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Equilibrium versus non-equilibrium magmatic degassing of noble gases from mid-ocean ridges: inferences on magma dynamics and upper mantle composition

A. Paonita and M. Martelli

Istituto Nazionale di Geofisica e Vulcanologia – Sezione di Palermo, ITALY

In magmatic systems having CO_2 as main volatile, the dynamics of magma ascent and decompression can be faster than that of CO_2 diffusion into bubbles. In this case, the diffusivity ratios between CO_2 and noble gases, rather than solubility ratios, are the main control of the proportions of CO_2 and noble gases in the exsolving gas phase. We have developed a model of bubble growth in silicate melts that calculates the extent of both CO_2 supersaturation and kinetic fractionation among noble gases in vesicles in relation to the decompressive rate of basaltic melts. By including the state-of art calculations of solubilities and diffusivities of the involved volatiles, the model predicts that magma degassing at low pressure fractionates both He/Ar and He/CO_2 ratios by a similar extent, due to comparable Ar and CO_2 diffusivity. In contrast, the slower CO_2 diffusion at high pressure causes early kinetic effects on Ar/CO_2 ratio and dramatically changes the degassing paths.

When applied to the global He-Ar-CO_2 dataset of fluid inclusions in mid-ocean-ridge glasses, the model displays that non-equilibrium fractionations among He, Ar and CO_2, driven by their different diffusivities in silicate melts, are common in most of the natural conditions of magma decompression and their signature strongly depends on pressure of degassing. The different geochemical signatures among suites of data coming from different ridge segments mainly depend on the depth of the magma chamber where the melt was stored. Moreover, variations inside a single suite emerge due to the interplay between variable ascent speed of magma and cooling rate of the emplaced

lava.

As a result, two data groups coming from the Pito Seamount suite (Easter Microplate East ridge), showing different degree of CO_2 supersaturation and He/Ar fractionation, provide ascent rates which differ by ten folds or even more. The large variations in both the He/CO_2 and Ar/CO_2 ratios at almost constant He/Ar, displayed in products coming from the Mid-Atlantic Ridge 24–30˚N segment and the Rodriguez Triple Junction, require magma storage and degassing processes occurring at high-pressure conditions. In contrast, the simultaneous increase in both He/CO_2 and He/Ar of the East Pacific Rise and South-East Indian Ridge data sets suggests the dominance of low-pressure fractionation, implying that the shallow magma chambers are at a lower depth than those of the Mid-Atlantic Ridge 24–30˚N and Rodriguez Triple Junction. Our conclusions support the presence of a relationship between spreading rate and depth of high-temperature zones below ridges, and are consistent with the depth of magma chambers as suggested from seismic studies. Finally, the non-equilibrium degassing model provides striking constraints on the compositions of noble gases and carbon in mantle-derived magmas. Our results dispense in fact with the supposed need for He-Ar-CO_2 heterogeneities in the upper mantle, because the degassing of a single, popping-rock-like primary magma is able to explain all the available data.