Inference of mantle viscosity from geodynamic data: a genetic algorithm inversion method

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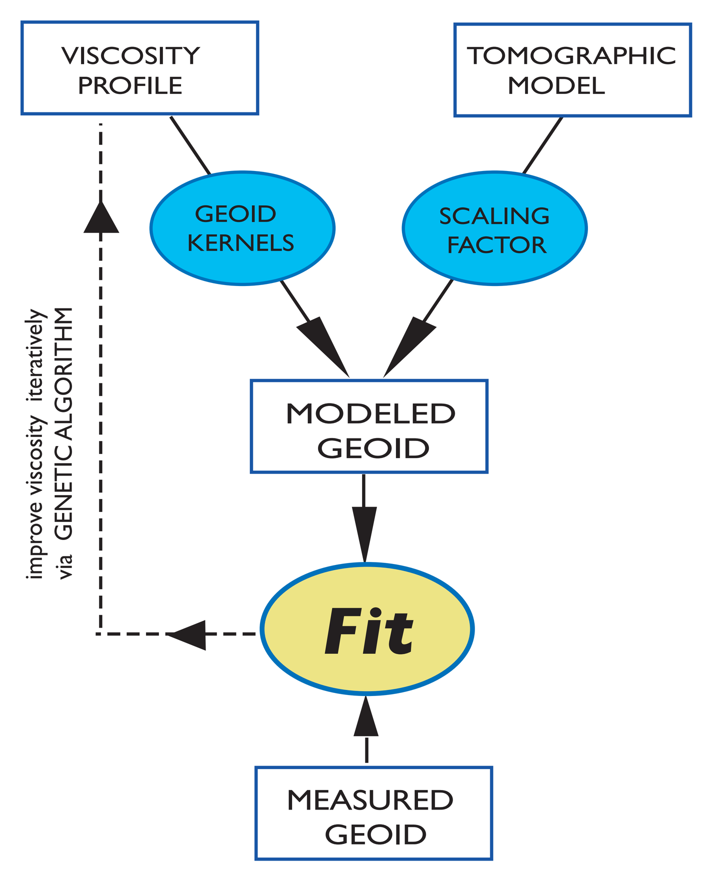
Relative radial variations in the viscosity of the mantle can in principle be determined from surface gravity measurements: an analytical theory of mantle flow provides geoid kernels relating density maps and viscosity profiles to the Earth's gravity field. A scaled global tomographic map of seismic wave speeds can be used as an estimate of the Earth's density distribution. A linear inverse problem can then be set up, with gravity observations as data, and the viscosity profile as the unknown. This method has the limit of constraining only the ratios between viscosity values at the different depths, rather than the viscosity values themselves. Additionally, the solution to this inverse problem is strongly non-unique. Last, seismic velocities in the mantle are known only approximately, and establishing an appropriate velocity-to-density scaling for the mantle is, likewise, not trivial. We attempt to account for non-uniqueness in the inverse problem by exploring the solution space, formed of all possible radial profiles of Earth viscosity, by means of a non-deterministic global optimization method: the genetic algorithm. For each sampled point of the solution space, a forward calculation is conducted to determine a map of gravity anomalies, and its similarity to GRACE is then measured; the procedure is iterated to convergence, according to genetic algorithm criteria.

Genetic Algorithm



Synthetic Tests. Nonuniqueness of viscosity profile

We randomly generate an "input" model of mantle viscosity, consisting of a given number n of uniform layers, and use our mantle flow formalism to predict a gravity anomaly map from it. We use the resulting, "synthetic" gravity anomaly map as the database to be inverted via the genetic algorithm.

We show here the results of 60 such synthetic tests. We conducted 10 synthetic tests with 2-layer viscosity models, 10 with 4-layer models, and so on with 6-, 8-, 10- and 12-layer models. These tests indicate that the nonuniqueness of the problem quickly grows with the number of inversion parameters; the chance of converging to a wrong solution is high, if the unknown viscosity profile is parameterized in terms of >4 uniform layers.

