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Review

Volatile flux from subduction zone volcanoes: Insights from a detailed evaluation of the fluxes from volcanoes in Japan

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ABSTRACT

Global volatile fluxes from subaerial volcanoes at subduction zones were estimated based on a compilation of fluxes from various sources, including persistent degassing, hot and cold springs, soil degassing, and eruptions. Because worldwide comprehensive datasets are not available, especially for diffuse volatile discharges, volatile fluxes from Japan arcs were estimated based on detailed datasets, and the regional fluxes were extrapolated to the global flux with consideration of the regional characteristics of volcanic volatile compositions, which were estimated based on volcanic gas compositions of persistent degassing. The estimated global fluxes indicate that persistent degassing is the major source of volatiles, especially for S with a contribution of 80%. Diffuse discharges and persistent degassing are similarly important sources of H_2O, CO_2, and Cl, but the contribution of explosive eruptions is less than 15% for all the volatiles. The estimates of diffuse degassing fluxes include large errors due to limited data. However, the potential impact of these sources on the global flux indicates the importance of further studies to quantify these fluxes. The volatile budget of subduction zone volcanism was evaluated by comparing the estimated volatile fluxes, the volatile contents in the crust, and the primitive magma volatile contents. The contribution of volatiles remaining in the crust are not significant; however, consideration of lower crust foundering significantly alters the volatile budget estimate because the primitive magma supply rate should be significantly increased to account for the lower crust foundering.

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1. Introduction

The emission of volatiles from volcanoes is the major process of Earth degassing, and the mass balance of volatiles between the mantle and the Earth's surface controls the stability of the present-day atmosphere and the ocean. Subduction zones are major sources of magma and volatiles, second only to mid-ocean ridges (Crisp, 1984; Torgersen, 1989). In addition to being important sources of volatiles, subduction zones are also sinks of volatile components, and the recycling of volatiles that occur at subduction zones controls the global volatile budget (Ito et al., 1983; Bebout, 1996). The volatile flux from volcanoes is a key factor in quantifying the volatile budget and has been estimated using various methods (Sano and Williams, 1996; Marty and Tolstikhin, 1998; Hilton et al., 2002; Wallace, 2005).

Most previous estimates of the volatile flux from subduction zones, obtained using various methods, are essentially based on either measured SO_2 fluxes (e.g., Stoiber et al., 1987) or estimated magma production rates (e.g., Crisp, 1984). Emissions of SO_2 from subaerial volcanoes are quantified by ultraviolet remote sensing of volcanic plumes discharged by either non-eruptive degassing or eruptions, and the global SO_2 flux has been estimated by compiling such data (Stoiber et al., 1987; Andres and Kasgnoc, 1998). Fluxes of other volatile components are commonly estimated by multiplying the SO_2 flux by the high-temperature fumarolic gas composition (Hilton et al., 2002; Fischer, 2008). Many previous studies have considered only volatile fluxes of volcanic gas emissions. The volatile fluxes of eruptions, diffuse emissions, and the volatiles remaining in erupted or intruded magmas have been poorly evaluated in the volatile budget, although some studies have discussed the possible importance of these sources (e.g., Seward and Kerrick, 1996; Taran, 2009).

Volatile fluxes are proportional to the magma flux, and volatile fluxes from subduction zones are estimated by comparing with the ^3He flux from mid-ocean ridges (Craig et al., 1975; Torgersen, 1989) or with the volatile contents of primitive magmas (Ito et al., 1983; Wallace, 2005). The fluxes of other components are estimated by multiplying with the composition ratios such as $CO_2/^3He$ or $N_2/^3He$, in the volcanic gases (Sano and Williams, 1996; Sano et al., 2001). The volatile contents of primitive magmas are estimated based on the volatile contents of melt inclusions (Wallace, 2005; Sadofsky et al., 2008; Ruscitto et al., 2012). Volatile fluxes estimated by this method represent input fluxes to the crust, but these are not necessarily the same as the output fluxes from volcanoes, such as those of volcanic gases and diffuse emissions. Some volatiles may remain in intruded magmas, and their inventory should be considered in the volatile budget of the crust. There is also a large uncertainty in the primitive magma supply rate to subduction zones because a large amount of mafic lower crust must be returned to the mantle (called lower crust delamination or foundering) in order to produce andesitic crust from primitive basaltic magmas (Kelemen et al., 2003; Rudnick and Gao, 2003). Because the mafic lower crust may not be volatile-free, the lower crust foundering also causes volatile recycling to the mantle, and these effects also need to be evaluated in order to estimate the volatile budget of subduction zones.

