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GLOBAL EMISSIONS OF HELIUM-3 BY SUBAERIAL VOLCANISM

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Abstract. The emission rate of helium-3 by subaerial volcanism is re-evaluated by coupling $^3\text{He}/\text{CO}_2$ ratios in volcanic gases with new estimate of the flux of carbon dioxide from both arc and non-arc volcanoes. Steady volcanic plume emissions are computed to supply 240-310 mole $^3\text{He}/\text{yr}$, most of which is due to non-arc volcanoes. Major eruptions represent minor additions on average, whereas diffuse ^3He emanations through volcanic piles may be important sources. Although not including this contribution, the above figure is equivalent to 20-40% of the ^3He flux from mid-ocean ridges and, thus, suggests that primordial ^3He degassing from subaerial volcanic regions may be larger than expected.

Introduction

Primordial helium-3 is still emanating from the Earth's interior, principally in active volcano-tectonic regions, and is the source of high $^3\text{He}/^4\text{He}$ ratios in modern volcanic rocks and fluids, compared to other terrestrial material (e.g. Lupton, 1983; Poreda and Craig, 1989). Quantifying the global volcanic flux of this isotope is thus central to the evaluation of present-day mantle degassing.

As estimated by Craig et al. (1975), the flux of primordial ^3He into the ocean, that principally results from igneous activity at mid-ocean ridges (MOR), is about $1,000 \pm 200$ mole $^3\text{He}/\text{yr}$. Revised estimates (e.g. 900 ± 250 mole $^3\text{He}/\text{yr}$; Torgersen, 1989) do not differ substantially from this original figure.

In contrast, the amount of ^3He directly injected into the atmosphere by volcanoes is poorly constrained. On basis of respective magma production rates, it was estimated as <10% (O'Nions and Oxburgh, 1983) to 25% (Torgersen, 1989) of the MOR ^3He flux. A much higher proportion is implied by the Sano (1986)'s figure of $\approx 1,600$ mole $^3\text{He}/\text{yr}$ from all volcanic regions, computed by rating ^3He emissions to their source area. An alternative approach consists in scaling the abundance of ^3He in volcanic gases to that of a species whose the subaerial volcanic output is reasonably well assessed. From volcanic SO_2 fluxes, Allard and Pardyanto (1981) and Marty et al. (1989) thus estimated the ^3He output from volcanic arcs as 10% and 0.3-13% of the MOR flux, respectively. Hence, the figures obtained by these different methods are quite contrasted.

Herein I attempt a new evaluation of the global release of helium-3 from subaerial volcanism, by coupling volcanic $^3\text{He}/\text{CO}_2$ ratios with new estimate of the volcanic flux of carbon dioxide from both arc and non-arc regions (6.8×10^{11} and 8.2×10^{11} mole/yr, respectively; P. Allard and H. Sigurdsson, in preparation). The latter values were derived from SO_2 fluxes and CO_2/SO_2 ratios at 23 representative volcanoes. Their sum is

consistent with a recent global estimate of 1.8×10^{12} mole/yr by Gerlach (1991), based on similar data for 7 volcanoes.

Computation procedure

Several limitations were considered. First, subaerial volcanism occurring in various plate tectonic setting, a simple distinction between arc (subduction-related) and non-arc volcanism has been used: the former includes $\approx 90\%$ of all actively degassing volcanoes, while the latter comprises a few most active sites of hot spot/rift basaltic magmatism (in Hawaii, Iceland, Reunion, Galapagos, and Afar) and continental alkaline magmatism (in East Africa, Sicily, and Antarctica). Second, the temporal variations of volcanic degassing must be smoothed by considering time-averaged ($\approx$ steady) activities, the impact of large eruptions being assessed separately. Last, the data base for ^3He and the species to which it is referred must be representative enough.