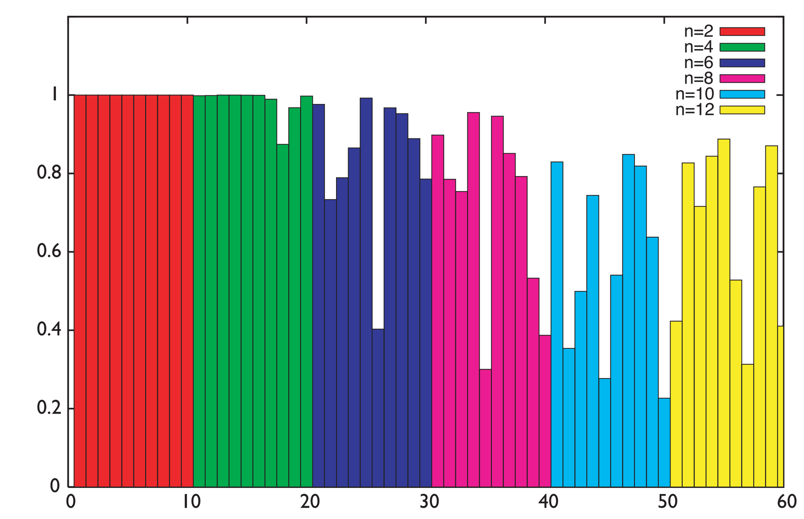


Fig.1 Fit of output to input model (maximum is 1)

Inversions of GRACE gravity data

1 We run the GA with a population size (nr. of models in each iteration) of 100 for 500 iterations (50.000 forward computations). Due to its stochastic nature, different runs of the GA inversion yield slightly varying results, but the important features are robust between different runs. The same holds true for the fit of the best models.

