



## **Metamorphic processes: what do we really know?**

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The modern study of metamorphism involves field work, laboratory experiments, state-of-the-art analytical techniques, thermodynamic modeling, and fundamental reaction-transport theory. In recent years, this integrated approach has provided new insights at the grain scale, outcrop scale, and regional scale that challenge accepted paradigms.

Chemical and isotopic diffusion profiles preserved within minerals offer great promise for quantifying the timescales of metamorphic thermal events. A particular strength in this regard is that diffusion systematics can reveal short-duration heating and/or cooling pulses in old rocks that are not resolvable using standard isotopic dating techniques. New analytical equipment, such as the field emission gun electron microprobe, can map chemical profiles to sub-micron scale spatial resolution, providing much tighter constraints on diffusion profile modeling. Furthermore, a new, relatively unexploited technique is to measure profiles for more than one diffusing species in a single grain to invert for a portion of the temperature-time history. Much work remains to quantify diffusion rates in common minerals. Tracers in compositionally simple minerals such as apatite, quartz, carbonates, and aluminosilicates may prove to be particularly useful.

Recent diffusion-based timescale estimates and high-precision isotopic dating have shown that some metamorphic events may occur on much shorter timescales than traditionally believed. Examples include rapid exhumation of HP/UHP rocks at plate tectonic rates, and rapid thermal pulses during typical Barrovian regional metamorphism that are probably driven by igneous activity and associated fluid circulation. While not all metamorphic terranes undergo rapid processes, those that do may be-

have quite differently than the conventional wisdom. For example, if rates of fluid transport, heating, or pressure changes are rapid relative to reaction rates, then kinetics will play an important role in governing reaction histories. In this case, the kinetics of crystallization must be understood before mineral compositions can be used to infer evolving P-T-X conditions. Pseudosections are most commonly used to model closed systems at equilibrium with water activity=1, but they can be very valuable for kinetic studies as well. Because of the great strides made in developing thermodynamic data sets and activity models, the expected equilibrium mineral assemblages, modes, and compositions can be predicted. Reaction histories preserved in rocks that deviate from the predicted trajectories will be valuable indicators of disequilibrium and kinetic processes.

Conductive models of P-T-t evolution often assume that the heats of metamorphic reactions, as well as the capacity for metamorphic fluids to transport heat, are minor. However, this reasoning is usually based on the concept that "peak" thermal events last millions or tens of millions of years such that heat conduction is dominant. If, however, they last for a million years or less, the timescale for conduction is more limited and reactions and fluids will have more opportunity to perturb regional geotherms. This raises many new questions. For instance, is mineral zoning that indicates a temperature decrease the result of a local reaction that consumes heat, or to a larger-scale cooling following events such as regional magmatism or fluid flow?

Fluid flow drives regional mass transfer and reaction. It is now established that metamorphic rocks can undergo a variety of chemical changes during prograde and retrograde events. Major elements, particularly Na and K, as well as trace elements can be mobilized. However, evidence that has accumulated to date suggests a wide variety of behavior is possible, and that the nature and extent of mass transfer can vary at the thin section, outcrop, and regional scales. Are specific kinds of chemical changes diagnostic of certain tectonic settings? Or are chemical changes mostly a function of local variations in fluid flux, concentration gradients that drive diffusion, and rock type?

Mapping of refractory minerals including garnet has uncovered a wealth of chemical zoning information, much of which remains to be interpreted. Oscillatory zonation, often particularly well-developed for Ca in garnet, is one example. Does it reflect local disequilibrium between matrix minerals, fluid, and garnet during growth? Is it related to the local breakdown of reactant phases with distinctive chemical compositions? Does it result from outcrop or larger scale variations in fluid pressure due to processes such as hydrofracturing or even seismic activity? Is it instead a consequence of even larger scale tectonic movements or magmatism that produce pulses of loading and/or heating?

In nature, all of these possibilities may be important in metamorphism, and the challenge to the petrologist is to determine the processes and their scale of operation. These efforts must be coupled to continued developments in our understanding of the dissolution, nucleation, and growth of metamorphic minerals. A particularly provocative development in recent years has been the discovery that kinetic reaction paths can in some cases produce the same mineral assemblages that are predicted by equilibrium theory. Differentiating between kinetic and near-equilibrium reaction pathways is an emerging frontier in petrology.