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Stratification at the Earth's largest hyperacidic lake and its consequences

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A B S T R A C T

Volcanic lakes provide windows into the interior of volcanoes as they integrate the heat flux discharged by a magma body and condense volcanic gases. Volcanic lake temperatures and geochemical compositions therefore typically serve as warnings for resumed unrest or prior to eruptions. If acidic and hot, these lakes are usually considered to be too convective to allow any stratification within their waters. Kawah Ijen volcano, featuring the largest hyperacidic lake on Earth (volume of 27 million m^3), is less homogeneous than previously thought. Hourly temperature measurements reveal the development of a stagnant layer of cold waters (<30 °C), overlying warmer and denser water (generally above 30 °C and density ∼1.083 kg/m^3). Examination of 20 yrs of historical records and temporary measurements show a systematic thermal stratification during rainy seasons. The yearly rupture of stratification at the end of the rainy season causes a sudden release of dissolved gases below the cold water layer which appears to generate a lake overturn, i.e. limnic eruption, and a resonance of the lake, i.e. a seiche, highlighting a new hazard for these extreme reservoirs. A minor non-volcanic event, such as a heavy rainfall or an earthquake, may act as a trigger. The density driven overturn requires specific salinity-temperature conditions for the colder and less saline top water layer to sink into the hot saline water. Spectacular degassing occurs when the dissolved gases, progressively stored during the rainy season due to a weakened diffusion of carbon dioxide in the top layer, are suddenly released. These findings challenge the homogenization assumption at acidic lakes and stress the need to develop appropriate monitoring setups.

1. Introduction

Hot lakes located in the crater of active volcanoes generally provide valuable information of the state of a volcano (Hurst et al., 2012), as the thermal energy and mass injected is intercepted by the lake rather than passing directly to the atmosphere (Terada et al., 2011). Among the 474 lakes listed within the new database of volcanic lakes, VOLADA (Rouwet et al., 2014), a substantial proportion belongs to the hot acidic lake class. These exceptional natural manifestations of volcanic activity are generally considered to be extremely dynamic and perfectly mixed systems, due to a wide and powerful permanent thermal plume at the lake bottom (Rouwet et al., 2014). This is thought to prevent the development of heterogeneities and/or stratification of lake waters within the lake volume, as commonly observed in 'Nyos-type' lakes (Rouwet et al., 2014 and references therein). Christenson (1994) specifically ascertained the behavior of Ruapehu volcanic lake during a quiescent period in February 1991. The lake showed little stratification and he concluded that the development of a gas enriched water column was unlikely. Assuming lake volumes are perfectly homogeneous, heat and mass balance approaches based on in-situ measurements can be applied to estimate mass and thermal fluxes emitted from the volcanic vents into the bottom of the lake, as an indication of the state of the underlying volcano (e.g., Pasternack and Varekamp, 1997).

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The acidity and/or difficulty of access to these lakes usually hinder a high frequency of data collection. Even acidic lakes which have been monitored for decades (Ruapehu (New Zealand) Dibble, 1974; Christenson, 1994; Christenson et al., 2010, Yugama (Kusatsu-Shirane, Japan) Ohba et al., 1994, 2008, Poás (Costa Rica) Rowe et al., 1992; Martinez et al., 2000; Rouwet et al., 2016) are generally sampled in the best case on a monthly basis and from the lake surface at the shores. Assumed to be representative of the whole lake, this classic approach has been demonstrated to be helpful for volcano monitoring efforts (e.g., Hurst et al., 1991; Ohba et al., 2008; Rouwet and Tassi, 2011.

Here, we first question the homogeneity assumption for acidic lakes by comparing a unique high-resolution temperature dataset (1-h data measured between May 2010 and July 2012, at depth greater than 2 m) recorded at the largest hyperacidic lake on Earth (Kawah Ijen) with weekly measurements. To better constrain the relevance and the understanding of this dataset, additional parameters such as lake water density and level, chemical composition of the top-17 cm of the lake, meteorological data, thermal infrared images of the lake, satellite measurements and historical records are discussed below. Our results highlight the dramatic heterogeneity of shallow lake waters, particularly during rainy seasons when a stratification develops. The implications and associated hazards are discussed at the end.

2. Background

Kawah Ijen volcano (East Java, Indonesia, Fig. 1a–c) is potentially one of the most dangerous volcanoes in Indonesia. The crater hosts a 27×10^6 m^3 lake (170 m deep Caudron et al., 2015a) which has been consistently hyperacidic (pH < 0.5) and hot ($T > 30\,^{\circ}\mathrm{C}$) for at least 50 yrs (Caudron et al., 2015b). Numerous areas with bubble activity were observed using an echo sounder (Caudron et al., 2016). According to Takano et al. (2004), the lake is chemically homogeneous. However, the first comprehensive measurements revealed the presence of short-lived and local differences in concentrations (Caudron et al., 2015b). Some fluctuations were due to seasonal effects, i.e., the surface waters were diluted during the rainy season while evaporation concentrated the solutes during the dry season (Caudron et al., 2015b).

