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Soil CO_2 flux in hydrothermal areas of the Tatun Volcano Group, Northern Taiwan

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ABSTRACT

We measured soil CO_2 flux in the representative hydrothermal areas of the Tatun Volcano Group (TVG), to better understand the volcano's dynamic nature, and to estimate its soil CO_2 degassing output. Results show that the average soil CO_2 fluxes obtained at Da-You-Keng (DYK), Geng-Tze-Ping (GTP), She-Haung-Ping (SHP), and Tatun Natural Park (TNP) were 128 g m^{-2} d^{-1}, 518 g m^{-2} d^{-1}, 420 g m^{-2} d^{-1}, and 25 g m^{-2} d^{-1}, respectively. The range is comparable to other active volcanic/hydrothermal areas in the world. Along with Liu-Huang-Ku (LHK), where the soil CO_2 flux is known, the total soil CO_2 output from measured areas is evaluated at 82 t d^{-1}. Furthermore, a first total soil CO_2 output from the whole hydrothermal areas of the TVG is roughly estimated at 113 t d^{-1}, which includes 15 t d^{-1} mantle contribution. Considering the mantle-derived CO_2 flux and H_2O/CO_2 ratio of fumarolic gas, thermal energy associated with the diffuse degassing at the TVG hydrothermal area is estimated at 8.2 MW. Carbon ($\delta^{13}C$) and helium ($^3He/^4He$) isotopic ratios of soil samples of the studied areas ranged from −4.4 to −6.7‰, and 2.45 to 6.98 R_A, respectively. The extent of air involvement in the soil-degassing system, as constrained by the helium and carbon isotopic compositions, provides essential information for depicting regional degassing features of the hydrothermal areas.

1. Introduction

To mitigate volcanic hazards, scientists monitor volcanic activity using various proxies, such as seismic events, ground deformation, remote sensing, chemical compositions of hot-spring water, volcanic gases, and so on. For volcanic gas studies, scientists usually sample fumaroles, and/or hot-spring bubbling gas, directly. However, direct sampling poses dangers when getting close to active fumarolic sites. Also, for monitoring volcanic activity, direct sampling requires instrumental analysis in the lab, which is unfeasible to reflect real-time variations on site. A soil-gas survey, on the other hand, only needs simple apparatus, and most of the equipment is designed to be highly portable and less expensive. Soil-gas-flux monitoring stations (such as on Mt. Etna, Stromboli, Solfatara, Vulcano and El Hierro) are capable of showing real-time flux variations, even though they are affected by more atmospheric contributions than hot-spring gases (Granieri et al., 2003; Brusca et al., 2004; Inguaggiato et al., 2011, 2012; Pérez et al., 2012; Gregorio et al., 2014).

Soil-gas surveys have been applied for various purposes in decades, such as oil and mineral exploration, hydrothermal investigations, location of active faults, precursory studies of earthquakes, and so on (e.g. Lombardi and Reimer, 1990; Baubron et al., 1991, 2002; Klusman, 1993; King et al., 1996; Chiodini et al., 1998, 2007; Chyi et al., 2005; Fu et al., 2005; Walia et al., 2005, 2009; Yang et al., 2005b, 2006b; Hanson et al., 2014; Harvey and Harvey, 2015; Jolie et al., 2015).

Among soil-gas species, carbon dioxide (CO_2) is the most common one applicable to monitor volcanic activity. CO_2 is one of the most abundant magmatic gases, and due to its low solubility, it is also one of the earliest gases exsolving from ascending magma (e.g., Gerlach and Casadevall 1986; Giggenbach, 1996). Therefore, surficial CO_2 flux variations can provide information at the early phase of magma uprising (e.g., Badalamenti et al., 2004). Detection of CO_2 emission is not necessarily limited to craters and fumaroles. By measuring CO_2 from the surrounding soil at sensitive sites, scientists can still observe CO_2 variations to avoid direct sampling on such dangerous areas. In recent decades, soil CO_2 flux has been regarded as one of the most useful indicators of volcanic activity (Allard et al., 1991; Giammanco et al., 1998; Hernández et al., 1998; Notsu et al., 2006; Inguaggiato et al., 2012; Tassi et al., 2013; Lucic et al., 2014). Furthermore, fractures or fissures in the volcano area provide

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good degassing channels for volcanic CO_2. Thus CO_2 flux-mapping is a useful method to investigate volcanic structures (Finlayson, 1992; Barberi and Carapezza, 1994). Consequently, measuring soil CO_2 flux during non-eruptive periods by deploying an on-site regional survey has become an essential proxy to study and to monitor volcanic activity.

