Seeing Beyond the Melt Lens Into Crustal Processes at Mid-Ocean Ridges

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Understanding the evolution of mid-ocean ridge (MOR) magmas from mantle melting to eruption on the seafloor has been a primary goal of ridge science for decades. Although a great deal has been learned from studies of erupted lavas, drill cores, hydrothermal fluids, and geophysical surveys, few studies can constrain geologic processes occurring at depth because direct observations and sampling of the lower oceanic crust is inherently difficult. Many geochemical studies of MORs focus on the compositions of glasses erupted on the seafloor; however, they provide only limited insights into deeper processes because these lavas are often homogenized in shallow magma chambers prior to eruption. One way to overcome this obstacle is to examine melt inclusions – droplets of melt trapped in crystals as they grow (in this case olivine) – which can preserve melt compositions from deeper in the magmatic system (Figure 1).

Figure 1: Olivine with several small melt inclusions trapped inside during crystal growth.

To see beyond the melt lens and gain insight to crustal accretion (accumulation) processes at fast- and intermediate-spreading ridges, we analyzed a suite of melt inclusions from the East Pacific Rise (EPR) and the Juan de Fuca Ridge (JdFR). We also measured volatile and major and trace element concentrations in melt inclusions from four different MORs. This combined geochemical approach, which was supported by the Ocean Ridge Initiative, enabled us to track magma evolution during ascent from the mantle by providing both the depths at which crystallizations occurred and the melt compositions. This study allowed us to address several outstanding questions regarding crustal genesis at MORs:

1. What is the range and distribution of crystallization depths at different spreading rates?
2. Are the depths of crystallization and compositions of the melt inclusions consistent with current models of how the ocean crust is formed?

In total, over 320 melt inclusions were analyzed from four MORs with variable spreading rates – the largest melt inclusion data set of the global MOR spreading system. The inclusions taken from the East Pacific Rise (EPR), Juan de Fuca Ridge (JdFR), Mid-Atlantic Ridge (MAR), and Gakkel Ridge were analyzed for volatile, major and trace element concentrations. Volatile compositions (water, carbon dioxide, sulfur, chlorine and fluorine) were measured on WHOI's 1280 ion microprobe and major element analyses were conducted on all melt inclusions at MIT. Trace element analyses of a subset of samples were measured at the Arizona State University.

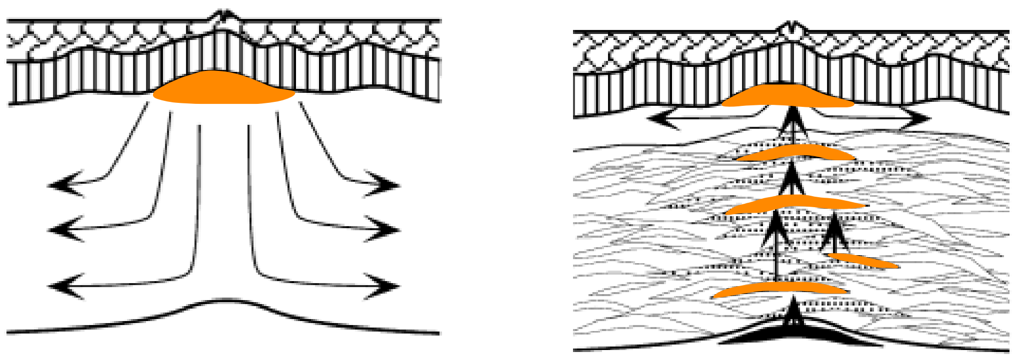

Figure 2: Two models for crustal accretion on MOR. **(Left)** Gabbro Glacier, where all crystallization occurs in the shallow magma chamber (orange) and crystals are then transported downward to create the lower crust. **(Right)** Stacked sill model for crust formation, where crystallization occurs in sills (orange) located throughout the crust.

A key aspect of our study was the approach of combining CO_2 and water concentrations to determine the minimum pressure (or depth) of melt inclusion entrapment. Knowing both the melt composition and the depth of crystallization provided constraints on models of how the crust is formed at MORs via gabbro glacier, where all crystallization occurs in the melt lens; or stacked sills, where crystallization occurs throughout the crust in a series of sills; or melt-rock reaction, where melts react with the crust during ascent (Figure 2). The pressures of crystallization were converted to depths of crystallization and plotted in histograms to examine the distribution of crystallization at the different MORs (Figure 3). Our results clearly show that crystallization occurs throughout the crust and even into the mantle (>nine kilometers) at all four ridges. These results confirm that crystallization is not confined to the shallow melt lens, effectively ruling out the gabbro glacier model for crustal accretion, which has been debated for decades.

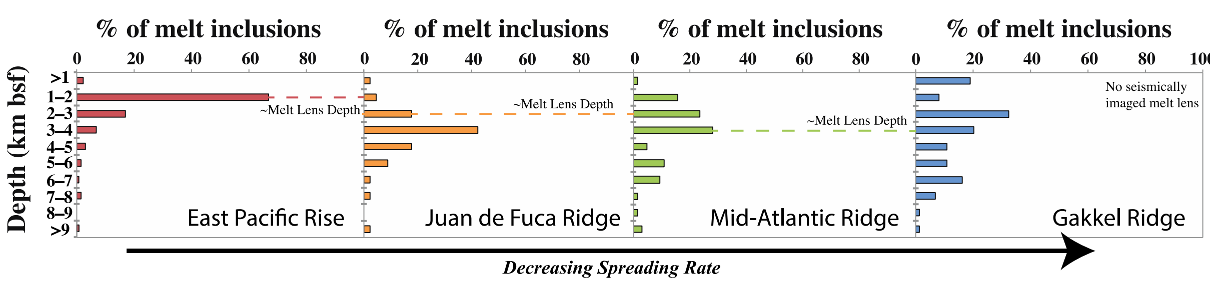

Figure 3: Histograms showing the distribution of crystallization depths from all four ridges. Crystallization occurs from >nine kilometers to the seafloor at all ridges, suggesting that the ocean crust is built at all depths. When a magma chamber or melt lens is present, there is a prominent peak in crystallization at that depth, suggesting this feature plays an important role in crust formation.

The distributions of crystallization also show that at ridges that have a shallow magma chamber, there is significant crystallization occurring in the shallow crust (Figure 3a-c). In general, the crystallization distribution becomes more uniform with decreasing spreading rate. There is a prominent peak in crystallization (>60%) at the EPR that corresponds to the depth of the magma chamber top (1.5 kilometers, Figure 3a). The peak in crystallization becomes progressively less prominent (JdFR >40%; Figure 3b and MAR >20%; Figure 3c) and deeper (3-4 kilometers) as the spreading rate decreases. In the absence of a known magma chamber (ultraslow-spreading Gakkel Ridge), the distribution of crystallization is relatively uniform (Figure 3d). These results show that the magma chamber is a region of significant crystallization, but it is not the only region where crystallization is occurring.

The results of this study have been presented at six international geology and geochemistry conferences. Additionally, results have been published in two peer-reviewed journals and have been submitted for publication in a third journal

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