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The time scales of magma mixing and mingling at mid-ocean ridges

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Approximately 20 km^3 of magma is processed through mid-ocean ridges (MOR) every year. Despite being the Earth's largest volcanic system, we lack information about the time scales of the processes that occur in the magma plumbing system and how they vary with spreading rates. A key observation made by early researchers is that magma mixing prior to eruption is a major petrogenetic process at MOR. Here we focus on determining the time scales for such mixing processes by modelling the zoning patterns of plagioclase crystals. We combine these with existing timescale data determined from isotopic disequilibrium in the Pb-Ra-Th system to work toward a more comprehensive and quantitative model of MORB petrogenesis.

We have studied the plagioclase textures and compositions from basalts from a slow (Mid-Atlantic) and an intermediate (Costa Rica rift) spreading ridge. The plagioclase phenocrysts at both ridges are dominated by a high-Ca population with anorthite (An) contents between 80 and 90 mol %. The high-Ca cores of crystals from basalts of the Mid-Atlantic ridge are surrounded by lower An rims (ca. 75-65) and co-exist with olivine of forsterite contents (Fo) at 77-84. In contrast, the crystals from the Costa Rica rift lack any rims of a different composition and coexist with olivines of forsterite contents up to Fo91. Phase equilibria studies show that none of the high-Ca plagio-

clase crystals can be in equilibrium with the surrounding glass, and these are thus are xenocrysts rather than phenocrysts. The intermediate plagioclase ($\sim$ An70) and the olivine in the Mid-Atlantic ridge samples are in equilibrium at ca.1200 ^{o}C. Thus, in both ridges the plagioclases show that the erupted basalts are the results of mixing or mingling between crystal-rich cumulates of mainly Ca-rich plagioclase and a normal MOR magma that lacked true plagioclase phenocrysts. Most of the Mg contents of the plagioclases from the slow spreading center have equilibrated with, or crystallized from, liquids with 8-9 wt% MgO, i.e., those of the bulk-rock. The plagioclase Sr concentrations are not in equilibrium in the bulk rock, and their diffusive reequilibration constrains a maximum of $<$ 5 years since the time of magma mingling and eruption. In contrast, the crystals from the intermediate spreading ridge show Mg contents that indicate crystallization from, or reequilibration with, liquids of high MgO (between 11 and 13 wt%). This is 2-4 % higher than the MgO concentration of the bulk rock or interstitial glass (and higher than any erupted MORB) and demonstrates that the time between magma mingling and eruption was on the order of a few days. These short times are in accord with the absence of lower An rims in the crystals of the basalts erupted at this intermediate spreading rate ridge, and could reflect faster magma intrusion rates compared to that at the slower spreading center, or a deeper magma chamber at slow spreading ridges as expected on thermal grounds.

These results are in broad agreement with the maximum times of a decade derived from Pb-Ra-Th disequilibrium data obtained from basalts at intermediate- and fast-spreading ridges. These data are consistent with the interpretation that such short times reflect the time since magma mingling between plagioclase-rich crustal gabbroic cumulates and ascending basalts, rather than the total time since partial melting of the mantle and eruption.