Bull. Inst. Oceanic Res. & Develop., Tokai Univ. (2013), 34, 17 - 27

Geomagnetic and Topographic Survey of the Main Crater Lake, Taal Volcano (Philippines) and an Outlet for a Large Hydrothermal Reservoir revealed by MT Observations.

Paul Karson B. Alanis[1), 2)], Makoto Harada[1),*)], Julio P. Sabit[2)], Juan M. Cordon Jr.[2)], Jacques Zlotnicki[3)], Yusuke Yamaya[4)], Akihiro Takeuchi[1)], Yoichi Sasai[1)], Frederic Fauquet[3)], Toshiyasu Nagao[1)] and Yoshihiro Okada[1)]

Abstract

A geomagnetic and topographic survey of the Main Crater Lake (MCL) on Volcano Island, Taal volcano, the Philippines, was conducted in March 2008 to identify the eruption mechanism of the volcano. A mound at the lake bottom was found near the northern part of MCL, which was not present at the 1986 survey. Called mound M, it was formed between 1986 and 2008 during a period of new fumarole activity, which started on the northeastern shore of MCL in the early 1990's. A geomagnetic survey found no Total Magnetic Field (TMF) anomaly corresponding to the mound, which implies that the mound M is non-magnetic. The site coincides with the location of a high-temperature area detected by the ASTER satellite during the early 2005 volcanic crisis. The mound M might contain chemicals (chloride or sulphide?) deposited from volcanic gas. A reason for the long quiescence of Taal volcano, i.e. 35 years since the latest eruption of 1977, has been surmised as due to the effective degassing from magma intruded at a shallow depth. The mound M could be a direct evidence of such repeated degassing. Magnetotelluric and audio-magnetotelluric surveys were conducted on Volcano Island, in March 2011 and March 2012 with the objective of creating a resistivity model of the hydrothermal system beneath the volcano. Initial (2-D) inversion modeling revealed a prominent and large zone of relatively high resistivity almost directly beneath the Main Crater and surrounded by zones of relatively low resistivity. The anomalous zone of high resistivity is hypothesized to be a large hydrothermal reservoir filled with volcanic fluids in a gaseous phase. Our three-dimensional forward modeling reveals the size of the reservoir to be as large as 3 km in diameter and its location to be between 1 km to 4 km in depth. In turn, the reservoir appears to be overlain by an impermeable cap exhibiting a lower resistivity signature compared to the hydrothermal reservoir. The presence of such a large hydrothermal reservoir could be related to the past activities of Taal Volcano. In particular, the 1911 January 30 eruption showed an anomalous feature similar to a gas explosion, which can be attributed to the large hydrothermal reservoir collapsing catastrophically.

---

1) Institute of Oceanic Research and Developments, Tokai University, 3-20-1 Orido, Shimizu-ku, Shizuoka, 424-8610, Japan.
2) PHIVOLCS (Philippine Institute of Volcanology and Seismology), C. P. Garcia Avenue, U. P. Campus, Diliman, Quezon City, Philippines.
3) Observatoire de Physique du Globe de Clermont-Ferrand, 24 Avenue des Landais, 63177 Aubiere Cedex, France.
4) Earthquake Research Institute, the University of Tokyo, Yayoi 1-1-1, Bunkyo-ku, Tokyo, 113-0032, Japan.
*) Now at MINDECO Co. Ltd., Osaki, 1-11-1, Shinagawa-ku, Tokyo, 141-0032, Japan.

(Received : December. 4. 2012 ／ Accepted : January. 22, 2013)

1. Introduction

Taal volcano is located in the southern part of Luzon Island, the Philippines (120° 57’ E, 14° 02’ N, Height 311 m). It consists of a large caldera lake of Taal with 25 km x 20 km wide and its central cone Volcano Island of 5 to 8 km in diameter. Volcano Island has the Main Crater of the diameter 2 km at its center, in which exists a Main Crater Lake (MCL) of 1.2 km in diameter and about 80 m in depth. See Fig. 1. This volcano was nominated as one of the decade volcanoes of 1990, being one of the frequently erupting and devastating volcanoes of the world (Punongbayan and Tilling, 1989).

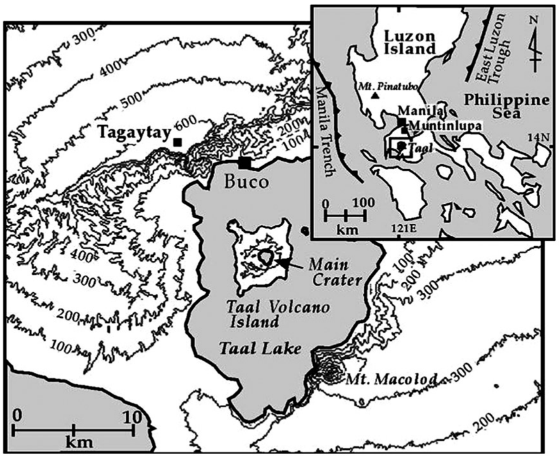

Fig. 1 The topography of Taal volcano in the southern part of Luzon Island, the Philippines.