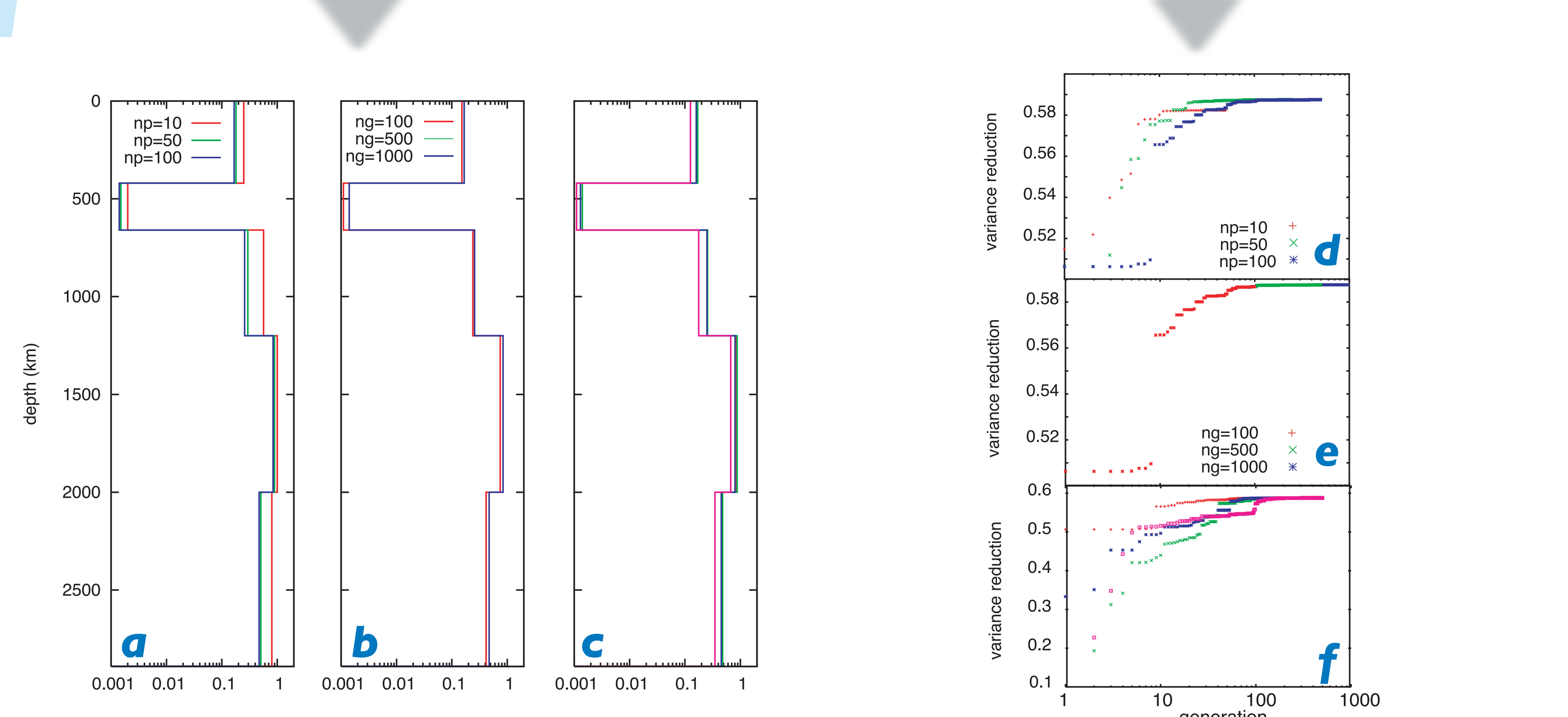


Fig.2 Best model from runs (starting model: S20RTS) with different population size (a), number of generations (b), and initial seed (c). Only relative variations can be inferred from these models. Fit of best model as a function of generation nr., from inversions a, b, and c (e,d, and f, respectively).

2 We invert gravity anomalies from GRACE (Tapley et al., 2005) starting from the shear wave model S20RTS (Ritsema et al., 1999) and assuming a density-to-velocity scaling as in Figure 4b (red line). We repeat the experiment varying the number of layers with uniform viscosity.

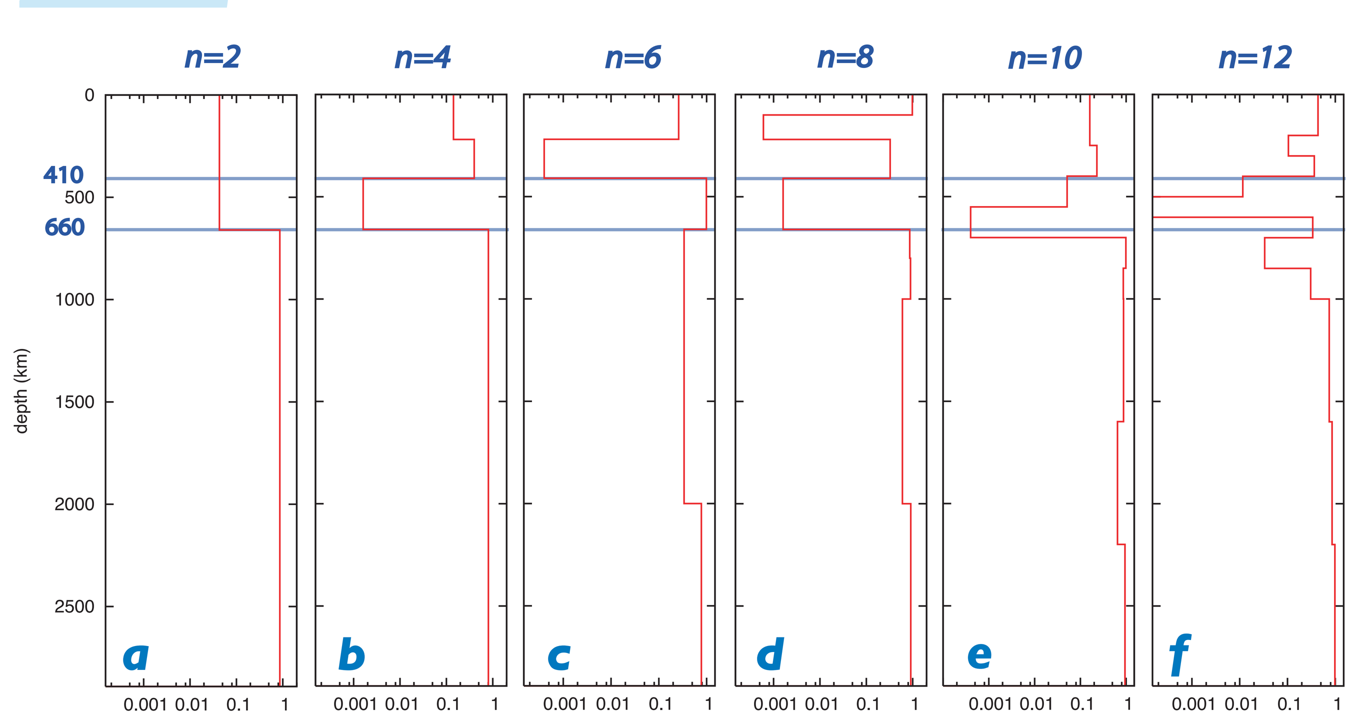


Fig.3 Bestfitting mantle viscosity models resulting from inversions with different number of layers. Only relative variations can be inferred from these models.