Referring to CO_2 , rather than SO_2 or other gases (e.g. HCl , ^{210}Po) whose global volcanic fluxes were estimated as well, was preferred for several reasons: 1) Analyses of volcanic $^3\text{He}/\text{CO}_2$ pairs are more numerous; 2) He and CO_2 have close solubility behaviour in magmas and $^3\text{He}/\text{CO}_2$ is little fractionated during magma degassing (e.g. Marty and Jambon, 1987). The other gases have more complex solubility patterns and, particularly, $^3\text{He}/^{210}\text{Po}$ is exposed to early loss of poorly soluble He , while ^{210}Po is continuously generated by radioactive decay of ^{222}Rn in the magma; 3) He and CO_2 remain stable species during gas transport and cooling, whereas SO_2 and HCl are more reactive and ^{210}Po condenses at $T \leq 350^\circ\text{C}$ (Le Guern et al., 1982); 4) Extensive soil emanations of magma-derived CO_2 and He , which are devoid of any SO_2 , HCl or ^{210}Po (for the above reasons), occur from active volcanoes (Allard et al., 1991). Accordingly, ^3He flux estimates based on the latter species will be necessarily conservative; and, 5) the uncertainty on global volcanic flux estimates for CO_2 (factor 2-3) is of the same order as that for other species (e.g. HCl , ^{210}Po).

In the following, I first compute the flux of ^3He from steady volcanism, by combining the plume CO_2 output from 17 (9 arc and 8 non-arc) volcanoes, most in persistent degassing, with the $^3\text{He}/\text{CO}_2$ ratio (corrected for air dilution) of corresponding gases (Table 1). Then, I assess the potential ^3He contribution of diffuse flank degassing and major eruptive degassing, respectively, using $^3\text{He}/\text{CO}_2$ and CO_2 flux data for single volcanoes.

Steady crater plume emissions

Arc volcanoes, although much more numerous, were estimated to supply $\leq 45\%$ of global crater plume emissions of carbon dioxide (P. Allard and H. Sigurdsson, in preparation). Data in the literature and in Table 1 show that their gases usually have $^3\text{He}/\text{CO}_2$ ratios within the range $(0.12 \text{ to } 2.5) \times 10^{-10}$ (Marty and Jambon, 1987; Allard, 1988; Marty et al., 1989; this paper),

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the mean being $\approx 10^{-10}$ compared to 5.0×10^{-10} for average MOR fluids (Marty and Jambon, 1987). Combining the mean arc ratio with the total arc CO_2 output thus yields a total flux of about 70 mole $^3\text{He}/\text{yr}$ from volcanic arcs. Such a flux can be accounted for by a sixty odd volcanoes emitting ^3He at the mean rate of 1.1 mole/yr inferred from data in Table 1.

Non-arc volcanoes provide 55% of steady plume emissions of carbon dioxide. $^3\text{He}/\text{CO}_2$ data are available for only three of them: Kilauea, Etna and Piton de la Fournaise, which are computed to release about 10, 60 and 1.0 mole $^3\text{He}/\text{yr}$, respectively. Etna and Kilauea alone would thus contribute as much helium-3 as arc volcanism. The contribution of other volcanoes in this category can be estimated by assuming realistic $^3\text{He}/\text{CO}_2$ ratios. Nyiragongo and Nyamuragira, two alkaline volcanoes of the East African Rift which are major CO_2 producers, are taken to have $^3\text{He}/\text{CO}_2$ within the range $(2.0\text{--}3.4) \times 10^{-10}$, as defined by the values for nearby Oldoinyo Lengai carbonatitic volcano (Javoy et al., 1989) and alkali basaltic Etna. Both would then release 96–163 mole $^3\text{He}/\text{yr}$, dominating the other contributions. Assuming a $^3\text{He}/\text{CO}_2$ ratio in the same range for trachyphonolitic magmatism at Erebus and a MOR-like ratio for tholeiitic rift magmatism at Erta Ale, these two volcanoes are much weaker emitters. As a whole, non-arc volcanoes are estimated to supply between about 170 and 240 mole $^3\text{He}/\text{yr}$.

A global volcanic plume output of about 240–310 mole $^3\text{He}/\text{yr}$ is then inferred, $\geq 70\%$ of which coming from non-arc volcanoes. Taking account of propagating errors in individual fluxes computed from measured parameters ($\pm 35\text{--}40\%$ precision; Table 1) and of assumptions in some estimates (e.g. Nyiragongo, Erebus), this figure is probably not accurate to better than a factor of 3.