According to historical documents, Taal volcano had erupted 33 times during the period from 1572 to 1977 (Catane *et al.*, 2005). Most of the eruption modes were phreatic and/or phreato-magmatic explosions. Large eruptions took place from the Main Crater in 1754 and in 1911. In particular, in the 1911 eruption, all the inhabitants (more than 1300 people) of Volcano Island were killed by the explosion and ash fell towards Metro Manila about 60 km to the north from Taal. At Mt. Tabarro on the southwestern side of Volcano Island, eruptions continued from 1965 to 1977. The base-surge event in 1965 is notable because this type of explosions was first documented in volcanology (Moore *et al.*, 1966). The phreato-magmatic explosions were followed by several effusive lava flow events and terminated in 1977. For the past 35 years since then, there have been no eruptions on this volcano.

However, since the early 1990's, volcanic swarm earthquakes began to occur beneath Volcano Island. In particular, in February 1992, the seismic crisis accompanied bubbling over the surface of MCL and ground uplift amounting to 20 cm. Ground cracks emerged on the northern slope of the island (Daang Kastila area) with fumaroles. These phenomena did not finally lead to eruptions (Catane *et al.*, 2005). Three major fumarole areas were formed on Volcano Island, i.e. the east and southwest coast of MCL and Daang Kastila areas.

Continuous monitoring of the ground deformation by GPS measurement was introduced in Taal volcano since 1998 (Bartel *et al.*, 2003). Deflation and inflation of the ground at the center of Volcano Island were repeated with several episodes from 1998 to 2000, which was modeled by the Mogi point sources at 4 to 5 km depth. Bartel *et al.* (2003) suggest that the inflation events result from episodic intrusions of magma into a shallow reservoir centered beneath Volcano Island. Subsequent deflation was ascribed to discharge of magmatic fluids and/or gases into an overlying, unconfined hydrothermal system.

Such a shallow hydrothermal system has not so far been identified by geophysical and geochemical means (Delmelle *et al.*, 1998). However, the seismic crisis in 2004 to 2006 terminated during the latter half of the activity with the appearance of geysers, bubbling in MCL, and withering of vegetation, together with some prominent electric and magnetic field changes (Harada, *et al.*, 2005; Zlotnicki *et al.*, 2008). In particular, TMF (Total Magnetic Field) changes on the eastern coast of MCL clearly indicated that the ground temperature at a very shallow depth (~10 m) was raised by a few degree C or so (Zlotnicki, *et al.*, 2008).

Wide-band magnetolluric (WMT) and audio-frequency magnetolluric (AMT) surveys were conducted on Volcano Island in March 2011 and March 2012 as part of the PHIVOLCS-JICA-SATREPS Project. AMT soundings were taken at 15 stations while both MT and AMT soundings at 19 stations for a total of 34 stations. 2-D models of resistivity structure are presented by Yamaya *et al.* (2012) by carefully examining the effect of electric currents induced in the surrounding sea around Taal volcano. Alanis *et al.* (2012) present a 3-D model for resistivity to interpret the overall feature of MT data which shows the approximate size and position of a possible hydrothermal reservoir. Based on the geomagnetic and topographic survey of Main Crater Lake already reported by Sasai *et al.* (2008), this paper briefly summarizes the results of electromagnetic studies on Taal volcano conducted by an international research group EMSEV (Electro Magnetic Study of Earthquake and Volcanoes, http://www.emsev-iugg.org/emsev/) since 2005.

2. Outline of electromagnetic observations in Taal volcano

In the history of electromagnetic observations on active volcanoes, geomagnetic measurement was initially introduced by Rikitake, (1957) and Yokoyama (1969), which was followed by a number of research papers in recent year (Sasai *et al.*, 1990 ; Tanaka, 1993 ; Del Negro *et al.*, 2004 ; Hurst *et al.*, 2004). The resistivity measurement was later introduced, which, for example, successfully detected the silently uprising magma through a vent before the 1986 eruption of Izu-Oshima volcano (Yukutake *et al.*, 1987). Further, the self-potential (SP) measurement turned out to be promising, because SP did change associated with magma intrusive events on Unzen volcano (Hashimoto and Tanaka, 1995), and Piton de la Fournaise volcano, Reunion island, French Indian Ocean (Michel and Zlotnicki, 1998 ; Zlotnicki and Nishida, 2003). In recent years, combination of three observations is emphasized as effective as was the case of the 2000 eruption of Miyake-jima volcano (Sasai *et al*, 2002 ; Zlotnicki *et al.*, 2003).

We installed 21 repeat magnetic survey points on Volcano Island at the initial field campaign in January, 2005. Some felt earthquakes happened to occur in Volcano Island, which led a number of local people to evacuate from the island by boats. We resurveyed the TMF values at the survey points on the east coast of MCL to detect significant changes in TMF amounting to +2.5 nT within only 5 days. Then the geothermal activity became high, such as the bubbling on the lake surface, the withering of vegetation and so on. At the end of January 2005, the main crater area was claimed as off-limit ; the volcano alert level was raised from 0 to 1. Repeat SP surveys revealed the rise of SP values on the northern slope of the volcano (Harada *et al.*, 2005).

During the period from January 2005 to March 2008, repeat TMF surveys were conducted 11 times. For the same three years period, the volcano alert level was raised from 0 to 1 twice, i.e. (i) the period from January to June 2005, and (ii) November 2006 to April 2007. During the term (i), bubbling on MCL water surface and withering of vegetation were noticed, while during the term (ii) there appeared geysers along the east coast of MCL. We observed the increase of TMF along the northern slope of Volcano Island (Daang Kastila area), where the fumarole along the fissures activated. The increase in TMF in the eastern coast of MCL and Daang Kastila can be explained as due to thermally demagnetized flat ellipsoidal bodies which lie 10 to 30 m beneath the ground surface. The demagnetization is only 1 % of the average magnetization of rocks, which can be attained by the ground temperature rise of a few degree C (Zlotnicki *et al.*, 2008).

