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Transdimensional Bayesian Thermochemical Joint Inversion of Seismic, Gravity and Surface Elevation Data

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Summary

We introduce a transdimensional probabilistic inversion algorithm in which seismic traveltime, gravity and surface elevation data are inverted for thermochemical parameters of the crystalline crust.

Wide-angle seismic and gravity data are among the most commonly used sources of information about the crystalline crust and the uppermost mantle. Large uncertainties are inherent to both geophysical inversion of these data and to (quantitative) interpretation of the inverted velocity/density models in terms of parameters of geological interest – chemical composition, structure and thermodynamic state of the rocks. To allow for a comprehensive quantification of these uncertainties, we develop a Bayesian inversion framework in which geophysical data are inverted directly for chemical and thermodynamic parameters.

Similar inversion schemes have been developed previously for the mantle; the case of the crust, however, is complicated by a more heterogeneous composition and the lack of thermochemical equilibrium in large portions of the shallow crust. Primary unknowns of our inverse problem are percentages of oxides of the major petrogenic elements and H_2O. Forward problem is solved as follows: 1) Temperature (T) and pressure (P) fields are computed. 2) Using Perple_X software, mineral assemblage, stable at given chemical composition and P-T, is computed, providing two elastic moduli (Voigt–Reuss–Hill average over the phases) and density of the rock. To account for metastability, temperature of the equilibrium is treated as an additional unknown of the inversion, while physical properties are computed at the in-situ P-T. 3) Once the seismic velocities and density have been computed in the model domain, associated geophysical data are predicted. This approach allows for mapping the diversity of lithologies representative of the crystalline crust to the amounts of several oxides and the equilibrium temperature, and for consistent joint inversion of multiple data types.

Currently, we consider a 2D case and use first-arrival traveltimes and gravity data; to complement gravity and constrain the absolute values of density, we also invert surface elevation through modeling isostatic compensation. Integration of other data types, such as S-waves attributes and heat flow, is straightforward. Sediments are effectively excluded from the inversion by fixing their velocity from tomography and predicting their density via a Gardner-type relation.

To reduce the dimension of the model space and to regularize the inversion, we adapt transdimensional framework similar to previous developments in seismic tomography: the crust is parameterized by sparse nodes, number and positions of which are unknown. Such parsimonious model parameterization is especially important in view of the ray coverage typical for seismic refraction experiments. The composition is defined at the nodes, and their envelope defines the basement surface and the Moho. Thermochemical modeling is performed at the nodes, and predicted physical properties are then linearly interpolated within the crustal domain.

The posterior probability density function (PDF) of the model parameters is generally multimodal, therefore to sample it comprehensively we use Markov chain Monte Carlo with Parallel Tempering, which is well suited for massively parallel computing. We show that Gaussian mixture model can be used to analyze the sampled multimodal PDF.

As a case study for benchmarking purposes, we use a synthetic model based on a wide-angle seismic profile in the Porcupine Basin (North-East Atlantic). Analysis of the posterior PDF suggests that dramatic crustal thinning and mantle serpentinization conjectured in the center of the Porcupine Basin, as well as composition of the upper crust in the margins, should be well constrained by the available seismic data, satellite gravity and bathymetry.