Diffuse flank emissions

Measurable amounts of magma-derived CO_2 and He, with $^3\text{He}/^4\text{He}$ and $^3\text{He}/\text{CO}_2$ ratios similar to those of crater emissions, diffusively escape through the flanks of active volcanoes (e.g. Baubron et al., 1991a and 1991b; Allard et al., 1991). At Etna, this degassing supplies nearly as much CO_2 as the crater emissions, while at Vulcano, a fuming volcano, it provides some 30% of the total CO_2 discharge. Table 1 shows that it would also involve an important contribution of ^3He , quite proportional to that of CO_2 ; total ^3He release at Etna may thus be about twice the figure inferred from crater emissions. Available data suggest that diffuse volcanic degassing is widespread (e.g. Baubron et al., 1991b), being even dominant at dormant volcanoes. Accordingly, any global flux estimate for ^3He derived from only crater plume emissions should be conservative, possibly by a factor of 2. Such an underestimation applies to the global figure computed above.

Major eruptive emissions

Intermittently, very large eruptions may enhance the volcanic flux of ^3He and the order of magnitude of their contribution may be tentatively assessed on basis of $^3\text{He}/\text{CO}_2$ data.

Two examples are the major eruptions of Laki (1783, Iceland) and Tambora (1815, Indonesia). From the amount of tholeiitic magma erupted by Laki (12.5 km^3) and a measured original CO_2 content of 0.85 wt % (Oskarsson et al., 1984), the maximum CO_2 yield is 7×10^{12} mole. Taking a minimal $^3\text{He}/\text{CO}_2$ ratio of 2×10^{-10} for Laki eruptive gases, as suggested by ^3He and CO_2 data for nearby volcanic-hydrothermal fluids (Polak et

al., 1974; Björnsson and Kristmannsdóttir, 1984), the eruption might have released 1.4×10^3 mole ^3He . This is comparable to the MOR flux and about 5 times the subaerial steady flux. A same computation can be done for Tambora eruption, whose CO_2 yield may have reached 4.5×10^{12} mole (Allard and Sigurdsson, in prep.). Using the He/CO_2 ratio (7×10^{-6}) of present-day (290°C) crater fumaroles (P. Allard, unpub. data, 1979) and a $^3\text{He}/^4\text{He}$ ratio identical to that for nearby Sangang Api volcano (9×10^{-6} ; Hilton and Craig, 1989), would result in a total output of 280 mole ^3He .

These crude estimations thus show that Laki- or Tambora-size eruptive events may lead to temporary doubling or more of the annual volcanic output of ^3He . When averaged over their period of recurrence (one century or so), however, their contribution equals the addition of only about one Kilauea-type source to the steady flux. Hence, steady emissions dominate the subaerial volcanic flux of ^3He , at least as regards modern volcanism.

Conclusions

The global release of ^3He by steady volcanic plume emissions is computed to be in the range 240–310 mole/yr, with a factor 3 uncertainty. This figure is comparable to the Torgersen (1989)'s estimate, but differs from it (and other estimates) in that non-arc volcanoes, especially alkaline intra-plate ones, are shown to be the main contributors. Arc volcanoes, though more numerous, supply only about 70 mole $^3\text{He}/\text{yr}$, a result which reflects both their lower CO_2 output and lower $^3\text{He}/\text{CO}_2$ ratio and which is consistent with previous estimates derived directly from SO_2 fluxes (Allard and Pardyanto, 1981; Marty et al., 1989).

At the rate inferred here, steady subaerial volcanism would produce as much ^3He as 20–40% of the mid-ocean ridge system (Craig et al., 1975), thus ranging from a significant to an important source of mantle helium. Adding persistent ^3He emanations through volcanic piles should strengthen this conclusion. Total release of primordial helium-3 by volcanism, $(1.0 \text{ to } 1.5) \times 10^3$ mole $^3\text{He}/\text{yr}$, greatly dominates the other sources (Torgersen, 1989). Further improvement of the present estimate requires more systematic measurements of volcanic CO_2 fluxes and $^3\text{He}/\text{CO}_2$ ratios, especially at non-arc volcanoes.

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