

A large hydrothermal reservoir beneath Taal Volcano (Philippines) revealed by magnetotelluric observations and its implications to the volcanic activity

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Abstract: Taal Volcano is one of the most active volcanoes in the Philippines. The magnetotelluric 3D forward analyses indicate the existence of a large high resistivity anomaly ($\sim 100 \Omega\cdot\text{m}$) with a volume of at least $3 \text{ km} \times 3 \text{ km} \times 3 \text{ km}$, which is capped by a conductive layer ($\sim 10 \Omega\cdot\text{m}$), beneath the Main Crater. This high resistivity anomaly is hypothesized to be a large hydrothermal reservoir, consisting of the aggregate of interconnected cracks in rigid and dense host rocks, which are filled with hydrothermal fluids coming from a magma batch below the reservoir. The hydrothermal fluids are considered partly in gas phase and liquid phase. The presence of such a large hydrothermal reservoir and the stagnant magma below may have influences on the volcano's activity. Two possibilities are presented. First, the 30 January 1911 explosion event was a magmatic hydrothermal eruption rather than a base-surge associated with a phreato-magmatic eruption. Second, the earlier proposed four eruption series may be better interpreted by two cycles, each consisting of series of summit and flank eruptions.

Keywords: magnetotellurics, resistivity structure, Taal Volcano, magmatic-hydrothermal eruptions, hydrothermal reservoir

Introduction

The volcanism of Taal Volcano is associated with the eastward subduction of the South China Sea (Eurasian Plate) beneath the Philippine Archipelago along the Manila Trench¹⁾ (Fig. 1a). As shown in Fig. 1b, the volcano itself rises at the center of a freshwater lake, about 25 km in diameter called Taal Lake. This lake is a caldera formed from at least four major ignimbritic eruptions 500–100 ka.²⁾ An island approximately 8 km in its maximum length and with a maximum height of 311 m a.s.l., which lies at the

lake's center, is called Volcano Island. The Main Crater is a large depression approximately 2 km wide at the center of the island. In the Main Crater, there is a 90 m deep, slightly acidic lake^{3),4)} known as the Main Crater Lake (MCL) (Fig. 1c). Eruptive products range from ignimbrites (calc-alkaline dacites), lava flows and tephra (tholeiitic basalts and basaltic andesites).^{2),5)}

Because of its frequent activity, numerous eruption centers and proximity to Metro Manila, the volcano is extensively monitored and studied by the Philippine Institute of Volcanology and Seismology (PHIVOLCS). Monitoring systems⁴⁾ include water and gas chemistry, ground deformation measurements (precise leveling and GPS) and seismology. From 2005 onwards, the Working Group on Electro-Magnetic Studies for Earthquakes and Volcanoes (EMSEV) of the International Union of Geodesy and Geophysics (IUGG) has been cooperating with the Philippine Institute of Volcanology and Seismology (PHIVOLCS) to develop and apply electromagnetic methods together with other geophysical monitoring techniques on Taal Volcano.^{6),7)}