3. Bathymetry and magnetic survey of the Main Crater Lake

We conducted the bathymetry and TMF survey on the surface of MCL in late March to early April in 2008. We used a small boat made of FRP (non-magnetic) with an outrigger, at the bow of which were installed an Oberhauser type proton precession magnetometer (GSM19, measurement accuracy 0.01 nT), a supersonic sounder, a GPS and a water-temperature meter. All the measurements were done automatically at every 5 seconds. The water temperature was measured to avoid the dangerous zone of hydrothermal activity. However, no anomalous high water temperature was detected over 40 degree C. Fig. 2a shows the bottom topography of MCL observed in 1986 (Ramos. 1986), while Fig. 2b the one measured in this study. A crag stands on the southwestern area of the lake, which is called 'Boulder'. The deepest area extends on the north of Boulder. Comparing Fig. 2a and Fig. 2b, we find that the overall features of the depth topography as well as the value of the deepest depth are similar to each other. However, we notice that the bathymetric line of 40 m in Fig. 2b largely swells out to the south as compared with the one (1986) in Fig. 2a. Within the past 22 years, the depth around this area became shallower by 10 to 20 m. We call this mound or the deposit as mound M.

Fig. 3 shows the distribution of TMF over the surface of MCL. The corrections were made for the daily variations with the aid of data from a magnetometer at Daang Kastila. We do not notice any particular TMF anomalies around the mound M. This implies that the mound M is non-magnetic. We may surmise two possibilities which could have produced the mound M : (a) A large-scale landslide could have taken place along the northern cliff of the crater rim, (b) Volcanic gas emanated from the bottom of MCL contains much amount of chemical materials, which made a deposit mass of chloride and/or sulfate. However, the rock mass of the landslide should be magnetized and it could produce more or less magnetic anomalies. Moreover, there is no trace of such landslide along the wall of the northern cliff. On the other hand, the area corresponding to the mound M is the place where the high temperature zone was identified by the ASTER satellite thermometry (Zlotnicki *et al.*, 2008). The mound M is most probably the center of the outlet of the effective degassing on this volcano.

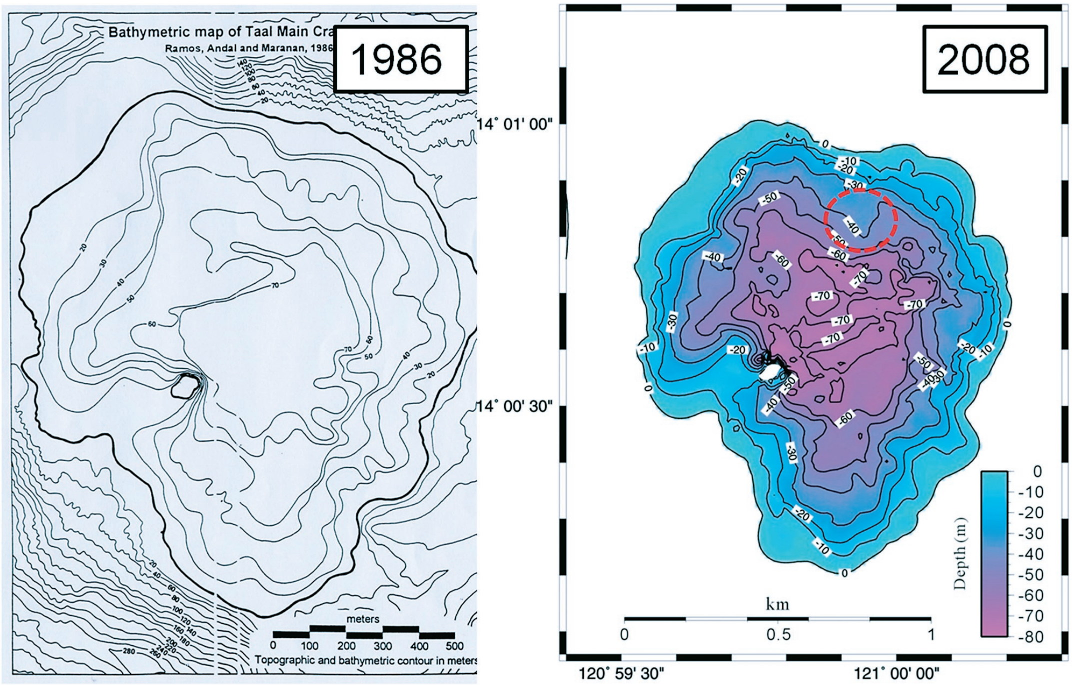

Fig. 2 Bathymetry of the Main Crater Lake : (a) [Left] by Lamos *et al.* (1986), and (b) [Right] this study (2008). Red dotted circle represents the mound M.

4. A large hydrothermal reservoir as revealed by MT soundings

Wide-band magnetolluric (WMT) and audio-frequency magnetolluric (AMT) surveys were conducted on Volcano Island in March 2011 (lines 300 and 500) and March 2012 (lines 100, 200, 400 and 600) as part of the PHIVOLCS-JICA-SATREPS Project. See Fig. 4. AMT soundings were taken at 15 stations, while both MT and AMT soundings at 19 stations for a total of 34 stations. Electromagnetic data were collected using 2 Phoenix Geophysics MTU-5 receivers. AMT observations (between 0.01-10,000 Hz) were made for a minimum of three (3) hours at each station, while WMT observations (between 0.001-1,000 Hz) were made overnight (minimum of 12 hours). An almost complete lack of electrical power on Volcano Island made it possible to obtain good quality magnetotelluric soundings even in the daytime.

