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An integrated numerical modeling, petrochronology, and microstructural approach to understand deep-crust exhumation processes

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Plate convergence leads to burial of continental crust by subduction or by crustal thickening, creating vast regions of hot, low-viscosity deep crust. In orogens, this weak deep crust flows laterally to maintain a relatively flat Moho and flows upward to fill gaps created in the shallow crust during syn-convergence extension or transtension. The magnitude of vertical flow has been estimated by 2D and 3D numerical modeling and by field-based studies, both of which show that deep crust can traverse nearly the entire thickness of the orogenic crust to within 2-10 km of the Earth's surface in a single, rapid (<10 myr) event. 3D models show that flow may be at a high angle to the direction of extension but that deep crust nevertheless is exhumed rapidly to shallow levels. The result of vertical flow of ductile crust is a domal structure comprised of high-grade metamorphic rocks (gneiss, migmatite). These gneiss domes, which are abundant worldwide in exhumed orogens of all ages, are the 'tip of the iceberg' of crustal flow systems and are archives of data on the magnitude, rate, and conditions of deep-crust exhumation. Most dome rocks, however, record only the conditions at or near emplacement in the mid- to shallow crust; e.g., mineral assemblages in quartzofeldspathic rocks that dominate migmatite domes typically record high-temperature – low-pressure conditions. The record of high-pressure metamorphism is in more refractory compositions such as mafic rocks, which occur as lenses and layers within migmatite and gneiss. The P-T-t-d record of these rocks can be compared with model predictions to gain insights into deep-crust exhumation, which is a first-order process in continental differentiation and stabilization.

The Montagne Noire, French Massif Central, is a migmatite dome that contains mafic rocks dominated by amphibolite but that in two locations preserve relics of fresh eclogite (garnet + omphacite + rutile + quartz). One eclogite is in the core of the dome and the other at the margin. Age (zircon, rutile U-Pb) and trace element data for both eclogites show that high-pressure metamorphism was broadly coeval with the earliest crystallization of monazite in the host migmatite. Numerical models predict that material at the dome margin ascended first and then flowed outward from the dome core, whereas dome-core rocks ascended directly from the deep-crust before cooling at shallower levels. Both eclogites contain the same peak mineral assemblage but differ in mineral (garnet, omphacite) composition, reflecting slightly lower P-T conditions for the dome-margin eclogite: $\sim$1.2 GPa, 680°C, compared to dome-core eclogite: $\sim$1.4 GPa, 725°C. A significant difference is that omphacite in the dome-core eclogite preserves a CPO that indicates flattening strain (consistent with HP metamorphism under transpression), whereas omphacite in the dome-margin eclogite records a constrictional fabric (consistent with HP metamorphism under transtension). Both of these fabrics occurred under eclogite facies conditions and can be understood in the context of 3D numerical models for deep-crust exhumation in a migmatite dome.