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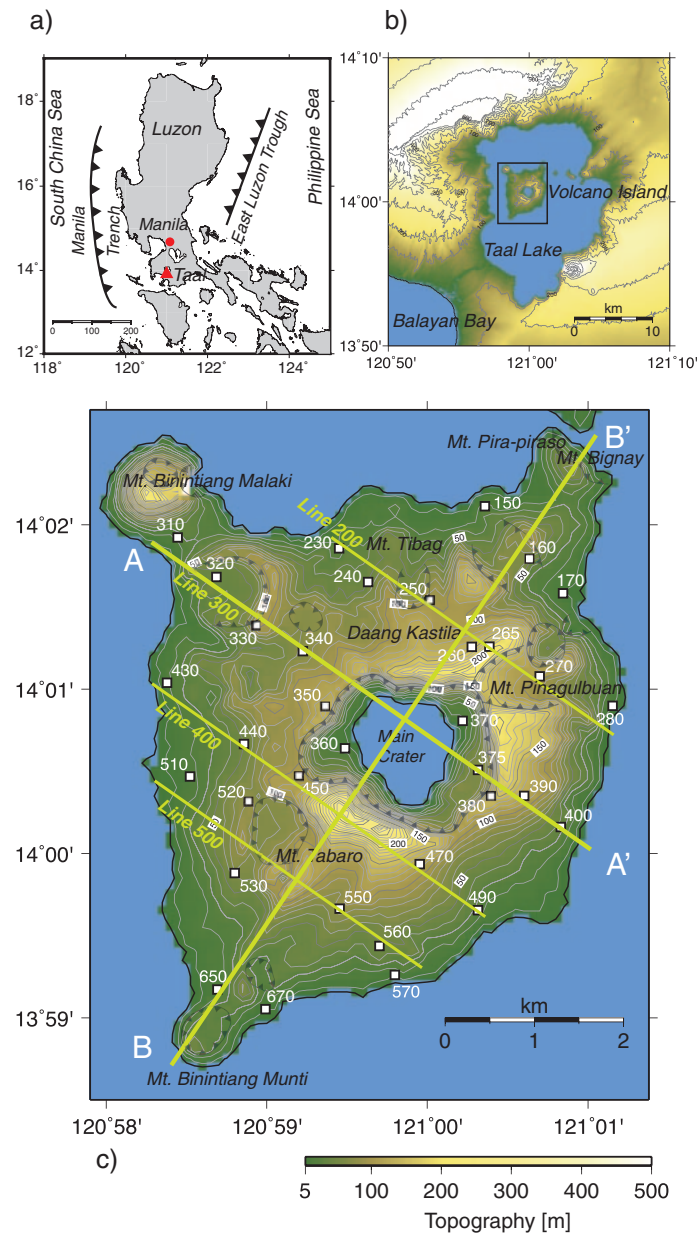


Fig. 1. a) Index map of northern and central Philippines showing location of Manila (red dot), Taal Volcano (red triangle) and regional tectonic structures. b) Black rectangle indicates the study area. c) Map of Volcano Island, showing the various eruption centers. White squares show locations of MT measurement stations. Modified from Yamaya *et al.* (2013). A–A' and B–B' denote the locations of 3D analysis shown in Fig. 4.

In this study, after introducing the eruption history of Taal Volcano, we will first present the results of magnetotelluric observations and 3-D forward modeling which reveals a more definite shape and extent of the resistivity anomalies than the 2-D resistivity profiles by Yamaya *et al.*⁽⁸⁾ Then, we will analyze the peculiar features of the

1911 eruption and attempt to put forward a new eruption cycle model that will help in explaining the numerous and shifting eruption centers. These considerations will hopefully contribute to the understanding of the past events and perhaps assist disaster-risk planners on the future volcanic activity of Taal Volcano.