As had been fully investigated in Yamaya *et al.* (2012), the magnetotelluric data on Taal volcano are severely contaminated by electric currents induced in the surrounding sea. Hence we are only able to use MT data for period ranges shorter than 100 seconds (or frequencies higher than 0.01 Hz). This imposes limits on our model in that we can only discriminate the resistivity structure at depths shallower than several km below the surface and limits resolution of structures in any detail deeper than 5 km.

Prior to inverting for the two-dimensional (2-D) resistivity structure, we attempted to obtain the electromagnetic 2-D strike by calculating the phase tensor (Caldwell *et al.* 2004), in which we find a dominant preferred direction as N 35° E. Taking into account that one of the major crater chains runs in NE-SW, we selected the N 35° E as the 2D structural direction. The 2-D inversion of the impedances was made using Ogawa and Uchida's (1996) inversion code. The details of 2-D models are discussed by Yamaya *et al.* (2012). In Fig. 5, we present 2-D cross sections of resistivity structure along the four

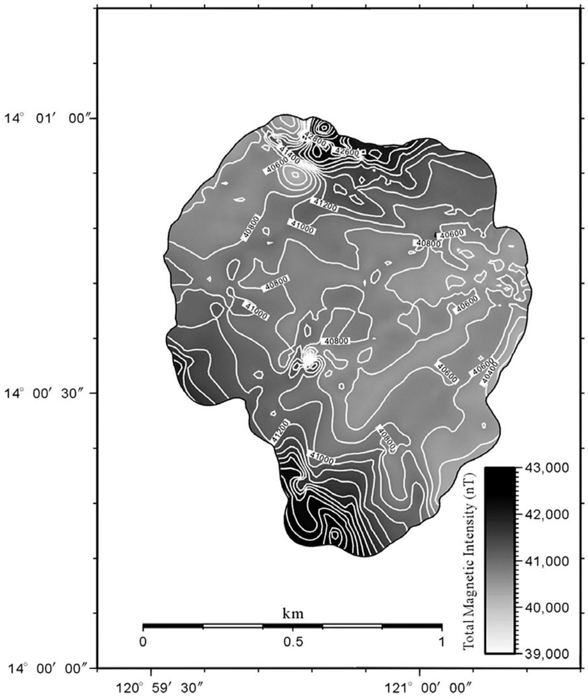

Fig. 3 The distribution of TMF on the surface of MCL. Unit in nT.

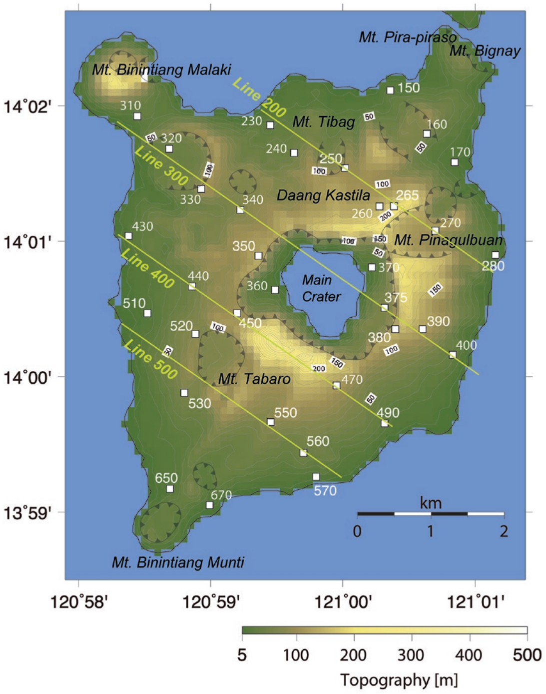

Fig. 4 Survey lines of MT measurements on Volcano Island.

section lines in Fig. 4. We find a relatively resistive area (R2 : ~ 100 ohm-m), surrounded and overlain by conductors (C1 and C2). The resistive zone is surmised as a hydrothermal reservoir, while the conductors as cap rocks composed of altered clay.

In line 300 (Fig. 5) there appears to be a relatively higher resistive body piercing the lower resistive cap rock at 500 m depth directly beneath the Main Crater Lake. This could be acting as a conduit for the release of hydrothermal fluids and the source of geysers, solfataras and steaming vents on the northern shore of the MCL as well as the northern slopes of Volcano Island. Around 4 km depth and beyond however, the resistivity generally follows a simple layered structure with the resistivity values increasing as one goes deeper, although because of the frequency cut-off inversion results at this depth are not reliable. The resulting 2-D models were used afterwards as the initial models for the subsequent 3-D forward modeling.

The calculations for the three-dimensional (3-D) MT responses were made using the 3-D numerical modeling code developed by Fomenko and Mogi (2002). This forward modeling method utilizes a finite-difference staggered grid of non-uniformly sized rectangles, giving highly accurate results even with irregular grids. The dimensions of these bodies were determined by trial and error until a small misfit was achieved between the calculated and observed apparent resistivity and impedance tensors at each site. The final 3-D model is shown in Fig. 6 and 7. The discrepancies in residuals of the apparent resistivity between the 1-D and final model are possibly due to static shift, due to small inhomogeneous structures near the surface, which in the case of Taal Volcano is quite severe. We therefore consider the improved misfit of the impedance phase instead.

