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Constraining effective rheology through parallel joint geodynamic inversion

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ABSTRACT

The dynamics of crust and lithosphere is to a large extent controlled by its effective viscosity. Unfortunately, extrapolation of laboratory experiments indicates that viscosity is likely to vary over many orders of magnitude. Additional methods are thus required to constrain the effective viscosity of the present-day lithosphere using more direct geophysical observations.

Here we discuss a method, which couples 3D geodynamic models with observations (surface velocities and gravity anomalies) and with a Bayesian inversion scheme on massively parallel high performance computers.

We illustrate that the basic principle of a joint geodynamic and gravity inversion works well with a simple analytical example. In a next step, we test our approach using a synthetic 3D model of salt tectonics with erosion and sedimentation, and check how much noise conditions, model resolution, and sparse data coverage affect the resolving power of the method. Results show that it is possible to constrain the effective viscosity and density of layers that contribute to the large-scale dynamics, provided that those layers are numerically well resolved. The properties of thin layers that do not contribute much to the overall dynamics cannot be constrained, but noise or sparse data sampling does not significantly affect the inversion results.

This thus illustrates that a joint geodynamic and gravity inversion is a potentially powerful method to constrain the dynamics of the crust and lithosphere. Having better constraints on the structure of the present-day crust and lithosphere will help to narrow the parameter space for models that aim to unravel lithosphere dynamics on a geological time scale.

1. Introduction

Arguably, one of the most uncertain parameters in geodynamic models is the rheology that is employed in the models (e.g., Burov, 2007). Typically, rheological parameters are estimated from laboratory experiments on small sample sizes which results in creep laws that have to be extrapolated over ten orders of magnitude to geological conditions. Whether this is correct or not is questionable and given that laboratory-based viscosity estimates vary widely between different rock types, it is desirable to have additional independent methods to constrain the viscosity of the Earth or parts of it.

Doing this is not new, and one of the first to look at the problem was Haskell (1935), who estimated the viscosity of the asthenosphere to be around 10^{21} Pa s based on postglacial rebound data. More recently, semi-analytical instantaneous mantle flow models were developed in which surface plate motions were imposed as boundary conditions with the aim to find appropriate radial viscosity distributions by comparing model predictions against observations such as stresses associated with post-glacial rebound (Hager and O'Connell, 1979, 1981). For a given a priori knowledge of mantle density distributions (e.g. seismic tomography), these geodynamic models were extended to also fit the geoid (Forte and Peltier, 1987; Ricard et al., 1984; Richards and Hager, 1984), which can be seen as the most reliable constraint on mass heterogeneities of the mantle apart from seismic tomography (Thoraval and Richards, 1997).

On a global scale, several authors explicitly performed inversions of a number of different observations (e.g. plate motions, geoid undulations, global free air gravity, seismic tomography, body wave traveltimes, post glacial rebound data and mineral physics) to constrain radial viscosity profiles. A variety of inversion methods has been applied, including Monte Carlo (Ricard et al., 1989), probabilistic approaches (Forte et al., 1991; Ricard and Wuming, 1991), evolutionary (Soldati et al., 2009) and more specific genetic algorithms (King, 1995), simplex methods (Steinberger and Calderwood, 2006) and Occam inversion approaches (Moucha et al., 2007; Simmons et al., 2006). The authors of these studies use spectral, semi-analytical codes, which efficiently solve the instantaneous mantle flow problem for a limited resolution, and in the case that there are no lateral viscosity variations. A slightly different approach that theoretically allows much higher resolution was followed by Bunge et al. (2003) (excluding lateral viscosity variations) and Liu and Gurnis (2008) (temperature-dependent viscosity structure) who use a fully numerical finite element mantle convection method in conjunction with the adjoint method (Talagrand and Courtier, 1987; Tarantola, 1984).

All of the geodynamic inverse approaches discussed so far focus on constraining the rheology of the mantle using flow models and large-

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scale first-order observations. Many of these models assume: (i) that the Earth is radially symmetric, meaning that viscosity only varies with depth and lateral viscosity variations are ignored (e.g. King, 1995; Simmons et al., 2006; Soldati et al., 2009; Steinberger and Calderwood, 2006); and (ii) that the Earth's surface has a prescribed horizontal plate-motion and no vertical motion, or that it is a free-slip boundary condition. Whereas these assumptions may hold for mantle scale convection models, where lateral variations in viscosity have a minor influence on the geoid (Moucha et al., 2007), it is questionable whether they are still correct for inferring upper mantle and lithospheric viscosity (Thoraval and Richards, 1997). This is supported by the results of Becker and Boschi (2002), who find minor agreement between seismic tomography and semi-analytic geodynamic models for intermediate wavelengths, mainly because subducting slabs are not resolved. Subducting slabs are, however, the major driving-force of plate-tectonics (Bercovici, 2003; Lithgow Bertelloni and Richards, 1998) even though the dynamics and the rheology of slabs are not perfectly understood (Becker and Faccenna, 2009). Recent findings also show that subduction dynamics is strongly affected by the type of upper boundary condition (e.g. Kaus et al., 2010), and Crameri et al. (2012a) demonstrate that a free surface boundary condition in combination with a sufficiently large viscosity contrast between slab and surrounding mantle is required to obtain asymmetric subducting plates in self-consistent spherical models of mantle convection. On a lithospheric-scale a free surface provides a potential driving force of tectonic processes, through lateral variations in the gravitational potential energy, and many numerical codes of lithosphere dynamics therefore include this effect (e.g. Fullsack, 1995; Gerya and Yuen, 2007; Kaus et al., 2008; Popov and Sobolev, 2008).

