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3D modelling of non-linear visco-elasto-plastic crustal and lithospheric processes using LaMEM

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LaMEM (Lithosphere and Mantle Evolution Model) is a three-dimensional thermo-mechanical numerical code to simulate crustal and lithospheric deformation. The code is based on a staggered finite difference (FDSTAG) discretization in space, which is a stable and very efficient technique to solve the (nearly) incompressible Stokes equations that does not suffer from spurious pressure modes or artificial compressibility (a typical feature of low-order finite element techniques). Higher order finite element methods are more accurate than FDSTAG methods under idealized test cases where the jump in viscosity is exactly aligned with the boundaries of the elements. Yet, geodynamically more realistic cases involve evolving subduction zones, nonlinear rheologies or localized plastic shear bands. In these cases, the viscosity pattern evolves spontaneously during a simulation or even during nonlinear iterations, and the advantages of higher order methods disappear and they all converge with approximately first order accuracy, similar to that of FDSTAG [1]. Yet, since FDSTAG methods have considerably less degrees of freedom than quadratic finite element methods, they require about an order of magnitude less memory for the same number of nodes in 3D which also implies that every matrix-vector multiplication is significantly faster.

LaMEM is build on top of the PETSc library and uses the particle-in-cell technique to track material properties, history variables which makes it straightforward to incorporate effects like phase changes or chemistry. An internal free surface is present, together with (simple) erosion and sedimentation processes, and a number of methods are available to import complex geometries into the code (e.g, http://geomio.bitbucket.org). Customized Galerkin coupled geometric multigrid preconditioners are implemented which resulted in a good parallel scalability of the code (we have tested LaMEM on 458’752 cores [2]).

Yet, the drawback of using FDSTAG discretizations is that the Jacobian, which is a key component for fast and robust convergence of Newton-Raphson nonlinear iterative solvers, is more difficult to implement than in FE codes and actually results in a larger stencil. Rather than discretizing it explicitly, we therefore developed a matrix-free analytical Jacobian implementation for the coupled sets of momentum, mass, and energy conservation equations, combined with visco-elasto-plastic rheologies. Tests show that for simple nonlinear viscous rheologies there is little advantage of the MF approach over the standard MFFD PETSc approach, but that iterations converge slightly faster if plasticity is present.

Results also show that the Newton solver usually converges in a quadratic manner even for pressure-dependent Drucker-Prager rheologies and without harmonic viscosity averaging of plastic and viscous rheologies. Yet, if the timestep is too large (and the model becomes effectively viscoplastic), or if the shear band pattern changes dramatically, stagnation of iterations might occur. This can be remedied with an appropriate regularization, which we discuss.

LaMEM is available as open source software.

[1] Thielmann, M., May, D.A., and Kaus, B., 2014, Discretization Errors in the Hybrid Finite Element Particle-in-cell Method: Pure and Applied Geophysics,, doi: 10.1007/s00024-014-0808-9.

[2] Kaus B.J.P., Popov A.A., Baumann T.S., Püsök A.E., Bauville A., Fernandez N., Collignon M. (2015) Forward and inverse modelling of lithospheric deformation on geological timescales. NIC Symposium 2016 - Proceedings. NIC Series. Vol. 48.