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Consistent implementation of phase changes into geodynamic models

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Numerical modelling of geodynamic processes occurring on geologic timescales is a rapidly evolving field of research. Despite this rapid growth, one of the initial simplifying assumptions of early numerical models is still overlooked, as the continuity equation regarding mass is mostly left out of consideration. In fluid dynamics this is known as the Boussinesq approximation. In visco-elastic models of the lithosphere this manifests in using phase equilibria calculations to modify the density of rocks without considering any volumetric effect. We explore the consequences of this simplification by developing an approach that allows us to obtain rigorously correct solutions for continuity.

In technical terms, we use the finite element thermo-mechanical modelling tool Cast3M. This tool was previously developed for geodynamic applications, and handles elastic and visco-elastic rheology, erosion laws, as well as remeshing. We further develop the numerical code to incorporate the volumetric changes due to mineralogic phase transformations through modification of the regional stress-field. Exact density values are derived from petrogenetic grid calculated by software Perple_X.

Our application focuses on mountain range evolution. We study the evolution of its deformation at surface as well as at depth, with and without different modelling conditions to evaluate their respective importance: elastic vs. visco-elastic behaviour; erosion; horizontal convergence; hydration level of the mafic lower crust; and consistent application of phase changes. We focus on the metamorphic reactions occurring in the lower crust, as this is where the largest density and hence volumetric effects are expected to occur in the lithosphere. The results after 4 Myr simulation time show that, when enforcing continuity, metamorphic reactions play an important role on the deformation of the orogen: the effects on the evolution of topography are of the same order of magnitude as effects resulting from the action of surface erosion. The two processes compete in shaping the orogen and in localizing deformation: the dominance of either process over the other depends on the magnitude of lower crustal density variations and the efficiency of erosive processes. While the most important factor in localizing deformation remains rheology, it is necessary to respect continuity. Otherwise not only are the resultant errors with regard to mass conservation significant, but the importance of the physical processes governing topographic evolution of the orogen are also misrepresented.