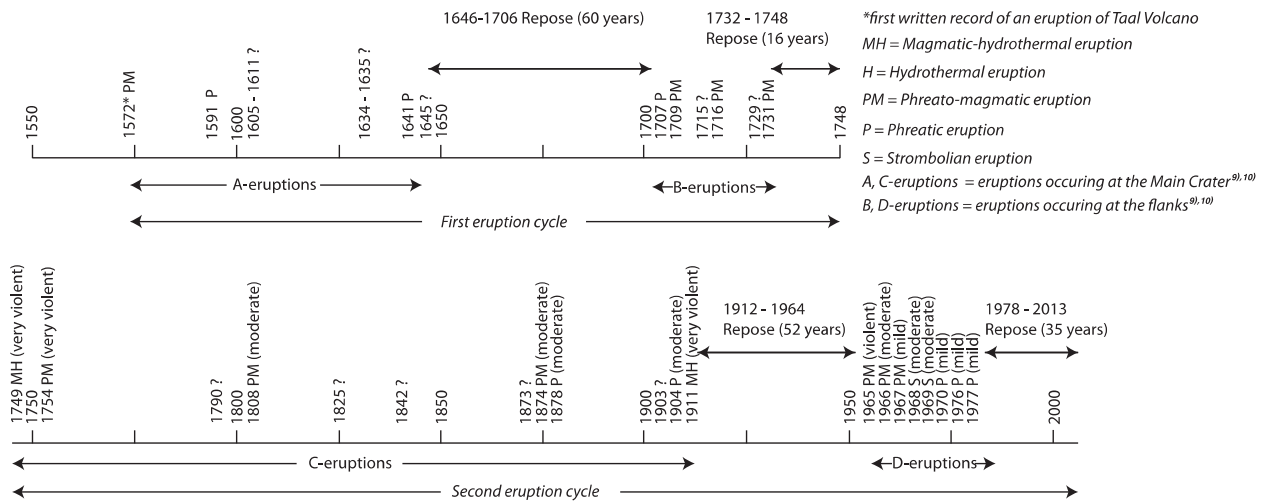


Fig. 2. Eruption history of Taal Volcano since 1572. Previous authors^{11,12} classified 4 eruption series (A–D). In this paper, taking into account hydrothermal reservoir replenishment history, we propose two eruption cycles (upper and lower panels) instead of four series.

Eruption history of Taal Volcano

Figure 2 shows the history of the documented eruptions of Taal Volcano. This figure is compiled based on Torres *et al.*⁹ and Catane *et al.*¹⁰ Typical Taal Volcano eruptions are described to be phreatic and phreato-magmatic type and to originate alternately from the Main Crater and the centers on the flanks. The first recorded eruption was in 1572, centered at the Main Crater and continued until 1645. These eruptions were referred by Torres *et al.*⁹ and Catane *et al.*¹⁰ as the Series A eruptions. Then there was a 60-year lull in activity (1646–1706). In 1707 eruptive activity started anew and continued sporadically until 1731 but at various sites on the flanks. These flank eruptions are called the Series B eruptions. After a 16-year repose period (1732–1748), eruptive activity returned to the Main Crater in 1749 and culminated in the violent 1911 eruption (Series C eruptions). The volcano again entered a 52-year quiet period from 1912–1964. Series D eruptions, centered on Mt. Tabaro on the southwestern slopes of the volcano (Fig. 1c) started in 1965 and continued until 1977. Since then the volcano has remained relatively quiet.

The 3-D resistivity structure beneath Taal Volcano Island

Magnetotelluric 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 JST/JICA-SATREPS (Science and Technology Research Partnership for Sustainable Development) Project (see Fig. 1c). Yamaya *et al.*⁸ presented 2-D resistivity profiles beneath the four lines (200, 300, 400 and 500). However, owing to the limitation of the 2-D analysis, the resistivity structure across the NE-SW direction was not clear.

In order to reveal a more exact shape of the resistivity anomaly, we calculated three-dimensional (3-D) MT responses using the 3-D numerical forward modeling code developed by Fomenko and Mogi.¹¹ In this calculation, we adopted 2-D structures of Yamaya *et al.*⁸ as the initial model. The dimensions of the structure were determined by trial and error until a small misfit was achieved between the calculated and observed apparent resistivity, impedance phases and magnetic transfer functions at each MT site shown in Fig. 1c.

The final 3-D model is illustrated in Figs. 3 and 4. We envision a large inclined high resistivity anomaly ($\sim 100 \Omega\cdot\text{m}$) with an estimated volume of $3 \text{ km} \times 3 \text{ km} \times 3 \text{ km}$ between 1 and 4 km in depth, which is capped and surrounded by a conductor ($\sim 10 \Omega\cdot\text{m}$). Yamaya *et al.*⁸ proposed that this high resistivity body to be a large hydrothermal reservoir composed of cracks filled by hydrothermal fluids. The hydrothermal reservoir, because of the cracks and fluids, can be a zone of high attenuation and low velocity of seismic waves.¹² Moreover, the hydrothermal reservoir, despite being highly fractured, is considered structurally rigid¹³ and dense enough to

