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Constraining the rheology of the lithosphere and upper mantle with geodynamic inverse modelling

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The rheology of the lithosphere is of key importance for the physics of the lithosphere. Yet, it is probably the most uncertain parameter in geodynamics as experimental rock rheologies have to be extrapolated to geological conditions and as existing geophysical methods such as EET estimations make simplifying assumptions about the structure of the lithosphere. In many geologically interesting regions, such as the Alps, Andes or Himalaya, we actually have a significant amount of data already and as a result the geometry of the lithosphere is quite well constrained. Yet, knowing the geometry is only one part of the story, as we also need to have an accurate knowledge on the rheology and temperature structure of the lithosphere.

Here, we discuss a relatively new method that we developed over the last few years, which is called geodynamic inversion. The basic principle of the method is simple: we compile available geophysical data into a realistic $geometric$ model of the lithosphere and incorporate that into a thermo-mechanical numerical model of lithospheric deformation. In order to do so, we have to know the temperature structure, the density and the (nonlinear) rheological parameters for various parts of the lithosphere (upper crust, upper mantle, etc.). Rather than fixing these parameters we assume that they are all uncertain. This is used as a priori information to formulate a Bayesian inverse problem that employs topography, gravity, horizontal and vertical surface velocities to invert for the unknown material parameters and temperature structure. In order to test the general methodology, we first perform a geodynamic inversion of a synthetic forward model of intra-oceanic subduction with known parameters. This requires solving an inverse problem with 14–16 parameters, depending on whether temperature is assumed to be known or not. With the help of a massively parallel direct-search combined with a Markov Chain Monte Carlo method, solving the inverse problem becomes feasible. Results show that the rheological parameters and particularly the effective viscosity structure of the lithosphere can be reconstructed in a probabilistic sense. This also holds, with somewhat larger uncertainties, for the case where the temperature distribution is parameterized.

Next, we apply the method to a cross-section of the India–Asia collision system. In this case, the number of parameters is larger, which requires solving around 2 million forward models. The resulting models fit the horizontal and vertical GPS data, the topography and the Bouguer anomalies within their respective uncertainty bounds, and show that the Indian mantle lithosphere must have a high viscosity. Results for the Tibetan plateau are less clear, and both models with a weak Asian mantle lithosphere and with a weak Asian lower crust fit the data nearly equally well. The exponential volume of the upper mantle is well constrained in our inversion to be $22 \pm 2 \times 10^{-6}$ m^3/mol.

Finally, we discuss results of a full 3D geodynamic inversion of the whole India-Asia collision zone.