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On the development of fat plumes in a visco-plastic lower mantle

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Recent tomographic imaging of the mantle below major hotspots shows slow seismic velocities extending down to the core-mantle boundary, confirming the existence of mantle plumes. However, these plumes are much thicker than what was previously thought based on convection in a newtonian or a power-law mantle. In those two rheological frameworks, hot « fat » plumes can only be produced either if hotter plumes are also more viscous than ambiant mantle, or if the plume conduit is thickened by a recirculation of thermo-compositional heterogeneities within the conduit itself.

Combining the recent results of seismic tomography, fluid mechanics experiments and numerical simulations of bridgmanite deformation, we suggest here that there is yet another avenue: thick hot thermal plumes could be produced in the lower mantle if the latter had a visco-plastic rheology, where flow occurs only when the local deviatoric stress becomes greater than a critical yield stress.
In recent laboratory experiments, we observed that thermal plumes developing in such a visco-plastic fluid present much larger diameters than plumes developing in a newtonian fluid. Such a rheology requiring a yield-stress is consistent with a lower mantle predominantly deforming by pure dislocation climb as recently proposed for bridgmanite in the lower mantle by numerical modeling. Moreover, scaling laws derived from the experiments tightly relate the buoyancy and diameter of the hot plumes to the value of the yield-stress, and the latter to mantle material microstructure. To reproduce the plumes morphology observed in tomographic images, yield stress values between 1 and 10 MPa, implying dislocation densities between 10^8 and 10^{10} m^{-2}, would be sufficient.

The existence of a critical yield stress in the lower mantle rheology would have important implications for mantle stirring and mixing. Such a rheology strongly localizes motions and shear, while "dead zones" develop in the remaining fluid. Their existence might strongly impede mantle stirring efficiency, leading to the long-term preservation of primitive material.