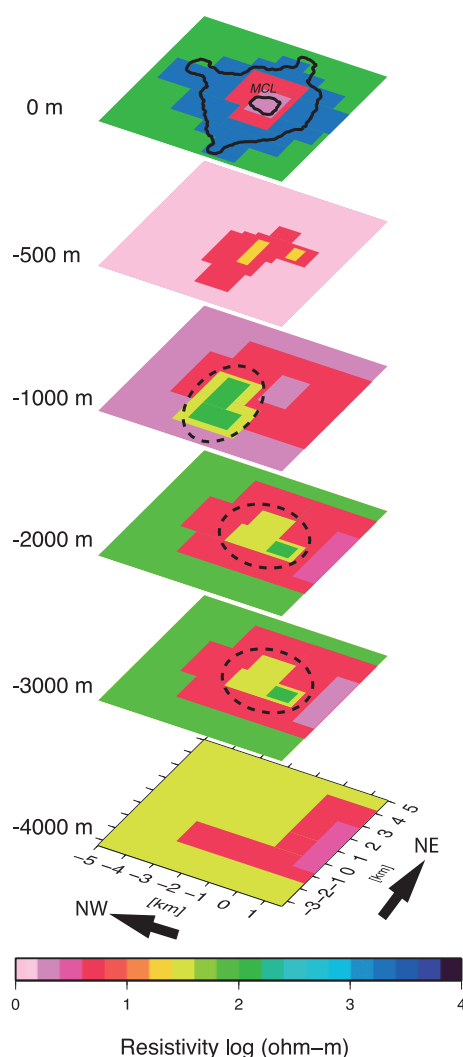


Fig. 3. Horizontal sections of the 3-D resistivity model at various depths. Area highlighted by the broken lines is the proposed hydrothermal reservoir. Outline of Volcano Island and Main Crater Lake (MCL) are shown at 0 m depth.

show a high gravity anomaly.¹⁴⁾ The resistivity value of $\sim 100 \Omega \cdot \text{m}$ can be explained by the presence of hydrothermal fluids in a gas phase. However, it seems that co-existence of hydrothermal fluids in liquid phase is needed for causing a large eruption.¹⁵⁾ The hydrothermal fluids are considered to originate from stagnant and congealing magma below the hydrothermal reservoir as well as from meteoric water (Taal Lake) and sea water (South China Sea).¹⁶⁾ Upon reaching 4–6 km depth, volcanic fluids begin to exsolve from the upwelling magma (one such occurrence being in 2001¹⁷⁾). The fluids subsequently accumulate in the cracks of the perched hydro-

thermal reservoir. The capping and surrounding conductive structure (possibly made up of altered clays) between 0.5 km to 1 km in depth is probably impermeable to ascending fluids and confines the fluids within the hydrothermal reservoir. At the moment, below 4 km depth, the resistivity structure is still ambiguous. Further study including MT observations in and out of Taal Lake is required to clarify the electrical state beneath the hydrothermal reservoir.

Anomalous features of the 1911 eruption

The 1911 eruption was preceded by a rapid increase in seismic activity beginning on 27 January 1911. These were recorded by seismometers of the Manila Observatory over 60 km away, and were accompanied by audible rumbling sounds.^{18),19)} The eruption reached its peak at around 0200H (local time) on 30 January when a big explosion occurred.

Previous authors classified the 30 January 1911 explosion event as a base-surge associated with a phreato-magmatic eruption,^{9),10)} which results from direct contact of magma and water at shallow depth. However, our interpretation is that this was a magmatic-hydrothermal eruption. A magmatic-hydrothermal eruption is a new concept introduced by Browne and Lawless.¹⁵⁾ It can occur when magmatic material is injected into a pre-existing hydrothermal reservoir at depth. In such cases, juvenile magmatic material may or may not be identified.