As shown in Fig. 6 (encircled in a broken line), we find a relatively resistive (> 1000 ohm-m), elongated body, oriented with the long axis at N35° W, between 1 km and 2 km in depth at its top end. This resistive body is about 4 km long and 2 km wide. It is then connected to another slightly narrower, but equally resistive body (> 1000 ohm-m) about 2.5 km long and 2.5 km wide, at a depth of 2 to 4 kilometers. These bodies form rather eccentric, interconnected L-shaped

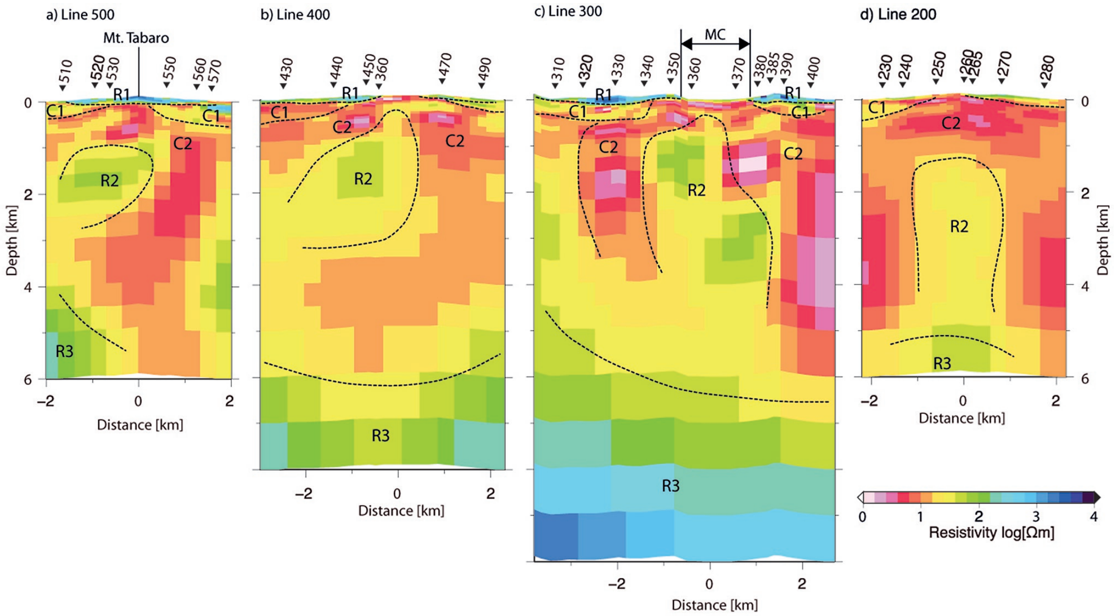

Fig. 5 2-D inverted resistivity sections (see Fig. 4 for section lines). Numbered inverted black triangles are MT stations. Major topographic structures are indicated such as Mt. Tabaro and MC for Main Crater.

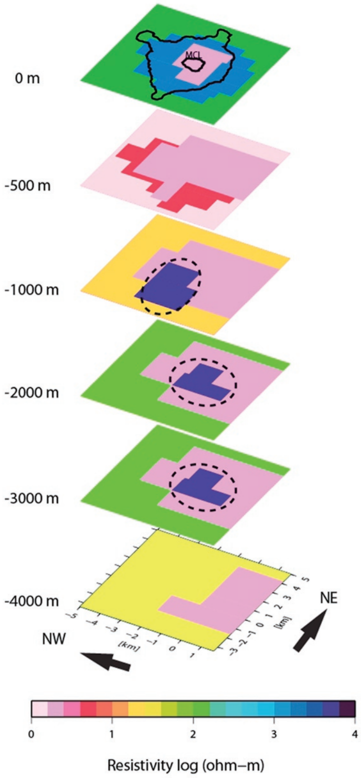

Fig. 6 Horizontal sections of the 3-D resistivity model at various depths. Area highlighted by the broken lines us the proposed hydrothermal reservoir. Outline of Volcano Island and Main Crater Lake (MCL) are shown at 0 m depth.

resistive bodies. We propose that this resistive body to be a large hydrothermal reservoir. These are in turn surrounded and overlain by relatively more conductive structures starting at 500 m depth, which possibly acts as an impermeable cap to confine the fluids (in a gaseous phase) within the hydrothermal reservoir. The contrast in resistivity properties between the resistive hydrothermal body and the surroundings is due to the former being an aggregation of interconnected cracks. These cracks are in turn partly filled with volcanic fluids in a gaseous phase, and although highly fractured is quite rigid (Maeda *et al.* 2012) resulting in a high resistivity signature. The relatively conductive zone, which surrounds the hydrothermal reservoir, on the other hand could be saturated by fluids in a liquid phase, contributing to the resistivity contrast (Yamaya *et al.* 2012). Between 4 and 5 km, however, the resistivity structure becomes almost homogenous, except for a continuous low resistivity zone (<10 ohm-m) at the western part of the volcano, which began from a shallow depth of 50 m and extends vertically downward to at least 5 km.