The Tatun Volcano Group (TVG) is a volcanic area in Northern Taiwan, only few kilometers from two nuclear power plants, and 15 km from the metropolitan Taipei City, where more than 7 million people live. Understanding the behavior of the TVG, and mitigating the damage from possible eruptions, are tasks for geoscientists. Previous gas geochemistry studies in the Liu-Huang-Ku (LHK), one of the hydrothermal areas in the TVG, indicated that soil CO_2 flux there is high for a single edifice, and comparable to many active hydrothermal areas worldwide (Lan et al., 2007). Soil CO_2 and ^{222}Rn flux surveys, as well as a continuous soil-gas monitoring study, based on the station in the Shiao-You-Keng (SYK) hydrothermal area, also showed volcanic unrest of the TVG (Yang et al., 2011).

In this study, we investigate soil CO_2 flux in all measurable hydrothermal areas in the TVG, to estimate the soil CO_2 degassing budget. This is a crucial contribution for evaluating deep global carbon emissions from volcanic/hydrothermal areas. Helium and carbon isotopes of soil gas are analyzed to decipher the gas sources, and to depict the regional degassing features.

2. Geological background

Tectonically, Taiwan is located at the junction of the Philippine Sea Plate and the Eurasian Plate, and the TVG is situated at the westernmost point of the extensional Okinawa Trough, related to the Ryukyu arc-trench system (Fig. 1a). Volcanoes in the TVG are composed mostly of andesitic lava and pyroclastic flows, and more than 20 Holocene volcanoes are distributed in an area of 250 km^2 (Chen and Wu, 1971). The basement of the TVG is composed of successions of Miocene sedimentary strata intercalated with limestone lenses. The entire TVG is cut by the Shan-Chiao Fault, which is a major normal active fault system, with a NE–SW strike dipping to the southeast. Most active hydrothermal areas are distributed along the Shan-Chiao Fault, on the hanging wall (Fig. 1b). The Kan-Chiao Fault is regarded as the eastern boundary of the TVG, which is now an inactive thrust fault, having a NE–SW strike with the fault plane dipping southeast.

A few earlier hypotheses proposed that the volcanic activity in Northern Taiwan volcanic zone is related to island arc magmatism, caused by collision between the two aforementioned plates (Teng et al., 1992; Teng, 1996). More recently, Wang et al. (1999, 2002) suggested that the volcanic activity in the TVG is the result of post-collisional collapse. Following their model, the volcanic activity in Northern Taiwan could gradually become more prevalent as a consequence of further crustal extension.

The TVG is considered as an active volcano. The radiocarbon dating results of eruptions no older than 6000 years (Belousov et al., 2010) and a 17,000-year-old volcanic ash layer in the Taipei Basin (Chen et al., 2010) along with other geochemical and geophysical observations (Yang et al., 1999; Lin et al., 2005a; Konstantinou et al., 2007; Murase et al., 2014; Pu et al., 2014) are all solid evidences. Based on the noble gas geochemistry, the fumarolic and bubbling gases of hot springs contribute more than 60% of mantle helium. Together with the spatial variation of helium isotopes, a potential magma chamber existing beneath the Da-You-Keng (DYK) hydrothermal area was implied (Yang et al., 1999; Yang, 2000). This implication is supported by a progressive increasing trend of HCl concentration and SO_2/H_2S in the long-term volcanic gas compositional variation since August 2004, and the rising temperature of fumaroles in the DYK hydrothermal area (Lee et al., 2008).