The following observations on the temperature and contents of the ejecta, as well as the amount of juvenile magmatic material support our assertion. Maso¹⁸⁾ and Worcester¹⁹⁾ wrote that, in the affected villages close to the crater, casualties and structures showed no signs of burns or carbonization (which indicate high temperatures), instead exhibiting effects similar to chemical burns. 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 similar effects. These observations suggest that the acidic fluids contained in the hydrothermal reservoir were ejected and mixed with the mud to form low temperature ejecta. Furthermore, only very small amounts of juvenile magmatic material were found in the 1911 eruption deposits (Bornas 2013 personal communication).

A magmatic-hydrothermal eruption meanwhile differs from an ordinary phreatic eruption in that it is caused by extrusion of hydrothermal fluids (vapor and liquid) from a hydrothermal reservoir, without the need for substantial energy or mass input from

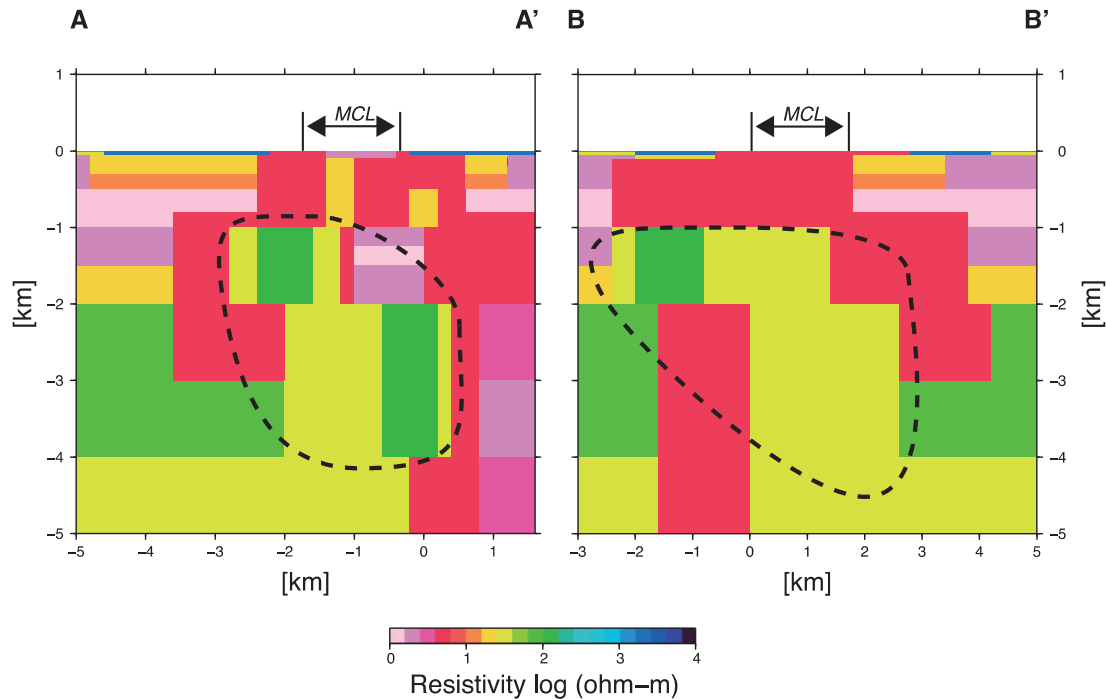


Fig. 4. Vertical section along A-A' and B-B' (see Fig. 1) of 3-D model showing proposed hydrothermal reservoir encircled by broken line.