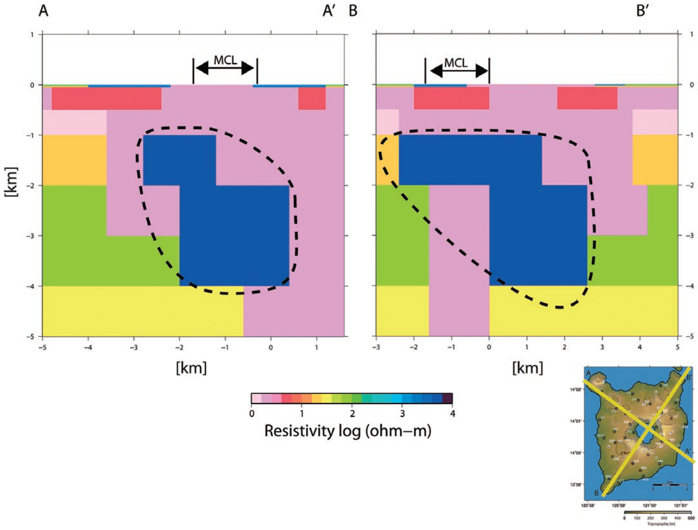

Fig. 7 Vertical section along A-A' and B-B' (inset map) of 3-D model showing proposed hydrothermal reservoir encircled by broken line.

5. Discussion and the future subjects

The eruptions of Taal volcano have been characterized by their destructive and violent nature. The 1911 eruption (the most destructive) led to the deaths of 1,335 persons (Worcester 1912). Typical Taal volcano eruptions can be described to be of the phreatic to phreato-magmatic type and can originate alternately from either the Main Crater or from various craters at the flanks, where a complete eruption cycle consists of Main Crater eruptions, followed by eruptions at the flanks (Torres *et al.* 1995; Catane *et al.* 2005). Volcanic hazards associated with eruptions of Taal volcano include base surges, ashfall, ballistic projectiles, lava flows, poisonous volcanic gases, acid rains, seiches and flooding, fissuring, ground subsidence and lakeshore landslides (Catane *et al*., 2005). For this study we focused on the 1911 eruption and its possible relationship to the hydrothermal reservoir.

Alanis *et al*. (2012) discuss volcanological implications for the existence of such a large hydrothermal reservoir beneath Taal volcano. Here we must emphasize anomalous features of the 1911 eruption, which can be realized only on the assumption of such a large hydrothermal reservoir. Prior to the 1911 eruption, the last abnormal activity of Taal volcano was in 1904. The latter was characterized as a mild phreatic eruption accompanied by earthquakes and ejection of tephra from the Main Crater (Catane *et al*. 2005). On the other hand, the 1911 activity was marked by its violence. This eruption was preceded by a rapid increase in seismicity beginning on 27 January 1911. These were not only felt in the immediate vicinity of Taal volcano, but were also recorded by seismometers of the Manila Observatory over 60 km away, and accompanied by audible rumbling sounds (Maso, 1911; Worcester, 1912). The eruption however reached its peak at around 0200H (local time) on 30 January when a terrible explosion occurred. We believe that this explosion was caused by the hydrothermal reservoir collapsing. As evidence of this, Maso (1911) and Worcester (1912) wrote that even when the ejected mud reached distances of up to 10 km from the volcano, the plants, people and animals covered by the mud exhibited discoloration and flesh burns similar to what one might suffer from exposure to caustic substances. Whereas in villages closer to the crater, casualties and damaged properties showed no signs of scorching or discoloration, which could have indicated exposure to high temperatures. Hence, the absence of scorch marks and singed clothing on people, and the presence of chemical burns suggested a relatively low temperature for the eruption. There were no eyewitness accounts (Maso, 1911; Worcester, 1912), nor remnants of fresh magma in the 1911 eruption (petrologic examinations of 1911 eruption deposits show no signs of juvenile pyroclasts [pers. com. Palladio-Melosantos, 2012], which could have indicated fresh magmatic components for the eruption), although injection of magma into the hydrothermal reservoir may have triggered the 1911 explosion. Another possibility is that the overlying confining layer of clays could have been weakened by cracks resulting from the numerous strong earthquakes that preceded the eruption. This could result in an explosive decompression of the hydrothermal reservoir. Moreover a post-eruption subsidence was recorded to be between 2.5 m to 3 m (Worcester, 1912), and while this large subsidence could be attributed to a discharge of magma at a deeper depth, given the physical evidence stated above, a breaching of the impermeable layer and collapse of the shallow large hydrothermal reservoir is more likely.

While magma itself is electrically conductive, because of severe contamination of the MT data by induced electric currents flowing the Verde Island Strait at the lower frequencies (< 0.01 Hz), we are limited to modeling less than 5 km in depth and hence, cannot resolve the presence of magma underneath. In the future, in order to model the deeper layers, long period MT soundings will have to be made outside Taal Lake.

The presence of a perched hydrothermal reservoir in a volcano is not new, however in the case of Taal volcano it is particularly significant because of its size relative to the actual size of the volcano. A collapse of such a huge reservoir could have tremendous destructive potential, as what occurred in 1911. Phreatic eruptions in general are difficult to predict, not for a lack of precursors, but because of the difficulty of assigning a specific precursor (Barberi *et al*. 1992), e.g. eruptions triggered by magmatic events can also exhibit the same precursors. Accordingly conventional methods of volcano monitoring such as geodetic measurements and seismology can fail in this regard. It is thus important to observe the state of the hydrothermal reservoir by every geophysical and geochemical method available. As shown above, the application of electromagnetic methods for volcano monitoring is one of the most effective.