3 We invert GRACE data assuming different density structures (obtained applying the appropriate scaling factors to seismic shear-wave models S20RTS, TRP246, SPRD6).

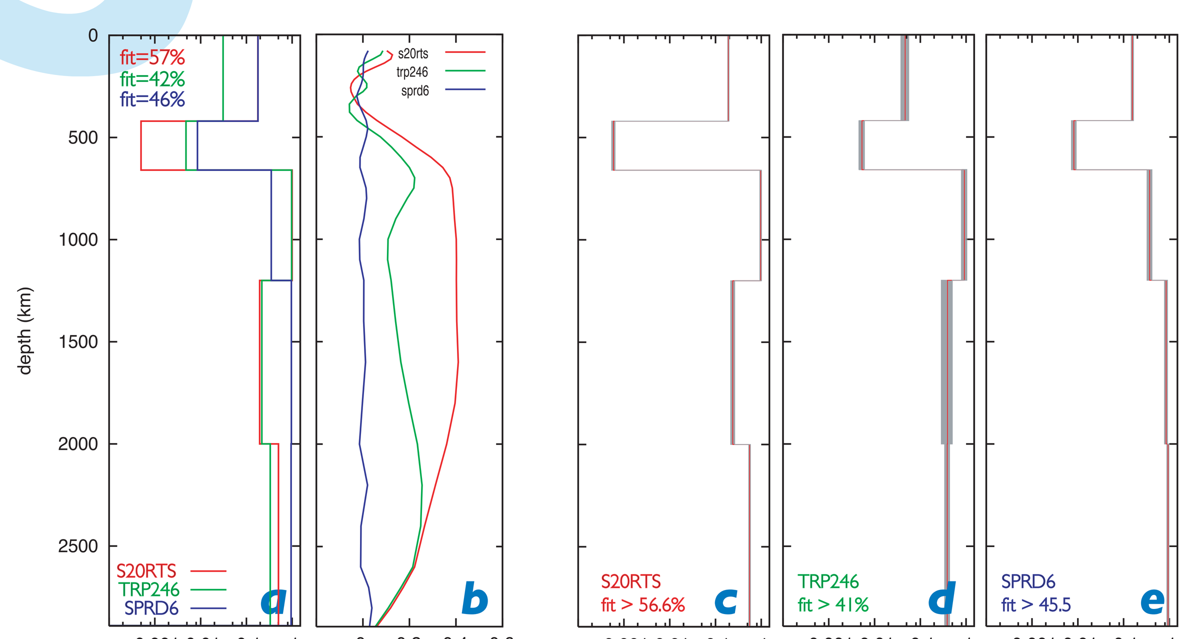


Fig.4 Best viscosity profile (a) obtained on the basis of some v_s models, assuming $n=5$ and converting velocity anomalies to density anomalies via the scaling factors in (b). Frames (c-d-e) show average viscosity and standard deviation of models with fit greater than a given threshold.

To analyze the range of variability of these viscosity models, we plot for the case S20RTS the 5 values of viscosity (one for each layer) for all the models with fit better than 30% (a),40% (b), 50% (c). We see that also models with low fit to GRACE data are characterized by low viscosity in the second layer (420-660 km) i.e. by low viscosity transition zone.

