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Dating deformed rocks at the km scale: the role of nm-scale processes

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Dating deformation requires understanding textures of deformed rocks and petrogenesis of multiple mineral generations. An apparent difficulty is that geochronometry is pursued by communities that often do not communicate. Hygrochronology dates the retrograde metasomatic/metamorphic reactions caused by aqueous fluid circulation events. Thermochronology models time-temperature histories by assuming that mineral ages can be uniquely assigned to a "closure temperature T_c", the only process occurring in rocks being Fick's Law diffusion. This assumption is easily checked, as diffusion by definition produces a bell-shaped concentration profile. In contrast, patchy intra-grain element and isotope concentration profiles denounce aqueous retrogression reactions, whose rate is orders of magnitude faster than diffusion.

Petrochronology is based on opposite physics, as the mobility of structure-forming major cations is higher than the slow diffusivity of radiogenic Pb, Ar, and Sr. Since the formation of most minerals occurs at $T < T_c$, their apparent ages date their formation. Nanochronology analyzes samples at the nm scale [1]. It illuminates atomic-scale processes, e.g. open-system transport of soluble ions along self-sealing networks of nanopores [2].

Robust geochronology requires combining microtextural groundwork, resolving nanostructures correctly, with electron microprobe µm-scale characterization of the multiple generations that usually make up the petrologically useful geochronometers, with multichronometry on such phases, e.g. U-Pb on monazite and ^{39}Ar-^{40}Ar – Rb-Sr on micas [3].

The key to dating deformation and producing correct, regional-sized (up to 100s of km) tectonic models is the realization that minerals consist of atoms, whose behavior is only firmly constrained by nm-scale analyses. The different length scales, at which petrogenetic processes occur, define a "Goldilocks zone": the scale of the in situ analysis must neither be too coarse, lest several different mineral generations be averaged into meaninglessness, nor too fine, lest the nm-sized clusters formed by few hundred atoms and observed by AtomProbe disproportionate parent from daughter isotopes [4,5].

[1] Valley &al 2015, *American Mineralogist*, 100, 1355-1377

[2] Plümper &al 2017, *Nature Geoscience* 10, 685-690

[3] Villa &al 2023, *Journal of Metamorphic Geology*, doi:10.1111/jmg.12700

[4] Seydoux-Guillaume &al 2019, *Geoscience Frontiers* 10(1), 65–76

[5] Kusiak &al 2013, *Geology*, 41, 291-294