Acknowledgements

The authors would like to thank the Philippine Institute of Volcanology and Seismology (PHIVOLCS), the Japan International Cooperation Agency (JICA) and the Science and Technology Research Partnership for Sustainable Development-Japan Science and Technology Agency (SATREPS-JST) for funding the study, Hokkaido University for lending instruments used in the study and the local people of Taal Volcano Island for assistance during the surveys. P. K. B. Alanis would like to thank the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT-Japan) for funding a long-term scholarship (2011/2013) allowing him to conduct research at the Earthquake Research Prediction Center, Tokai University, where this work was done. This study was partly supported by Tokyo Geographical Society (2008), JICA-SATREPS project (2010-2014) and Tokai University.

References

Alanis, P. K. B., Yamaya, Y., Takeuchi, A., Bornas, M. A. V., Cordon, Jr., J. M., Puertollano, J., Clarito, C. J., Hashimoto, T., Mogi, T., Sasai, Y., Nagao, T., A Large Hydrothermal Reservoir beneath Taal Volcano (Philippines) revealed by Magnetotelluric Survey: Its Implications to the Volcanic Activity, submitted to Natural Hazards, 2012.

Barberi FA, Bertagnini PL, Principe C., A review on phreatic eruptions and their precursors. J Volcanol. Geotherm. Res 54, 231-246, 1992.

Bartel, B. A., Hamburger, M. W., Meertens, C. M., Lowry, A. R., Corpuz, E., Dynamics of active magmatic and hydrothermal systems at Taal Volcano, Philippines, from continuous GPS measurements, J. Geophys. Res., 108, B10, 2475-2489, doi : 10. 1029/2002 JB 002194, 2003.

Caldwell, T. Bibby, H. M., Brown, C., The magnetotelluric phase tensor. Geophys. J. Int. 158, 457-469, 2005.

Catane,, S. G., Taniguchi, H., Goto, A., Givero, A. P., Mandanas, A. A., Explosive volcanism in the Philippines, CNEAS Monograph Series No. 18, 146 p., CNEAS, Tohoku Univ., 2005.

Delmelle, P., Kusakabe, M., Bernard, A., Fischer, T., de Brouwer, S., del Mundo, E., Geochemical and isotopic evidence for seawater contamination of the hydrothermal system of Taal volcano, Luzon, the Philippines, Bull. Volcanol. 59, 562-576, 1998.

Del Negro, C., Currenti, G., Napoli R. and Vicari A., Volcanomagnetic changes accompanying the onset of the 2002-2003 eruption of Mt. Etna (Italy), Earth Planet. Sci. Lett., 229, 1-2, 1-14, doi : 10. 1016/j. epsl. 2004. 10. 033, 2004.

Fomenko E. Y., Mogi, T., A new computation method for a staggered grid of 3D EM field conservative modeling. Earth Planets Space, 54, 499-509, 2002.

Harada, M., Sabit, J. P., Sasai, Y., Alanis, P. K. B., Cordon Jr., J. M., Corpuz, E. G., Zlotnicki, J., Nagao, T., Punongbayan, J. B., Magnetic and electric field monitoring of Taal volcano, Part I : Magnetic measurements, Proc. Japan Acad., Ser. B, 81, 261-266, 2005.

Hashimoto, T., Tanaka, Y., Self-Potential observations on Unzen volcano, Shimabara Peninsula, Kyushu Island, Japan, Geophys. Res. Lett., 22, 191-194, 1995.

Hurst, A. W., Rickerby, P. C., Scott, B. J., Hashimoto, T., Magnetic field changes on White Island, New Zealand, and the value of magnetic changes for eruption forecasting, J. Volcanol. Geotherm. Res., 136, 53-70, 2004.

Maeda Y, Kumagai H, Lacson R, Figueroa M, Yamashina T., Oscillation of a Shallow Hydrothermal Fissure Inferred from Long Period Seismic Events at Taal Volcano, Philippines. Abstract V 53 B-2816 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., USA, 3-7 Dec., 2012.

Maso S., The eruption of Taal Volcano Jan. 30, 1911. Weather Bureau Rep Manila, pp 1-45, 1911.

Michel, S., Zlotnicki, J., Self-Potential and magnetic surveying of La Fournaise volcano (Reunion

Island) : Correlations with faulting, fluid circulation and eruption, J. Geophys. Res., 103, 17845-17857, 1998.

Moore, J.G., Nakamura, K., Alcaraz, A., The 1965 eruption of Taal volcano, Science, 151, 955-960, 1966.

Ogawa, Y. Uchida, T., A two-dimensional magnetotelluric inversion assuming Gaussian static shift. Gephys. J. Int. 126, 69-76, 1996.

Punongbayan, R. S., Tilling, R. I., Recent case histories, in Volcanic Hazards, in Short Course in Geology edited by Tilling, R. I., 1, 81-101, AGU, Washington D. C., 1989.

Ramos, E. G., Bathymetry Map of Taal Main Crater Lake, unpublished PHIVOLCS internal map, 1986.

Rikitake, T., The distribution of magnetic dip in Oshima (Oo-sima) island and its change that accompanied the eruption of volcano Mihara, 1950, Bull. Earthq. Res. Inst., Univ. Tokyo, 29, 161-181, 1951.

Sasai, Y., Shimomura, T., Hamano, Y., Utada, H., Yoshino, T., Koyama, S., Ishikawa, Y., Nakagawa, I., Yokoyama, Y., Ohno, M., Watanabe, H., Yukutake, T., Tanaka, Y., Yamamoto, T., Nakaya, K., Tsunomura, S., Muromatsu, F., Murakami, R., Volcanomagnetic effect observed during the 1986 eruption of Izu-Oshima volcano, J. Geomag. Geoelectr., 42, 291-317, 1990.