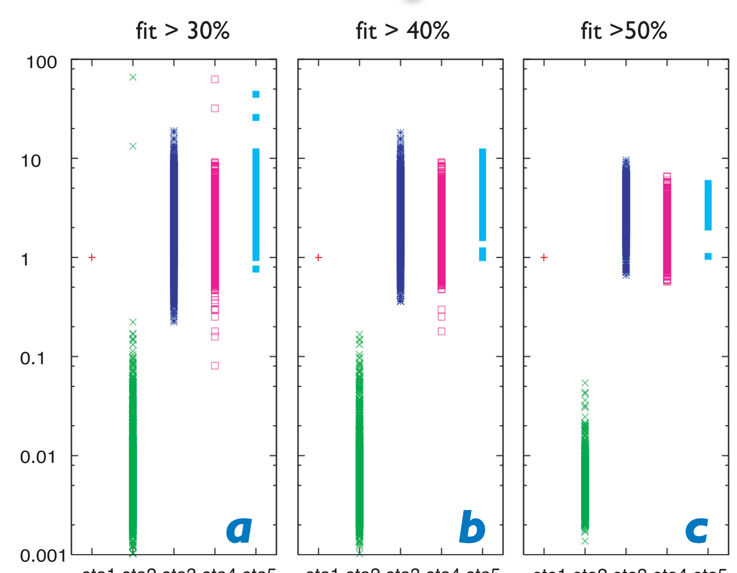


Fig.5 Range of variability of viscosity of the 5 layers (normalized to eta1)

4 Results based on tomographic models like S20RTS depend on a scaling factor used to convert velocity to density (see Fig.6a). Decorrelation between estimates of velocity and density structure has been observed, however, which would invalidate this approach. As a possible alternative, we replaced S20RTS with density models also determined from seismic (normal-mode) data, namely TRP246 (Trampert et al., 2004) and SPRD6 (Ishii and Tromp, 1999). Using either of these models as a starting point for our inversions, the fit of solution viscosity models to GRACE turned out to decrease. This is an unexpected result.

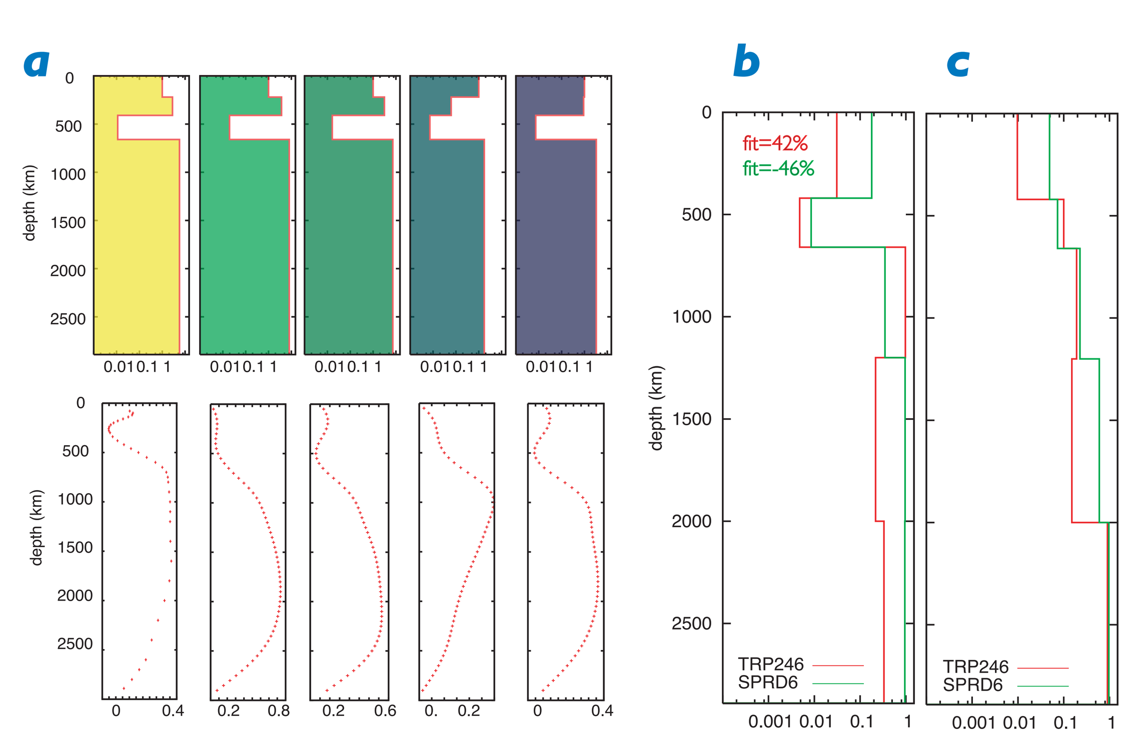


Fig.6 Mantle viscosity models from inversion of GRACE data ($n=4$) with different scaling factors (a). Best viscosity profiles ($n=5$) based on shear-wave models (b) and density models (c).

References

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PIKAIA (a Fortran77 subroutine based on a GA) is avaliable at http://www.hao.ucar.edu/Public/models/pikaia/pikaia.html