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Very-low-frequency resistivity, self-potential and ground temperature surveys on Taal volcano (Philippines): Implications for future activity

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ABSTRACT

Taal volcano is one of the most dangerous volcanoes in the Philippines. Thirty-three eruptions have occurred through historical time with several exhibiting cataclysmic phases. Most recent eruptions are confined to Volcano Island located within the prehistoric Taal collapse caldera that is now filled by Taal Lake. The last eruptive activity from 1965 to 1977 took place from Mt. Tabaro, about 2 km to the southwest of the Main Crater center. Since this time, episodes of seismic activity, ground deformation, gas release, surface fissuring, fumarole activity and temperature changes are recorded periodically around the main crater, but no major eruption has occurred. This period of quiescence is the third longest period without eruptive activity since 1572. In March 2010, a campaign based on Very-Low-Frequency (VLF) resistivity surveys together with repeated surveys of self-potential, ground temperature and fissure activity was intensified and the results compared to a large-scale Electrical Resistivity Tomography experiment. This work fortunately occurred before, within and after a new seismovolcanic crisis from late April 2010 to March 2011. The joint analysis of these new data, together with results from previous magnetotelluric soundings, allows a better description of the electrical resistivity and crustal structure beneath the Main Crater down to a depth of several kilometers. No indication of growth of the two geothermal areas located on both sides of the northern crater rim was apparent from 2005 to March 2010. These areas appear controlled by active fissures, opened during the 1992 and 1994 crises, that dip downward towards the core of the hydrothermal system located at about 2.5 km depth beneath the crater. Older mineralized fissures at lower elevations to the North of the geothermal areas also dip downward under the crater. Repeated self-potential and ground temperature surveys completed between 2005 and 2015 show new geothermal and hydrothermal activity in the areas of these older mineralized fissures that occurred during the April 2010 to March 2011 seismovolcanic crisis. This dramatically extends the geothermal activity further to the North on the volcano. The occurrence of these newly activated fissures after a long period of quiescence and indications of inflation in mid-2010 under the North rim of the Main Crater suggests that new eruptive activity near the North rim of the crater could occur in the future.

1. Introduction

Taal volcano (14°N, 121°E) is a composite stratovolcano in the Philippines located in the Macolod Corridor on Luzon Island (Galgana et al., 2014) (Fig. 1). Taal's large prehistoric caldera was formed during at least four major eruptions between 500 and 100 ky (Torres et al., 1995) and is now filled by a fresh water lake known as Taal Lake. Taal Lake reaches a depth of 198 m in the southern sector (Ramos, 2002a; Papa et al., 2011). Most recent eruptions are confined to Volcano Island in Taal Lake. Volcano Island consists of overlapping sequences of smaller stratovolcanoes, cinder cones and tuff rings with Taal's currently active crater on Volcano Island now filled by the Main Crater Lake (MCL). Some submerged potentially eruptive features in Taal Lake seem to be more or less active as indicated by intermittent clusters of seismicity together with releases of hot water and gas.

Information on current volcanic activity is used to routinely check against the historical record for indications of repeating patterns of behavior. Since the major eruption in 1572, 33 major eruptions have occurred causing severe damage and casualties. Eruptive behavior ranges from phreatic (i.e. 1878, 1911, 1970), phreatomagmatic (i.e. 1749, 1965, 1966), strombolian (i.e. 1968, 1969) to plinian (i.e. 1754). A number of eruptive episodes are also accompanied by large eruptions

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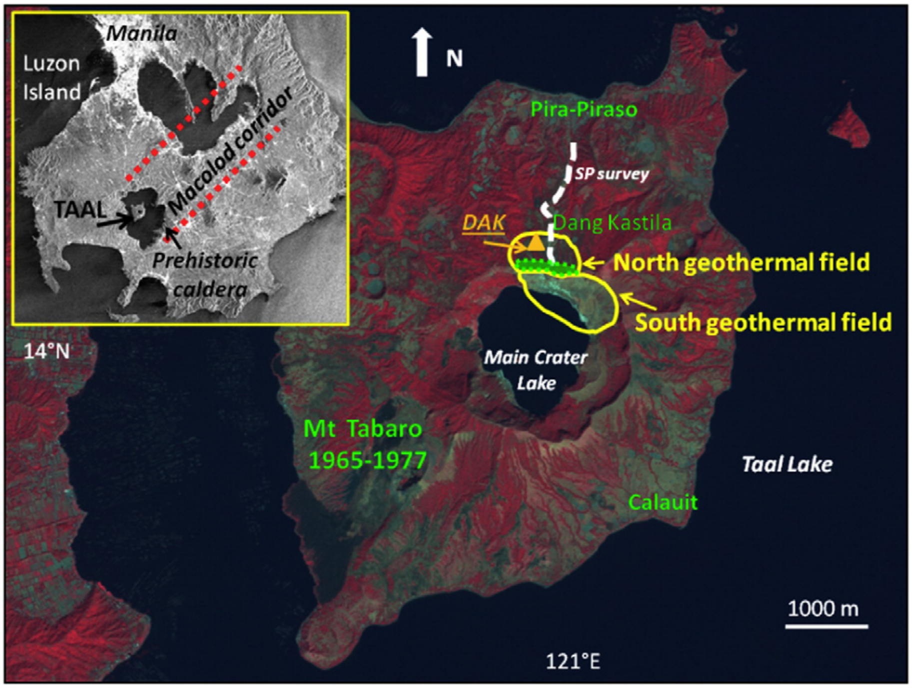

