the depth, is not very high because a regional velocity model is assumed.

3.3. Interpretations and Implications

Pronounced low resistivity is often seen at shallow depths in geothermally active fields, as is reported in the recent MT surveys such as at Iwo-yama in Kirishima Volcanic Complex [5] and Hakone Volcano [36], both of which are based on 3D inversion modeling. As summarized in (3) and (4) in the previous section, similar low resistivity zones indicating 1−10 Ωm are identified in our study at KVG as C1 and C2.

In the Noboribetsu area, active fumaroles and hot springs are present. Goto et al. (2013) [27], based on a trench survey, found that hydrothermally altered minerals, such as smectite and/or kaolinite, were abundant in the deposits of phreatic eruptions in the past. Geochemical analysis by NEDO (1991) [37] reported that the isotopic ratios of oxygen and hydrogen of the hot spring water of Noboribetsu spa was suggestive of a deep origin. Taking the above supplemental information into account, it is likely that the low resistivity C1 results from the combined effects of the conductive hot water ascending through fractures, high temperature due to hot water and gas, and altered minerals that forms less permeable layers. Such an environment (co-existence of hot water/gas with a seal layer) suggests the relatively high potential of wet eruptions in this area. In addition, the deeper extension of the remarkable low-resistivity zone suggests that hot water is supplied from northwest of the Noboribetsu spa, rather than from right below, though this should be carefully investigated elsewhere through a sensitivity check.

In the case of Iwo-yama in Kirishima Volcanic Complex, it is confirmed with a several lines of supporting evidence, such as the depth of the ground deformation and the epicenters of micro-earthquakes, that the low resistivity layer corresponds to the impermeable layer, which is rich in altered clay minerals [5]. However, this is not verified in the case of KVG, in which no obvious ground deformation of volcanic origin, which would be suggestive of an inflating pressure source, has been observed. The accuracy of hypocenters in KVG is not very high because of the relative sparseness of the seismic network when compared to other well-monitored volcanoes, and of the low level of seismicity itself. In this respect, the relationship between the low-resistivity zone C1 and the present volcanic activity is unknown. Seeing these things differently, this area might be too stable for ground inflation or seismic swarms to take place, since volcanic fluids are smoothly transported to the ground surface without significant interruption on the way. If this is the case, such unrest events are expected in the future because of imbalances in the system, such as a temporary oversupply of fluids, or insufficient upward and/or lateral drain of fluids due to mineral precipitation and depleted permeability in the pore network [38]. Considering the recently improved seismic network in the KVG area as compared with the previous decade and the ability to detect even very local ground deformation by the up-to-date InSAR technology, we anticipate that more detailed prospects in terms of the plausibility of a wet eruption is discussed in relation to the electrical structure when such unrest phenomena take place.

Next, we discuss the mushroom-cap-like low resistivity (1 to 10 Ωm) underlying Kuttara Volcano, as pointed out in (4) in the previous subsection. Such a low resistivity bell-shaped layer, underlain by an intermediate resistivity zone, is reported at Hakone Volcano by Yoshimura et al. (2018) [36]. They attributed this structural feature to a hydrothermal reservoir at the central part of Hakone Caldera (10 to 100 Ωm), capped by a clay-rich impermeable layer (< 10 Ωm). In the Kuttara case, the low-resistivity umbrella appears to extend from the center of the edifice of Kuttara Volcano approximately 0.5 km deep down to the eastern and western piedmont approximately 2–3 km deep (**Fig. 5**). However, the depth extent of the layer is not definitive, since no sensitivity check regarding this point has been performed in Hayakawa (2018) [23]. There is no deep drilling data available except for the Noboribetsu and Carls areas, so that we lack direct evidence to identify the conductive mushroom cap as a clay-rich impermeable layer, particularly for C2. If we attribute the low-resistivity to the percolating groundwater within the edifice, composed mainly of porous volcanic deposits (i.e., pyroclastic flow, scoria, pumices, and fractured lava flows), it is required to consider the highly conductive saline water subjected to injection of volcanic fluids, since neither fresh water of meteoric origins (generally 10–100 Ωm) nor the lake water of Kuttara (ca. 140 Ωm; a direct measurement by Goto and Johmori, 2015 [22]) is enough to lower the bulk resistivity. If this is the case, it is also likely that the percolated media is altered to some extent and is accompanied by an adjacent less permeable clay zone. In summary, based on the present knowledge of the resistivity structure, we should also regard C2 as a potential zone causative of wet eruptions in the future, which needs further detailed investigation in relation to issue (2) in the previous subsection.

