Insights from modeling superposed and coupled metamorphic processes

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Continuum models of a variety of metamorphic processes, solved analytically or numerically, have provided us with much insight and understanding. Superposition of and coupling between different kinds of processes are the rule in nature and common in many models. Notable among these are, for example, the England, Richardson and Thompson models of how thrusting followed by conductive cooling and erosion can explain many first order features of metamorphic rocks such as the occurrence of clockwise P-T paths in collisional settings. Other examples include the coupling of thermal fields, evolution of permeability and fluid flow, as studied, for example, in the early models of Skaergaard intrusion by Norton and Taylor. In this talk we will focus on how such superposition and coupling on different scales can further our understanding of metamorphic processes. On the largest geodynamic scale, a first order question has been – Where does the heat for Barrovian metamorphism come from? Simple models of thrusting have been shown to be inadequate for producing widespread migmatites. It is shown that at least in some settings, the combination of thrust stacking, enhanced radioactive heat generation and shear heating may provide an answer to this dilemma, while raising other questions. On the outcrop scale, while it has been clear that thermal pulses can cause brittle fractures and enhance permeability, the location of such fractures and timing of their development have been difficult to predict. Recent models that combine continuum approaches with damage theory allow us to make some such predictions, which may be checked against mapped veins and fracture zones in contact aureoles. On the scale of thin sections, the interaction between diffusion and nucleation rates determine whether new phases form as a corona or as individual crystals in a matrix – it is possible to make some generalized conclusions by extending existing analytical models. And finally, the behavior of defects on the nanometer scale are determined by the relative rates of element exchange and net transfer reactions, and these determine whether enhanced, reactive diffusion rates apply. In cases where they do, it is necessary to consider the effects in determining time scales (durations, cooling rates) using geospeedometric methods.

Thermal gradients in the Himalaya using muscovite as a monitor of the activity of rutile combined with Ti-thermometry

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For rutile-absent rocks, the trace-element thermometers Ti-in-Qz and Ti-in-Zrc require specific mineral assemblages to estimate the activity of rutile, *a* (Rt). To allow ready estimation of *a* (Rt) in a wide variety of rock types, we have empirically calibrated a muscovite monitor of *a* (Rt) using the cation exchange reaction $Ti^{VI}Al^{IV} = Al^{VI}Si^{IV}$ with ~250 analyses from natural and experimental published data [1]. The r^2 value for $\ln K_{id}$ is 0.98, with a 2σ error of ~0.2.

One application of this technique is in determining field *T* gradients across transects in orogens: as only quartz and muscovite are required in the mineral assemblage, felsic rocks e.g. orthogneiss, that are typically unsuitable for traditional thermo-barometry, may be analysed. In the Sutlej Valley (NW Indian Himalaya) a ~30 km deep section beneath the Main Central Thrust (MCT) is dominated by the Wangtu orthogneiss. Field *T* gradient information from this section will provide key data in understanding the geodynamics of the MCT and the thermal evolution of the Himalaya. Preliminary results including cathodoluminesence (CL) images of quartz zoning, and Ti concentration data for quartz and muscovite (from LA-ICPMS and electron microprobe, respectively), will be presented.

The success of this study relies upon a sound interpretation of the Ti data from both quartz and muscovite in relation to metamorphic reactions, deformation and diffusion processes (e.g. [2]). Previously, CL imaging of quartz has only been used as a qualitative tool in understanding the interplay between these processes. We intend to determine the structural state of Ti in quartz in the Sutlej Valley samples, how exactly this contributes towards quartz luminesence, and how it relates to metamorphic grade and/or deformation processes.

[1] Chambers & Kohn (submitted) *Contributions to Mineralogy & Petrology*. [2] Spear & Wark (2009) *J. Metamorph. Geol.* **27**, 187–205.