

Solving the pyroxene paradox in mid-ocean ridges with trace element mapping, image analysis, and thermodynamic modelling

**TERESA UBIDE¹, DAVID T MURPHY², ROBERT EMO³
AND MR. MARCO ANDRES ACEVEDO ZAMORA²**

¹The University of Queensland

²Queensland University of Technology

³University of Cologne

The composition of global mid-ocean ridge basalts (MORBs) requires early crystallisation of clinopyroxene at depth, however, petrological observations in MORBs (scarce clinopyroxene phenocrysts) and gabbros (clinopyroxene occupying intercumulus space) suggest clinopyroxene crystallisation is late and restricted to relatively low pressure. These competing inferences constitute the long-standing ‘pyroxene paradox’. Here, we report the discovery of rare (up to 4 vol.%) relict clinopyroxene ‘cores’ in intercumulus clinopyroxene from the Atlantis Bank slow spreading centre (southwest Indian Ridge ODP Hole 735B).

We exploit slowly diffusing trace elements Cr, Zr and Ti to uncover relics that preserve evidence of an early, transported and largely resorbed, mafic pyroxene mush. Using dimensionality reduced semantic segmentation of elemental maps, we define the mode and outline of antecrysts cores. The cores have rare earth element systematics that agree with crystallisation from MORB liquids, providing an empirical connection between deep melt crystallisation and erupted basalts. In contrast, clinopyroxene rims are notably enriched in incompatible elements because of late melt-rock reaction in the gabbroic mush. The rims have strong negative Eu anomalies, indicating crystallisation after development of plagioclase-dominated mush at low pressure.

Thermodynamic modelling of clinopyroxene crystallisation from MORB parental melts at high pressure (8-10 kbar) reproduces the large spread in MORB Ca-Al-Mg systematics and generates a strong density contrast between the evolving liquid and cumulate pyroxenites. At the buoyancy peak, where crystallinity remains low, liquid compositions approach observed MORB chemistries and clinopyroxene compositions match antecryst cores. Our work supports the idea that polybaric mid-ocean ridge crystal mushes act as multi-stage magma filters, with cryptic clinopyroxene crystallisation as a driver of the early evolution of the oceanic crust.