Compared to global mantle flow models with a radial viscosity variation only, the presence of strong lateral variations in viscosity and a free surface strongly increases the computational demands of the forward models. Yet, on a lithospheric scale, the above mentioned complexities are likely to be important. Therefore, fully three dimensional models of forward models of lithospheric deformation have only appeared very recently, and nearly all studies perform parameter studies by manually changing input parameters to get some insights in the physics of the system (Li et al., 2013; Popov et al., 2012) or to constrain the rheology of slabs (e.g. Alisic et al., 2010; Moresi and Gurnis, 1996).

There are a few numerical studies on lithospheric or crustal scale which aim to infer best-fit rheologies. Burov et al. (1999) used a 2D numerical model to distinguish which rheological and density structures are dynamically most feasible for a cross-section through the Alps. Kaus et al. (2009) made an attempt to fit 2D models to observed GPS data and earthquake focal mechanisms in southern Taiwan. Yet, both studies changed model parameters manually. Boschetti and Moresi (2001) and Wijns et al. (2003) partly automatize this approach, by using a genetic algorithm to vary the model parameters, but they evaluate the mismatch of the models interactively.

Guiding the parameter search in a subjective manner is a possibility to reduce the number of required geodynamic forward models, but it might become infeasible for an increasing complexity of the model, i.e. a larger parameter space. Progress in computing power and in software to model 3D lithospheric deformation has been quite significant in recent years such that tackling the inverse approach, in which we determine optimal model parameters in an automated fashion, is now becoming feasible. Recently, Afonso et al. (2013a,b) used such an automated probabilistic inverse approach with a number of geophysical observables as constraints and thermal, seismological and petrological models as forward models, but they employed kinematic rather than dynamic models.

In fact, a large number of inverse modeling approaches exist and many of the sub-disciplines in geophysics routinely use, for example, descend-based algorithms. The problem with those algorithms is that they can be trapped in local minima in the parameter space, and that they give no information about the uncertainty of the “best-fit” model parameters which is arguably at least as interesting as the optimal parameters themselves. For that reason, we use a Monte Carlo based approach which was initially introduced in geophysics by Keilis Borok and Yanovskaja (1967) and Press (1968, 1970) for seismological inversion procedures and is still widely used in seismology. Particularly, the neighbourhood algorithm (NA, Sambridge, 1999a) is a popular method. It combines the geometrical concepts of Voronoi diagrams (Voronoï, 1908) with a Monte Carlo ensemble-based search approach (Sambridge, 1999a). The search process is self-adaptive depending on the properties of all previously created models (Sambridge, 1999a). Similar to genetic algorithms the sampling can be focused on multiple regions of the parameter space and can therefore account for ambiguities and local minima, but also in high dimensional parameter spaces (Sambridge and Mosegaard, 2002).

Although the NA can be used as a global optimization algorithm (Mosegaard and Sambridge, 2002), it was developed to efficiently sample a parameter space. As Sambridge (1999b) shows, the resulting model ensemble, i.e. all evaluations of the forward problem, can be used to estimate the posterior probability density function (PPD) as function a of model parameters. The combined approach can therefore be seen as an Bayesian approach (e.g. Tarantola and Valette, 1982) to solve high-dimensional nonlinear inverse problems.

Despite the fact that the Stokes problem is a computationally demanding task and seem to be not feasible for a largely integrated probabilistic approach, we do expect a complex nonlinear relationship between rheological model parameters and data, and we cannot be sure that a single global minima exist. Moreover, the dimension of the parameter space grows rapidly with the number of geological units of the model and at least some non-uniqueness is likely to exist as the gravity problem is a well known non-unique problem. A Monte Carlo based approach thus seems a natural choice to perform geodynamic inverse approach, although the major drawback of the method is that it require a large amount of forward models.

We employ the NA as it is more efficient than a standard Monte Carlo approach and as it suits itself well for parallelization (Rickwood and Sambridge, 2006). Yet in order to perform parallel inversions in combination with parallel forward models (in which the solution time of different forward models can vary dramatically), it was necessary to develop a completely new parallel layout for the NA including a fully non-blocking architecture and explicit MPI-buffer (Message Passing Interface) management.

In this paper we aim to demonstrate the potential of joint geodynamic inversions to constrain effective rheologies. We show that a Monte Carlo based, probabilistic inversion is a feasible method to approach geodynamic inverse problems with numerical three-dimensional models, which are computed in parallel. In general, this approach is scalable and applicable to either small scale dynamics or lithosphere scales. However, involving the entire lithosphere requires power-law rheology, and thus a large parameter space. Here, we focus on synthetic models with Newtonian rheology, for which we choose a salt-tectonics model scenario to keep the number of model parameters limited, although it has geometric complexities to benchmark the inverse approach.

In the following sections, we first discuss an analytical experiment to demonstrate that theoretically, performing an inversion with a geodynamic model helps to reduce ambiguities of the inverse problem. Next, the general methodology is described including the forward problems that have to be solved. Finally, we employ synthetic three-dimensional salt-tectonics models to conduct a detailed feasibility study of the methodology, which includes how model resolution, model geometry and different constraints on the data affect the inversion results. Details on the new parallel implementation of the NA and derivations for the analytical experiment are described in the appendix.