

## Imaging and *in situ* analyses for assessment of metamorphic reaction mechanisms and equilibration

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Reaction mechanisms and kinetic impediments to chemical equilibration in metamorphic rocks are revealed by combining a variety of imaging techniques - over a range of scales in both 2D and 3D - with chemical and isotopic analyses guided by the imagery.

For example, high-resolution X-ray computed tomography (HRXCT) of porphyroblastic rocks provides precise quantitative information on the sizes and locations of garnet crystals in 3D. Because these data can be collected for very large numbers of crystals, they provide a statistically rigorous basis for testing hypotheses for atomic-scale mechanisms of nucleation and growth during crystallization.

HRXCT imagery also facilitates precise sectioning of crystals through their morphological centers, which is essential to proper interpretation of compositional analyses that track the chemical evolution of the rock during crystallization. EPMA X-ray mapping and analysis of major and minor elements in garnet, along with EBSD measurements and orientation-contrast imaging, provide information that is used to discriminate among possible nucleation and growth mechanisms, and to identify features that record chemical disequilibrium during growth. Radial distributions of REEs in garnet, measured by LA-ICPMS, indicate diffusion-limited uptake during growth, pointing to kinetic limitations on the extent of these elements' equilibration. *In situ* SIMS measurements of oxygen isotopic ratios in garnet, combined with EPMA X-ray images of chemical zonation, define episodes of growth in the presence of fluids of anomalous compositions; these are correlated with periods of high strain rates in the host rock.

These diverse sources of imagery and chemical information have still further value when used to constrain numerical simulations that model crystallization processes. Comparison of model results to observations tests the mutual consistency of the postulates on which the models are founded, and permits estimation of the key kinetic parameters that govern rates and mechanisms of crystallization.

## Constraining reactions between MOR vent fluids and new oceanic crust: The hydrothermal upflow zone beneath M vent, 9°50'N EPR

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M vent, located at 9°50.7'N on the East Pacific Rise, is part of the Ridge 2000 (R2K) Integrated Study Site (ISS). It sits on the upper lip of the east wall of the ~20m deep axial summit collapse trough (ASCT) that marks the axis of spreading. The walls of the ASCT have been slowly receding as a result of mass wasting in the ~15 years since the 1991-2 eruption at this site. Hydrothermal vent fluids were collected from M vent from 1992-2004 [1], and in 2004 two samples of hydrothermal stockwork, or alteration pipe, were collected from ~17m below M vent. To date, these are the only samples recovered from beneath a vent where there has been an ongoing sampling program, and they record the last reactions that occurred between the hydrothermal fluids and the ocean crust. Sample 3987-2 contains anhydrite, kaolinite, chlorite, sepiolite, atacamite, and disseminated sulfides (pyrite, chalcocopyrite, sphalerite, pyrrhotite) and sample 3993-2 is primarily altered basalt and glass (from the 1991 eruption) and also contains chlorite, calcite, pyrrhotite, pyrite, kaolinite, and zeolites.

Cathodoluminescence imaging has shown that the anhydrite in 3987-2 is chemically zoned, with crystal growth zones recording the temporal variability of trace elements in the fluid. Major element analysis of the volcanic glass in 3993-2 shows that Ca has been progressively leached out of the rock via fractures. Selvages around fractures show a 6-10 wt% loss of CaO from the margins to the interior, while molal Ca in vent fluids increased from  $1.2 \times 10^{-2}$  to  $4.2 \times 10^{-2}$  during 1992-2004, indicating that at least some of the Ca in the fluid was due to alteration of volcanic glass in the stockwork.

[1] Von Damm, K.L. (2004) *AGU Monograph* **148**, 285-304.