4. Further Possible Applications and Future Outlook

As shown in the examples in the section above, the MT can be a powerful tool for screening the potential sites of wet eruptions from the electrical structure. Here we propose a few further possible applications of the resistivity information for the evaluation of eruption imminence. One of these is to understand the locations of unrest phenomena in relation to the subsurface structure. Recent case studies have provided the general notion that shallow micro-earthquakes and ground deformation are tightly controlled by hydrological structure, especially by an altered clay-rich conductive layer that works as an impermeable seal around a vent region of volcanoes with repetitive wet eruptions (e.g., Kuchino-erabu-jima [39], Kusatsu-Shirane [40], Hakone [36], Iwo-yama in Kirishima Volcanic Complex [5], Jigokudani Valley in Mt. Tateyama [41]). Such characteristic conductive layers beneath active volcanoes, recognized in some earlier studies as an aquifer that can be the site of a phreatomagmatic eruption, are rather recently interpreted to be an impermeable clay cap as a constituent of a hydrothermal reservoir system in conjunction with an underlying electrically less conductive zone. Similar well-developed shallow low-resistivity zone outlining the geothermal system has been found in Tongariro volcanic system, New Zealand [42] and Hengill geothermal area, Iceland [43]. Identification of the locations of unrest phenomena, as well as their migration with time, may help us understand the physical processes occurring in the system as an ongoing scenario (e.g. pressurization with thermal demagnetization just under an impermeable layer and subsequent upward migration of micro-earthquakes). In other words, it contributes to providing the criteria for the severity evaluation of such unrest phenomena. Of course, it is also important to accumulate such unrest events to make statistical or probabilistic treatment possible. KVG is also one of such examples.

Next, subsurface structure information can be utilized as a platform of numerical simulations for the preceding processes to characterize wet eruptions. Some numerical simulators used in geothermal engineering are applicable to wet volcanic environments to model the system behavior in an inter-eruptive period, given that the processes can be treated as water/vapor flows in a porous media. One possible framework is as follows. (1) Hydrological properties of the model space, such as the specific permeability and porosity, are configured. The resistivity information may help when available direct data is insufficient. (2) A steady state is simulated under a certain meteoric recharge, heat and/or fluid supply from below. (3) System behavior in terms of temperature and pressure is investigated in response to an altered heat/fluid supply and/or hydrological property, whether manually or spontaneously. There is a line of studies, such as [44, 45, 46], in which the response of a wet volcanic system is investigated based on versatile hydrothermal simulators under a simple topography and subsurface structure with modulated heat/fluid supply rate and/or vent permeability. We consider that such an approach has affinity to the evaluation of eruption imminence, since it deals with the temporal variation of the system itself, although the reality of the model configuration can be an intrinsic matter. Disregarding the calculation cost, probabilistic eruption prediction may also be possible given some prior distribution of the property values and boundary conditions. However, in that case, we will have to cope with another problem regarding how we define the condition of the initiation of an eruption.

It is easily imagined that the permeability of the vent region can affect the time period from an unrest event to an eruption. Therefore, the dynamic nature of the permeability would be a matter, if it does exist. Christenson et al. (2010) [38] numerically investigated the reactive transport of vent fluids and reported that the permeability in the vent could undergo a drastic decrease by several orders of magnitude in a few to 10 days to precipitate impermeable seals. Earlier work by Hurst et al. (1991) [47], noting the non-linear characteristics of the viscosity on the temperature of elementary sulfur, commonly seen at the bottom of active crater lakes, discussed the mechanism of cyclicity observed at Crater Lake of Mt. Ruapehu. Although they did not mention the time scale, we consider that quantitative investigation may be possible based on a numerical model, if realistic conditions are applied.