Sasai, Y., Uyeshima, M., Zlotnicki, J., Utada, H., Kagiyama, T., Hashimoto, T., Takahashi, Y., Magnetic and electric field observations during the 2000 activity of Miyake-jima volcano, central Japan, Earth Planet. Sci. Lett., 203, 769-777, 2002.

Sasai Y, Harada M, Sabit JP, Zlotnicki J, Tanaka Y, Cordon JM, Uyeda S, Nagao T, Sincioco JS (2008) Geomagnetic and Topographic Survey of the Main Crater Lake in Taal Volcano (Philippines) : Preliminary Report, (in Japanese with English abstract). J Geography 117 : 894-900

Tanaka, Y., Eruption mechanism as inferred from geomagnetic changes with special attention to the 1989-1990 activity of Aso volcano, J. Volcanol. Geotherm. Res., 56, 319-338, 1993.

Torres RC, Self S, Punongbayan RS (1995) Attention focuses on Taal : Decade volcano of the Philippines, EOS (Trans. Am. Geophys. Un.) , 76, 241-247.

Worcester, D. C., Taal Volcano and its recent destructive eruption. Natl. Geogr. Mag. 23, 313-367, 1912.

Yamaya Y, Alanis PKB, Takeuchi A, Cordon JM, Mogi T, Hashimoto T, Sasai Y, Bornas MAVB, Nagao, T., Large hydrothermal reservoir beneath Taal Volcano (Philippines) revealed by Magnetotelluric survey : 2-D resistivity modeling, submitted to Bull. Volcanol., 2012.

Yokoyama, I., Anomalous changes in geomagnetic field on Ooshima volcano related with its activities in the decade of 1950, J. Phys. Earth, 17, 69-76, 1969.

Yukutake, T., Yoshino, T., Utada, H., Watanabe, H., Hamano, Y., Sasai, Y., Shimomura, T., Changes in the electrical resistivity of the central cone Miharayama, of Izu-Oshima volcano, associated with its eruption in November, 1968, Proc. Japan Acad., 63-B, 55-58, 1987.

Zlotnicki, J., Nishida, Y., Review on morphological insights of self-potential anomalies on volcanoes, Surv. Geophys., 24, 291-338, 2003.

Zlotnicki, J., Sasai, J., Yvetot, P., Nishida, Y., Uyeshima, M., Fauquet, F., Utada, H., Takahashi, Y., Donnadieu, G., Resistivity and self-potential changes associated with volcanic activity : The July 8, 2000 Miyake-jima eruption (Japan) , Earth Planet. Sci. Lett., 205, 139-154, 2003.

Zlotnicki, J., Sasai, Y., Toutain, J. P., Villacorte, E. U., Bernard, A., Sabit, J. P., Cordon Jr., J. M., Corpuz, E. G., Harada, M., Punongbayan, J.B., Hase, H., Nagao, T., Combined electromagnetic, geochemical and thermal surveys of Taal volcano (Philippines) during the period 2005-2006, Bull.Volcanol. doi : 10.1007/s 00445-008-0205-2, 2008.

フィリピン・タール火山火口湖の全磁力および湖底地形探査と電磁探査により推定された火山島直下の巨大な熱水だまりの湧出口

Paul Karson B. Alanis[1), 2)]・原田　誠[1),*)]・Julio P. Sabit[2)]・Juan M. Cordon Jr.[2)]・Jacques Zlotnicki[3)]・
山谷祐介[4)]・竹内昭洋[1)]・笹井洋一[1)]・Frederic Fauquet[3)]・長尾年恭[1)]

要　旨

本論文では，フィリピン・タール火山の火山島火口湖の全磁力と地形探査結果について報告する．さらに電磁(Magneto Telluric，MT)法による火山体の3次元電気伝導度構造探査により，得られた熱水溜りについても言及する．火口湖の水深測量は2008年3月に主に実施され，1986年の測量と比較して，火口湖の北側に新たな地形の高まり(マウンド)が発見された．このマウンドは1990年頃から活発化した火口湖北部での噴気活動で生じた可能性が高い．地磁気全磁力探査ではこのマウンドは非磁性と推定され，塩化物ないし硫化物から成ると推定される．現在タール火山は1977年の噴火を最後に，35年に及ぶ静穏期が続いており，この非磁性のマウンドは継続的な脱ガスの結果，生じたものと考えている．

MT法による探査は，2010年から開始された科学技術振興機構(JST)と国際協力機構(JICA)が共同で実施している地球規模課題対応国際科学技術協力(SATREPS)『フィリピン地震火山監視強化と防災情報の利活用推進』の一環として，火山島直下の精密な電磁気学的構造の推定を目指して2011年春と2012年春に実施された．3次元フォワード解析の結果，浅部の透水率の小さなキャップロックの下，換言すれば火山島の直下1kmから4kmの深さに，直径3kmほどの相対的に電気抵抗の大きな領域が広がっている事が判明し，これが過去の噴火史などを考慮すると巨大な熱水だまりと推定している．そして今回発見されたマウンドは人工衛星からの熱映像解析などの結果も併せて解釈すると，熱水だまりからのガスが効率的に放出されている場所ではないかと考えている．

---

1)　東海大学海洋研究所

2)　フィリピン火山学地震学研究所

3)　クレモンフェラン地球物理学研究所

4)　東京大学地震研究所

(2012年12月4日受付／2013年1月22日受理)