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A massively parallel adaptive scheme for melt migration in geodynamics computations

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Melt generation and migration are important processes for the evolution of the Earth's interior and impact the global convection of the mantle.

While they have been the subject of numerous investigations, the typical time and length-scales of melt transport are vastly different from global mantle convection, which determines where melt is generated. This makes it difficult to study mantle convection and melt migration in a unified framework. In addition, modelling magma dynamics poses the challenge of highly non-linear and spatially variable material properties, in particular the viscosity.

We describe our extension of the community mantle convection code ASPECT that adds equations describing the behaviour of silicate melt percolating through and interacting with a viscously deforming host rock. We use the original compressible formulation of the McKenzie equations, augmented by an equation for the conservation of energy. This approach includes both melt migration and melt generation with the accompanying latent heat effects, and it incorporates the individual compressibilities of the solid and the fluid phase.

For this, we derive an accurate and stable Finite Element scheme that can be combined with adaptive mesh refinement. This is particularly advantageous for this type of problem, as the resolution can be increased in mesh cells where melt is present and viscosity gradients are high, whereas a lower resolution is sufficient in regions without melt. Together with a high-performance, massively parallel implementation, this allows for high resolution, 3d, compressible, global mantle convection simulations coupled with melt migration. Furthermore, scalable iterative linear solvers are required to solve the large linear systems arising from the discretized system.

Finally, we present benchmarks and scaling tests of our solver up to tens of thousands of cores, show the effectiveness of adaptive mesh refinement when applied to melt migration and compare the compressible and incompressible formulation. We then apply our software to large-scale 3d simulations of melting and melt transport in mantle plumes interacting with the lithosphere.

Our model of magma dynamics provides a framework for modelling processes on different scales and investigating links between processes occurring in the deep mantle and melt generation and migration. The presented implementation is available online under an Open Source license together with an extensive documentation.