In order to understand this volcano group, various geochemical proxies have been deployed, including: soil CO_2 flux surveys and

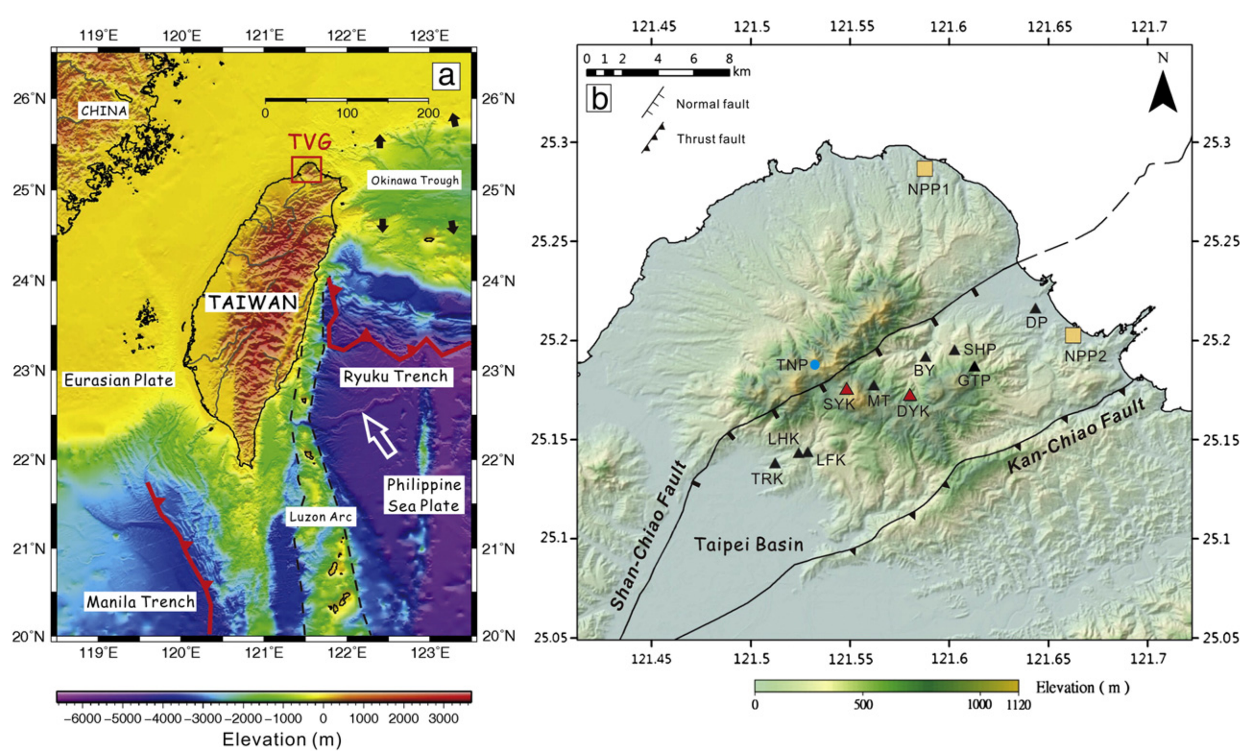

Fig. 1. (a) Tectonic setting of the Tatun Volcano Group (TVG); and (b) the studied areas. Red triangles are type-1 hydrothermal areas (DYK, Da-You-Keng; SYK, Shiao-You-Keng), black triangles are type-2 hydrothermal areas (DP, Da-Pu; GTP, Geng-Tze-Ping; SHP, She-Haung-Ping; BY, Ba-Yan; MT, Ma-Tsao; LFK, Long-Fong-Ku; LHK, Liu-Huang-Ku; TRK, Ti-Re-Ku), and blue circle is the background reference area (Tatun Natural Park, TNP). The black lines show the faults in the region of TVG: one active (Shan-Chiao Fault); and the other inactive (Kan-Chiao Fault). The yellow squares represent two nuclear power plants (NPP).