Electrical conductivity (reciprocal of the resistivity) is seemingly related to the fluid permeability, as both of which are transport properties. However, straightforward one-to-one translation from resistivity to permeability is impossible because of complex intervening factors, such as resistivities of solid phase and intermediate fluids, porosity, water saturation, surface conduction due to clay minerals, and melt fraction. Some recent studies have tried to incorporate the knowledge from other geophysical surveys, geological and/or petrological studies to interpret the resistivity model; a commonly used approach is that the resistivity is converted into some secondary variables such as the water content or melt fraction on the basis of Archie's law [48], its developed models (e.g. [49]), or SIGMELTS [50]. Thereafter, its consistency with other information is determined (e.g., [51, 52]). Reminding that Archie's law is an empirical model based on drilling data, we consider it possible to narrow down the probable range of the permeability in combination with those of accompanying parameters. Compilation of prior information (on various parameters including resistivity) as a database and some integrated statistical analysis, such as the machine learning in multiple dimensions, must be helpful for such evaluation, at least for specific environments like shallow volcanic fields.

A few 3D-MT inversion codes are currently available. For example, a data-space inversion with rectangular mesh (WSINV3DMT [53]), a finite difference method with rectangular mesh (ModEM [34, 54]), and a tetrahedral finite element method (femtic [55]) are recently used in application to volcanic fields. As any MT inversion generally does not give a unique solution, cross-checking by independent code is desirable to evaluate the robustness of the preferred model. Preprocessing, such as generating the model mesh and formatting the input data and parameter files, depends on each inversion code and often requires considerable experience and skill. Therefore, there is a practical need to develop tools that facilitate these pretreatments as future work in this research field.

5. Concluding Remarks

In the present paper, we summarized the recent volcanic eruptions in Japan, asserting that measures to evaluate the severity of volcanic activity during an inter-eruptive period, as well as multi-disciplinary monitoring, are necessary, especially for wet volcanoes, so as to extend the current knowledge and techniques in volcanology to the practical social benefits in terms of eruption prediction. We then stated that the imaging of the electrical internal structure of active volcanoes by EM surveys is useful in screening the potential sites of wet eruptions. We demonstrated the provisional results of a broadband MT survey in KVG, which we performed in 2017 as a recent field study, in which we discovered a prominent low resistivity zone C1 (1–10 Ωm), suggesting a hydrothermal system subjected to intensive alteration at a shallow part beneath Noboribetsu spa. Low resistivity patches C2 with the same resistivity and depth range as C1 were also imaged beneath the northeastern and eastern to southern zones of Kuttara Volcano, forming a conductive mushroom-cap-like structure when recognized as one together with C1. Such a characteristic structure, as recently reported for other volcanic areas, is suggestive of an underlying hydrothermal reservoir as a potential site of wet eruptions. Although further investigation utilizing multilateral data, such as the drilling by NEDO (1991) [37] and other geophysical surveys, as well as the robustness checking of the resistivity model itself is necessary, the extensive 3D structure of KVG obtained in the present study is one of the most important achievements.

In addition, we proposed other possible applications of the information from EM surveys to promote the development in the evaluation techniques of eruption imminence. Firstly, we asserted that the electrical structure can be used to better understand the background physical processes of unrest events, such as micro-seismicity, ground deformation, and demagnetization, in light of their locations, facilitating the severity evaluation of such unrest episodes during an inter-eruptive period. Next, we pointed out that the numerical approach based on hydrothermal simulations has some affinity to the imminence evaluation of wet eruptions, and the electrical structure based on EM surveys substitutes for information on hydrological properties of the model space when direct data is unavailable.

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