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Time scales of igneous differentiation obtained from diffusion modeling of compositional zoning in olivine

F. COSTA AND S. CHAKRABORTY

Institut für Geologie, Mineralogie & Geophysik, Ruhr-Universität, Bochum. Bochum 44780, Germany (Fidel.Costa-Rodriguez@rub.de; Sumit.Chakraborty@rub.de)

The duration of many magmatic processes is inherently difficult to determine because of the short timescales involved. Recent developments in analytical and isotopic techniques such as U-series disequilibria have yielded time scales for magma generation and eruption on the order of 10^2-10^5 years. However, the timescales of magma mixing, assimilation, or crystal fractionation remain elusive despite their great importance for the understanding of igneous processes and eruption forecasting. Here we take a complementary approach to that of U-series disequilibria which consists of modeling the diffusive modification of the zoning patterns from the igneous minerals to obtain timescales of magmatic processes. We have concentrated on the eruptive products of a silicic zoned eruption (~ 1 km^3) from Volcán San Pedro (36^o S, Chilean Andes). The eruption yielded lavas that range from silicic dacite, through andesite, to basaltic andesite and are the result of incomplete magma mixing between a silicic and a mafic end-member. Zoned olivine xenocrysts occur throughout the silicic lavas and are thought to have been derived from the numerous quenched mafic inclusions also found in the lavas. Thus, modeling the compositional zoning in the olivine xenocrysts from the silicic lavas and inclusions provides the time between intrusion of mafic magma and eruption, after partial hybridization. For modeling the concentration profiles we took into account the anisotropy of Fe-Mg diffusion in olivine. Two dimensional models were used for all crystals, and diffusion in three dimensions was also considered. Modeled in this manner, it is found that the retrieved timescales vary systematically with the composition of the host rock, from about a month for the most silicic dacite to 50 years for the andesite. This indicates that although the initial dacitic eruption might have been triggered by injection of basalt, at least 50 years were necessary to create the andesite by mixing - this is much shorter than the time required to produce andesite by fractional crystallization. Geophysical data obtained for the Pinatubo 1992 eruption also sets the time between intrusion of basalt and eruption on the order of days to months. This opens the possibility to relate the retrieved timescales obtained from geophysical data to specific magmatic processes identified from kinetic modeling.

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Mineral diffusive and ^{226}Ra/^{230}Th timescales for the genesis of Icelandic basalts: Laki and the Grimsvötn magma system

I. BINDEMAN[1], O. SIGMARSSON[2], J. EILER[1] AND Z. WANG[1]

[1] GPS, Caltech, Pasadena, USA (inbindem@caltech.edu)
[2] CNRS - Univ Blaise Pascal, Clermont-Ferrand, France

Many Icelandic magmas are 1-3‰ lower in $\delta^{18}O$ than typical terrestrial basalts. We report oxygen isotope and trace element analyses in individual grains and bulk separates of olivine, plagioclase, and clinopyroxene phenocrysts and of basaltic glass from the1783-4 fissure eruption of Lakagigar (Laki)—the largest historic basaltic eruption—and from subsequent, smaller volume 20th century ashes from the same magma system (the subglacial Grimsvötn caldera). Previously and newly analyzed ash and lava samples of Laki basalts are homogeneous in $\delta^{18}O$=3.1±0.1‰; 1996 and 1998 basaltic ashes are also homogeneous though slightly lower in $\delta^{18}O$ =2.9±0.1‰. In contrast, we find extreme heterogeneity in $\delta^{18}O$ in phenocrysts and disequilibrium and often reversed olivine-plagioclase and mineral-glass fractionations. Olivine phenocrysts (Fo_{89-75}) vary in $\delta^{18}O$ from 4.7‰ (typical of other low-$\delta^{18}O$ basalts from Iceland) to extremely low values of 2.5‰ (in equilibrium with the host glass). Plagioclase phenocrysts (An_{89-75}) are more uniformly low in $\delta^{18}O$, varying from 3.28 to 2.85‰. Larger and Mg-rich olivines and Ca-rich plagioclase tend to have higher $\delta^{18}O$ values than the smaller, more Fe- and Na-rich ones, but these correlations are poor, perhaps because the phenocryst population is a mixture of grains that grew from their host magmas at different times as it varied in $\delta^{18}O$, and/or of cumulates that precipitated from other magmas and were later entrained. Oxygen diffusion in plagioclase and olivine constrains their $\delta^{18}O$ zoning and reversed $\Delta^{18}O$(Pl-Ol) as being transient exchange feature at ~1-2 kyr. In contrast to $\delta^{18}O$ values, fast diffusing trace element Ni, Mn, Ca in olivine, and Mg in plagioclase are consistent with equilibrium partitioning, and thus require >100 yrs. Laki lavas and plagioclase have 15% excess in (^{226}Ra/^{230}Th) that require shorter than 8kyr magma residence, but mineral diffusion age may pre- and post-date magma segregation depending on the time of their growth/entrapment. These overall fast timescales and the surprising whole-rock $\delta^{18}O$ homogeneity with low $^3He/^4He$= 3.6, call for an effective magma mixing, storage, and homogenization for ~1 kyr. Mass balance requires that the initial normal $\delta^{18}O$ parental olivine tholeitic basaltic magma of the eastern rift zone, melted low-$\delta^{18}O$ Iceland crust 1000s yrs before eruption, followed by the addition of 15% of superliquidus, -10‰ silicic partial melt with 3-4wt% H_2O and 2-3wt% K_2O. Low-$\delta^{18}O$ Iceland's anomaly is viewed as crustal in origin caused by glaciation.