A fresh look at field-based metamorphic reaction kinetics

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The fundamental controls on reaction rates in metamorphic systems have long been the subject of discussion and debate. As early as the 19th century, Arrhenius showed that temperature plays a critical role in governing reaction kinetics. Nonetheless, it has long been observed that rates of contact metamorphism are orders of magnitude faster than those in regional metamorphic systems, even at similar temperatures. The presence of free fluid may contribute to the large discrepancy observed in natural systems, although recent work suggests that very little free fluid is needed to wet grain boundaries, and it is unclear what the kinetic advantage of excess fluid beyond that needed to wet intergranular surfaces may be.

We have compiled field-based estimates of reaction rates from regional, contact, subduction and exhumation-related metamorphic settings. Investigation of these reaction rates reveals a strong correlation between heating rate (dT/dt) and net reaction rate. This relationship is used to formulate a new expression relating net reaction rate (R_{net}), temperature (T) and heating rate (dT/dt):

$$\log R_{net} = 0.0029T + \log\left(4\text{E-11} \times \frac{dT}{dt}^{1.25}\right)$$

This expression provides a unifying theory of metamorphic reaction kinetics at the tectonic scale and accounts for the 4-7 orders of magnitude range in metamorphic reaction rates observed in natural systems. Thus metamorphic reaction rates can be predicted in any tectonic setting provided the temperature-time history of the rock can be estimated.

Very few direct observations of reaction rates in subduction zones have been made to date. Based on the above expression, we propose that the dynamic nature of subduction zones (high dT/dt) will result in large thermal overstepping, which drives faster reaction rates in these systems relative to typical regional metamorphic settings. Consequently, in a typical cold slab the dramatic increase in dT/dt at ~80-100 km slab depth due to slab-mantle coupling would accelerate dehydration reactions in a race to “catch up” to the equilibrium state of the slab, resulting in a pulse of fluid released at around this depth. Thus even continuous reactions could run to completion over a relatively short depth interval, explaining the pulse-like fluid release inferred from some arc magmas and exhumed subduction terranes.