

What are diffusing noble gases *really* doing?

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The diffusion behavior of noble gases, especially Ar and He, lies at the heart of recent advances in low temperature thermochronometry. When we interpret a parent/daughter ratio in terms of cooling path we are to a remarkable and disturbing extent relying on a black-box understanding of what is actually occurring as noble gases migrate through a crystal lattice, both in nature and in the laboratory. I will review recent developments that underscore the need to establish a more mechanistic understanding, and illustrate some of the routes by which it might be obtained.

As demonstrated by years of debate over the validity of the MDD model for Ar diffusion in K-feldspar, there is a disconnect between empirical interpretation of step heat data and its physical meaning. What (mineralogically) are diffusion domains? What are fast pathways? These same questions apply to the (U-Th)/He method. While strong evidence exists that apatite and zircon are (always?) dominated by whole-grain diffusion, evidence suggests that this may not be true for some other phases. Why? Even more so than bulk data, successful application of the $^4\text{He}/^3\text{He}$ method demands accurate knowledge of diffusion geometry. Insights to these questions may be gained from direct imaging of daughter distribution; some data now exist for Ar, but He imaging remains analytically very challenging.

Beyond domains, it is important to understand how diffusing noble gases navigate crystal structures. The need is well illustrated by the observation that radiation damage impedes He diffusion in apatite, but, at least at high doses, enhances it in zircon. What exactly is He doing as it diffuses? Some progress is being made on this topic. For example, recent work on monazite and zircon structures shows that ionic porosity, long thought to be a key control on noble gas diffusion, plays at best a limited role for He diffusion. Instead (and perhaps unsurprisingly) it is the details of the atomic arrangement rather than the packing density that matters most. The same considerations also explain the highly anisotropic He diffusion observed in the zircon structure. In addition to laboratory experiments, molecular dynamics simulations are beginning to provide insights to the behavior of noble gases diffusing through minerals.

Length scales of isotope heterogeneities: From D'' to a mantle plume conduit

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Most likely the only physical process able to sample the deepest part of the Earth's mantle is represented by vigorous mantle plumes, whose surface expression is a long lived intraplate volcanism, the best example being the Hawaiian chain. Recent Hawaiian volcanoes are distributed along two alignments with distinct isotope characteristics (the 'Kea' and 'Loa' trends), moreover the Hawaii Scientific Drilling Project has shown the existence of isotopic variations with time, as a volcano is carried by the Pacific plate across the plume. The geochemical variability registered by volcanoes belonging to the same trend (e.g., Kea) has been interpreted as the effect of distinct compositional streaks within the plume conduit. Finally, the heterogeneous nature of the Hawaiian plume has been revealed at shorter length scale by melt inclusions. A key question is then: is it possible to use surface observations of the spatio-temporal geochemical variability to constrain the heterogeneous structure of the plume conduit, and eventually to infer possible length scales of heterogeneities in the lowermost mantle?

We conducted high resolution numerical simulations of a fully three-dimensional vigorous plume to study the flow trajectories inside a plume sheared by a fast moving oceanic plate, and to quantify the deformations undergone by passive heterogeneities rising in the conduit. We then focus on the lower mantle plume fluid flow and investigate numerically the relation between a variety of assumed isotopic heterogeneous distribution inside the basal thermal boundary layer (TBL) and the consequent conduit internal structure. We find that a vertically stratified TBL induces a radially concentric plume conduit, while azimuthal variations in the TBL induce an azimuthally varying conduit, a bilateral structure being the simplest example. Finite size TBL heterogeneities with initial length scales of order 100 km, are sheared into elongated (several hundred km) and narrow (few km) filament-like structures, whose size, geometry and position in the conduit depend on their initial size, position and spatial orientation. Finally, TBL heterogeneities with initial length scales of order 10 km give rise to a 'fine structure' (a few hundred meters) inside the plume conduit. We speculate that this 'fine structure' may account for compositional heterogeneities preserved only in magmatic melt inclusions, while the filament-like structure may account for compositional heterogeneities registered during a volcano life time, while the largest scale, bilateral Hawaiian trends reflect azimuthal large scale compositional variations in the source region.