magma.²⁰⁾ In the case of the 1911 explosion, the injected magma could have vaporized the liquid component of the hydrothermal fluids inside the hydrothermal reservoir. The resulting phase change produced an explosion in the reservoir and breaching of the cap rock. Such magmatic-hydrothermal eruptions could produce larger eruptions compared with purely hydrothermal or phreatic eruptions with similar amounts of magma involved.¹⁵⁾ Thus, the fluids in liquid phase in the reservoir may have played an important role in producing the acid ejecta at the 1911 eruption. Although very little SO_2 gas is observed on the surface at present,¹⁶⁾ this can be understood since this gas stays in the reservoir because it is soluble in water in a liquid phase as H_2SO_4 .¹⁶⁾

Post-eruption subsidence was recorded to be between 2.5 m to 3 m along the shoreline of Volcano Island, which was eye-witnessed as submerging trees.¹⁸⁾ A similar subsidence event was observed in 1749.^{9),10)} While this large subsidence could be attributed to a discharge of magma at a deeper depth, given the physical evidence stated in the preceding paragraph, a breaching of the impermeable layer and destruction of the large hydrothermal reservoir is more likely.

Two eruption cycles related to the hydrothermal reservoir

Historical eruptions of Taal Volcano were earlier divided into four Series,^{9),10)} Main Crater—Flank craters—Main Crater—Flank crater. However, we propose that these four Taal Volcano eruption Series are better interpreted as two eruption cycles, where one eruption cycle consists of both the Main Crater and Flank eruption occurrences in succession (Fig. 2). We hereby offer an explanation for the alternating eruption centers.

The accumulated magma (congealing below the hydrothermal reservoir) although still in a fluid state cannot cause a magmatic eruption anymore after the loss of volatiles into the hydrothermal reservoir and becomes a barrier for the following magma. The stagnant, pooling magma impedes the ascent of more magma, causing the newly ascending magma to also pool below and spread laterally. It is possible that the laterally spreading magma could find a fissure, ultimately finding its way to the surface and leading to a flank eruption. Only when a new magma batch (*e.g.* with a higher temperature) forcibly intrudes into the pooling magma batch can a summit eruption re-occur.

The intervals between Main Crater eruptions (repose period plus the occurrence period of flank eruptions), which can be as long as 100+ years, allow the reservoir to attain a large size. The impermeable layer of clay on top of the hydrothermal reservoir can be breached, and explosive decompression of the reservoir can occur. A breaching of this impermeable layer and destruction of the hydrothermal reservoir can cause a catastrophic eruption from the Main Crater similar to the 1911 event. Similar eruption characteristics suggest a breaching event could have also preceded the 1749 eruption, which was then followed by ejection of fresh magmatic materials.

Conclusion

The large hydrothermal reservoir suggested by the MT study may be significant in controlling the eruptive activity. The long repose interval between the two eruption cycles allows time for the hydrothermal reservoir to re-fill. An explosion of such a huge reservoir could have tremendous destructive potential, as shown by the magmatic-hydrothermal eruption in 1911. Even though the reservoir acts as a buffer to the rising magma, it can contribute much more severe volcanic hazards on this volcano. An injection of magma into the hydrothermal reservoir can cause the liquid component of the hydrothermal fluids inside (in gas and liquid phase) to vaporize and lead to an explosion of the hydrothermal reservoir.

Hydrothermal eruptions in general are difficult to predict, not for a lack of precursors, but because of the difficulty of assigning a specific precursor, *e.g.* ordinary magmatic eruptions can also exhibit similar precursors such as increased occurrence of volcanic tremors.²⁰⁾ Accordingly conventional methods of volcano monitoring such as geodetic measurements and seismology may not be sufficient. It is thus important to monitor the state of the hydrothermal reservoir by every geophysical and geochemical method available. Perhaps electromagnetic methods may be quite useful, since prior to an eruption, drastic changes in the apparent resistivity of the hydrothermal reservoir can signal that the ratio of the gas-liquid phases within has changed.

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Author contributions

P.K.A., Y.O. and T.N. designed research; P.K.A., Y.Y, A.T. and Y.S. performed field surveys; P.K.A. constructed 3D model; all authors contributed writing of the manuscript through detailed discussions.

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