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Melt extraction at mid-ocean ridges: A story in three acts

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At mid-ocean ridges, lithosphere is created by melt extraction and metasomatism, and the oceanic crust forms as melt collects near the surface. As the presence of melt has both rheological and geochemical consequences for the lithosphere, it is of primary importance to understand the mechanisms that control melt migration and extraction at mid-ocean ridges.

Although melt migration is described rigorously by two-phase transport equations in porous or fractured media [1-3], scaling considerations and geological constraints lead to simplifications. It is possible to capture the essence of melt extraction by considering three principal stages:

Stage 1) Melt rises vertically from the zone of melt production to a melt-impermeable boundary, or permeability barrier the base of the thermal lithosphere. At this stage, melt trajectories are sub-vertical. They are controlled by melt buoyancy and the high permeability of the partially molten mantle, in which melt remains connected even for low melt porosity [4]. Decompaction channels induced by melt-rock reaction and/or melt weakening may further increase the effective permeability of the mantle [5-8].

Stage 2) Melt travels long a permeability barrier that forms at a crystallization front [9]. As melt enters the lithosphere and cools, it crystallizes and possibly clogs the pore space [10-12]. A barrier is most likely to form where crystallization rate highest, which, in basaltic systems, occurs at the point of plagioclase ± pyroxene saturation [13]. This location follows approximately $1240°+1.9z$, where z is depth in km [14,15]. As the depth of barrier depends on the thermal structure of the lithosphere, it is generally inclined so that melt, being buoyant, travels and is generally focused toward the ridge axis. If the thermal boundary layer is too thick, deep crystallization may be so slow that the lithosphere can decompact and accommodate the crystallization products leading to a metasomatized zone instead of a barrier [11,13]. This is most likely to occur at ultraslow spreading centers [15].

Stage 3) Melt is extracted to the surface, either because melt reaches a place where the barrier is horizontal and focusing stops, or because it enters a melt extraction zone (MEZ), which may be physically interpreted as the presence of faults and/or dikes leading to rapid lateral and vertical melt migration toward plate boundaries [16,17]. However, if focusing stops where the barrier is too deep, melt may instead crystallize at depth again metasomatizing the mantle at the level of the permeability barrier.

Stages 2 and 3 are directly influenced by the structure of the thermal lithosphere, which is itself controlled by segmentation of the ridge axis and spreading rate [16-21]. Thus, it is possible to use along-strike variations in melt deliver at well-studied geological examples to constrain the various parameters controlling each of these stage. Recently, it has been shown that the crust along transform faults at fast-spreading ridges is anomalously thick [22], which suggest melt redistribution toward transforms, intra-crustal melt production, or efficient extraction of melt in the transform domain [20]. Specific models of the Siqueiros transform along the East Pacific Rise shows that considering a melt extraction zone explains the presence of thickened crust in the transform domain

[16]. The ultraslow Southwest Indian Ridge at 10°-15°E illustrates the opposite end-member of ridge systems, where the lithosphere is thick and little melting occurs. Strong along-strike variations in crustal thickness [23] can be explained by the presence of a melt extraction zone less than 10 km wide and roughly 30 km thick [20].

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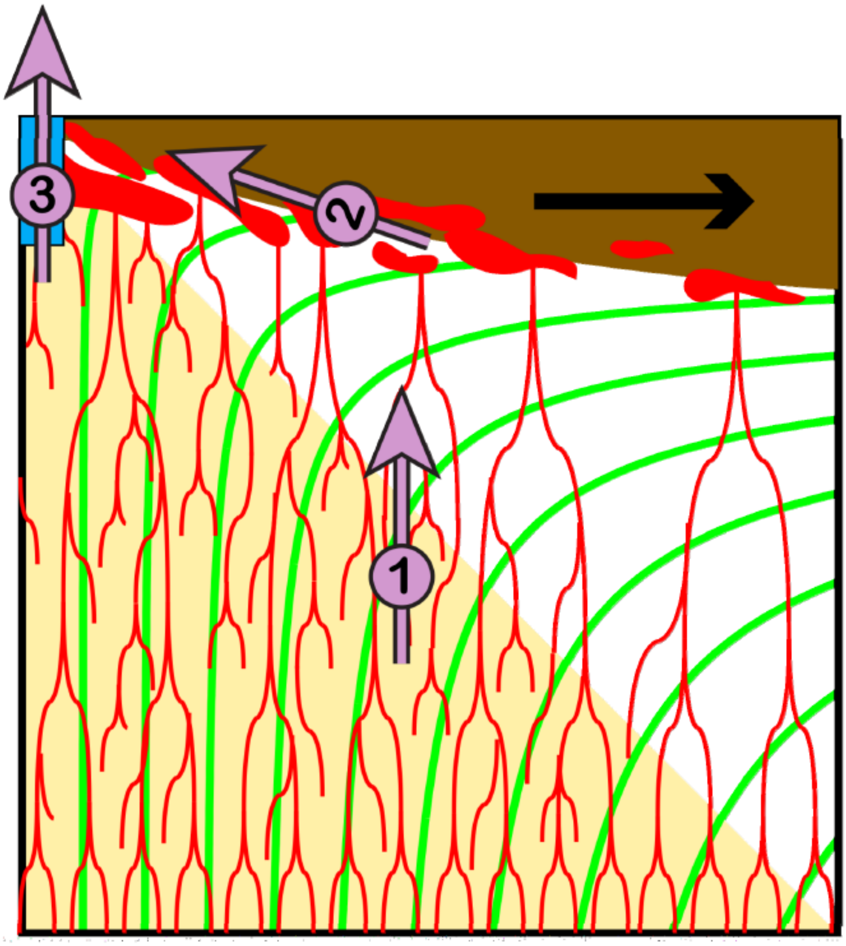

Figure 1: Schematic representation of melt focusing processes in a 2D section across a mid-ocean ridge. The lithosphere (brown) thickens away from the ridge. Green and red lines represent the trajectories of the solid mantle and melt, respectively. Extraction is vertical in Stage 1, possibly along dissolution channels that drain the melt production region (orange triangle). Extraction is sub-horizontal in Stage 2, along a permeability barrier near the base of the lithosphere, where temperature is 1240°+1.9z with z the depth in km. Finally extraction is sub-vertical again in Stage 3, in a tectonically controlled melt extraction zone (blue box) near the ridge axis and other plate boundaries. 3-D variation of melt focusing at ultraslow and ultrafast ridges imply that the melt extraction zone is less than 10 km and roughly 30 km deep;