The goal of this review is to outline the global volatile budget of subduction zone crust based on estimates of the volatile flux from subaerial volcanoes and the volatile inventory of the crust. We will focus the discussion on the major volatile components, H_2O, CO_2, S and Cl. In order to summarize the volcanic volatile flux, flux data were compiled for not only persistent volcanic gas emissions but also for emissions by eruptions and other diffuse emissions, such as those from hot springs, river waters (cold springs), and soil degassing. Because worldwide systematic flux data are not available for diffuse degassing, regional fluxes were estimated based on detailed data compilations on Japanese volcanoes. These regional fluxes are then extrapolated to the global flux considering the relative contribution of the Japanese volcanoes to the global flux by the persistent degassing. The volatile flux from eruptions is discussed on only a global scale because regional estimates are difficult due to the limited number of the measured eruptions. The estimated volatile fluxes are compared with the magma production rate and the volatile contents in primitive magma melt inclusions and in intruded magmas in order to evaluate the volatile budget of the crust.

2. Global flux estimate method

A simple method to estimate a regional or global flux of volcanic volatiles is a summation of an exhaustive set of flux data covering fluxes from most emission sources. In order to estimate the global SO_2 flux by persistent degassing, Stoiber et al. (1987) and Andres and Kasgnoc (1998) tried to obtain the exhaustive flux data set not only taken from the literature but also by sending inquiries to many researchers. The exhaustive flux data set, however, is difficult to obtain, in particular for the remote areas and also for diffuse emissions from numerous sources, and we need a method to estimate global fluxes based on a limited number of the data.

Mörner and Ethiope (2002) estimated that contribution of the soil degassing to the global CO_2 degassing is 0.1–0.5 of the plume degassing. This estimate, however, is based on a simple comparison of the subtotals of limited number of the flux data (~20) of each type of emission. Pérez et al. (2011) estimated the global CO_2 flux from volcanic lakes based on a simple extrapolation of the compiled flux data with the coverage proportion of the measured and existing volcano numbers. Burton et al. (2013) applied this method to estimate the global CO_2 flux by persistent and soil degassing. They calculated the average fluxes by each emission type based on flux data from about 30 volcanoes, and extrapolated them by the number of persistently degassing volcanoes (150) or of soil degassing volcanoes (550). This method, however, will cause a significant overestimate, because flux measurements are likely conducted at active systems rather than at inactive low flux systems.

Regional fluxes by various diffuse emissions were estimated based on intensive flux surveys of relatively small areas and the impacts of the diffuse emissions on the global flux were evaluated based on their extrapolation. Seward and Kerrick (1996) compiled the CO_2 flux by hydrothermal activity along the 150-km-long Taupo Volcanic Zone, New Zealand and evaluated the global impact of the hydrothermal CO_2 emission by extrapolating the regional flux to the global flux based on the length of subduction zone. James et al. (1999) measured the magmatic CO_2 flux from cold springs at 75 km segment of the Oregon Cascades, USA and estimated the global CO_2 flux by the extrapolation based on the subduction zone length. The simple extrapolation by the subduction length, however, may introduce significant errors, as activity of subduction zones is not uniform. For an example, the Taupo Volcanic Zone exhibits anomalously high heat flux compared with other subduction zones (Hochstein, 1995) and the simple extrapolation of its heat and volatile fluxes will cause a significant overestimate. Furthermore, composition of magmatic volatiles can be variable at different subduction zones depending on different contribution of source materials (Elkins et al., 2006; Ruscitto et al., 2012) and volatile composition variation should be also taken into account for the extrapolation.

In this study, the global fluxes of diffuse emissions are estimated by extrapolating the regional flux with factors obtained as the ratios of the regional flux and the global flux of the persistent degassing. Both the regional and global fluxes by the persistent degassing are better constrained than fluxes of diffuse emissions because of a larger data set, as will be discussed later. The regional to global flux ratios are obtained for each volatile component, H_2O, CO_2, S and Cl, and applied for the extrapolation in order to account for the volatile composition variation at different subduction zones with an assumption that the composition characteristics at different areas are caused by different contribution of source materials and should be appeared at any type of volatile emissions, i.e., the persistent degassing, eruptions or the