Fig. 1. Inset: tectonic setting of Taal Volcanic Island on Luzon Island in the Philippines. Main Map: Limits of the North and South geothermal fields (yellow lines) recognized before 2010. Dashed green colored area corresponds to the zone reactivated during larger seismic crises. Dashed white line represents the path of the primary self-potential (SP) and ground temperature (GT) surveys conducted between 2005 and 2015.

of ash and base surges (i.e. 1731, 1754, 1911, 1965) (PHIVOLCS, 2010). 46% of the eruptions had an explosivity index ('VEI') of 3 or more and it is noticeable that long periods of rest are followed by major eruptive activity characterized by a VEI up to 4 (Newhall and Self, 1982) (Fig. 2).

In late 2004, the Philippines Institute of Volcanology and Seismology (PHIVOLCS, http://www.phivolcs.dost.gov.ph/) and the international Electromagnetic Studies of Earthquakes and Volcanoes Working Group (EMSEV, http://www.emsev-iugg.org/emsev/) initiated a cooperative effort to understand Taal's volcanic structure and to continuously monitor volcanic activity using electromagnetic techniques together with other geophysical methods. This led to the identification of a huge hydrothermal system beneath the current Main Crater on Volcano Island with its center at about 2.5 km depth (Alanis et al., 2013; Yamaya et al., 2013). This hydrothermal system is expressed at the ground surface by two geothermal fields, one located on the northern flank of the volcano and the second inside the North part of the Main Crater. The geothermal fields are easily identified by active and mineralized fissures that continuously release thermal flux and CO_2 gas (Harada et al., 2005; Zlotnicki et al., 2009a, 2009b). In addition, Electrical Resistivity Tomography made by EMSEV across Volcano Island and on both sides of the northern rim of the crater indicated possible upward ground fluid channeling through the crater rim connecting into both the geothermal fields (Fikos et al., 2012).

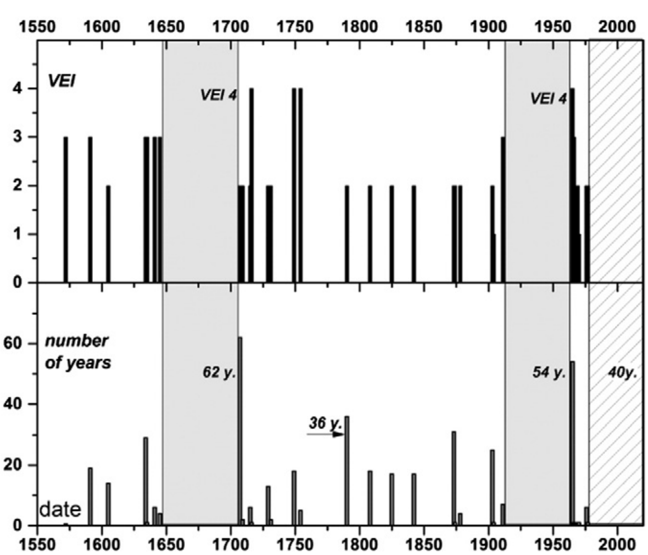

Fig. 2. Distribution of the historical eruptions with time. Top: volcanic explosivity indices of the historical eruptions. Bottom: Duration of rest between consecutive eruptions. Grey and dashed areas correspond to the longest periods of rest.

However, these independent studies did not identify the near-surface structure around the Main Crater or the role of the new and existing active fissures on the active geothermal fields. The present study fills the gap by combining data from surveys performed from 2005 to the present of combined self-potential (SP), ground temperature (GT) surveys and fissure activity that are repeated approximately twice yearly along the same NS line (also called horse trail) from Taal Lake up to the crater rim with data of Very-Low-Frequency (VLF) resistivity acquired in March 2010. In this manner, information on near-surface structure down to depths of about 200 m together with the likely location and geometry of surface and sub-surface fissures can be obtained. Results are then compared with those obtained from an independent large-scale Electrical Resistivity Tomography (ERT) experiment where the integration of magnetotelluric observations extends the knowledge of the volcanic structure down to several kilometers depth (Fikos et al., 2012; Alanis et al., 2013; Yamaya et al., 2013).

2. Learning from seismic and ground deformation after 1977

The last major explosive eruption on Taal ended in 1977. During the 40-year quiescence since 1977, the volcano has exhibited many seismic crises, sometimes accompanied by several phases of inflation and deflation and by the opening of fissures up to several hundred meters long (Julio Sabit, 2010; Lowry et al., 2001; Bartel et al., 2003; Galgana et al., 2014). From April 19, 2010 to March 2011, the volcano entered in a new period of activity initiated by swarms of earthquakes and the activation of an apparent inflation source at about 5 km depth under the