After a quiescence of 6 yrs, a magmatic intrusion triggered volcanic unrest that started in May 2011 (Caudron et al., 2016). It eventually culminated into multiple heat and fluids discharges into the volcanic lake.

3. Instruments and methods

Several sensors were immersed into the Kawah Ijen volcanic lake. Due to the extreme conditions, the instruments are all installed on the lake shores. An acid-proof buoy was installed in 2011, but sank in less than a year and instruments were never recovered. A temperature sensor (iButton, accuracy of 0.5 °C, resolution of 0.625 °C) has been located since June 2010 close to the western shore (DAM, Fig. 1d), at a depth of ~5 m. At exactly the same location, a Troll 500 device was installed between October 2010 and October 2011 to record the water level and temperature (In-Situ Inc., 0.1 °C of accuracy and 0.1 °C of resolution for temperature recordings and 0.1% of accuracy and 0.005% of resolution for pressure measurements).

The lake level has been weekly monitored for the last decade at the DAM (Fig. 1d) by the CVGHM (Center for Volcanology and Geological Hazard Mitigation) using a leveled wooden stick. The volcano observers also measure lake temperature at the DAM or the Solfatara every week (Fig. 1d) using a thermocouple. Based on historical records, the lake level generally varies by 4 m over a year and the temperature by 15 °C (Caudron et al., 2015b). An

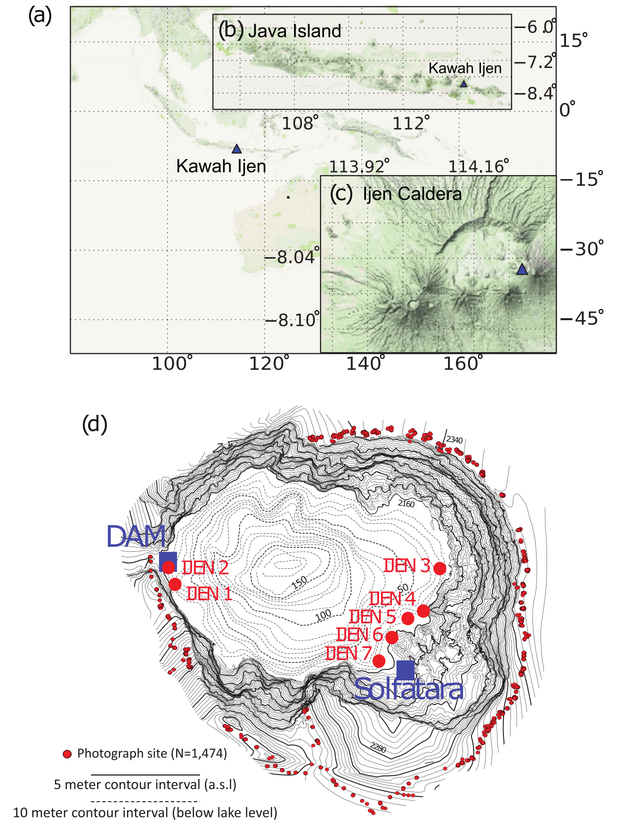

Fig. 1. Kawah Ijen location: (a) Kawah Ijen (blue triangle) location in South-East Asia (b) in Java island (c) in Ijen caldera. (d) Contour map derived from the structure-from-motion 0.2 m resolution Digital Elevation Model of Kawah Ijen (interval between contours is 5 m). Bathymetry is from Caudron et al. (2015b), contoured at 10 m intervals. Blue squares represent the locations for lake temperature measurements (DAM and Solfatara). The meteorological station and the continuous lake temperature acquisition at depth are located at the DAM. Large labeled red dots indicate the geochemical sampling sites. Small red dots are the 1,474 digital photographs used to construct the model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

anemometer (Windosonic) along with a pluviometer (SBS500 Raingauge) were connected to a datalogger on the lake shores at the DAM (Fig. 1d). Data were sampled every hour between October 2010 and July 2011.

In September 2014, Kawah Ijen lake water was sampled with a syringe at five depths in the top-17 cm of the lake (0, 5, 10, 15 and 17 cm) during two consecutive days under similarly dry climatic conditions, and analyzed for their chemical composition through standard procedures. All waters are passed through 0.45 micron filters before storage in polyethylene bottles. The anion concentrations in the water samples were measured by ion chromatography (accuracy ±5%). Cation (Na, K, Ca, Mg) concentrations were determined by Atomic Absorption Spectrometers (AAS, Thermo S Series). The analytical errors were below 5%. The pH values were measured by an alkaline titration with a 0.1 M NaOH solution (Capaccioni et al., 2016).

4. Results

Both lake temperature (small dots, Fig. 2b) and level (Fig. 2c) recordings followed the same trend: they rose in mid-December 2010, two months after the first significant rainfalls of the season (Fig. 2a). The lake level reached a maximum in early May 2011, then decreased until December 2011. The temperatures measured from the surface (blue squares and triangles, Fig. 2b) and at greater depths (gray dots, Fig. 2b) were only similar between