Estimating the stresses within the lithosphere: parameter check with applications to the African Plate

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Motivation

Several mechanisms control the state of stress within plates on Earth. The list is rather long, but well known and includes ridge push, mantle drag, stresses invoked by lateral variations of lithospheric density structure and subduction processes. We attempt to quantify the influence of these mechanisms and to construct a reliable model to understand modern and palaeo-stresses using the African plate (TAP) as an example.

The base model

Constructing the base model lithosphere of TAP we follow Steinberger et al. (2001). We first consider the model lithosphere consisting of two layers (water and lithospheric mantle). Density of the mantle is defined by the half-space cooling model and the age of the ocean floor (with flattening at 100 My). Then we put the model crust of certain thickness on the top of lithosphetic mantle and balance the system isostatically. The sea level is defined by correspondence of the model and observed topography in average over TAP.

Combining data on topography, age of ocean floor (fig. 1) and global model for crust structure, CRUST2 (Bassin et al., 2000), we are able to compute the gravitational potential energy (GPE) for the entire TAP. GPE, proportional to the double integration of the density profile through thickness of the model lithosphere, determines the forces rising from lateral density heterogeneities within lithosphere. In particular, GPE wihin our models accounts for push from the mid-oceanic ridges surrounding TAP and stresses rising from the crustal thickness changes.

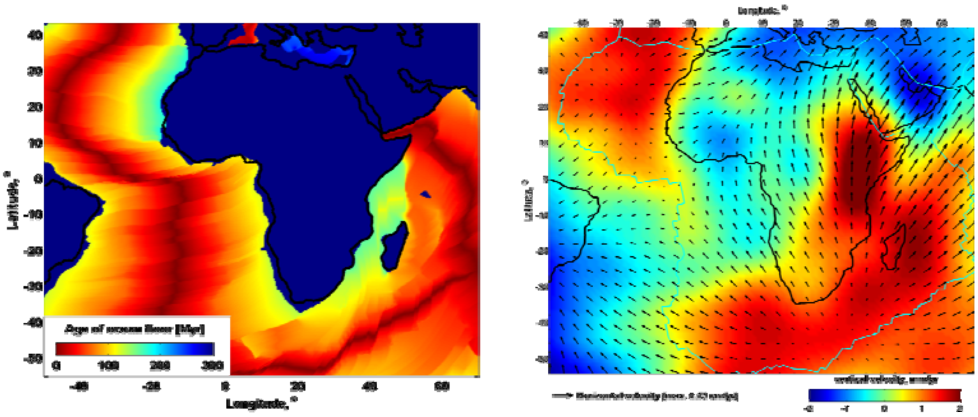

Figure 1. Apart from topographic data for TAP, we use the data on the ocean age (Muller et al., 2008) and mantle flow field (for models within series B and C) derived from the mantle convection models (Steinberger et al, in preparation). Cyan line on the left panel limits the African Plate (TAP) and black line borders continental part.

The finite-element based suite ProShell was utilized to calculate stresses using the real, non-planar geometry of TAP. The equations for integrated over depth of the lithosphere (from the surface topography down to level of isostatic compensation) stresses and moments for each element within finite-element formulation of the problem are constructed first within the local system of coordinates associated with each element, the equations then transformed into the global system of coordinate to construct the global system of governing equations. The system was then solved to find stresses, displacements, and rotations for each element (Kwon and Bang, 2000).

Models testing

The modeled results are tested and iterated to match the observed stress pattern recorded or derived from observations. We combined several studies to complete set of observational data. That includes non-seismic data from WSM (Heidbach et al., 2008), compilation of the field observation (Bird et al., 2006), and integrated inversion of focal mechanism data (Delvaux and Barth, 2010). Figure 2 presents the distribution of data on stress regimes and orientation of most compressive mean stress. The data is rather sparse, which prevents us from confident testing of significant portions of TAP, particularly eastern and central Africa.

We adopted several numerical characteristics describing proximity of model results and observations. (1) The average misfit angle presents simply the mean difference in orientations. (2) The observational data, however, has different quality (A-C) and thus the misfit should have different weight. We therefore introduce the angle fitting factor, which present the percentage of the number of observations which fits to model results within 90% confidence interval of the data. (3) Regime fitting factor illustrates the percentage of the successful match of observed and modeled regimes (we adopted quantitative measure of regimes described in Delvaux and Barth, 2010).

Figure 3 presents the fitting characteristics for approximately 700 model runs. The figure also shows that the results may fall below limit provided by random average.

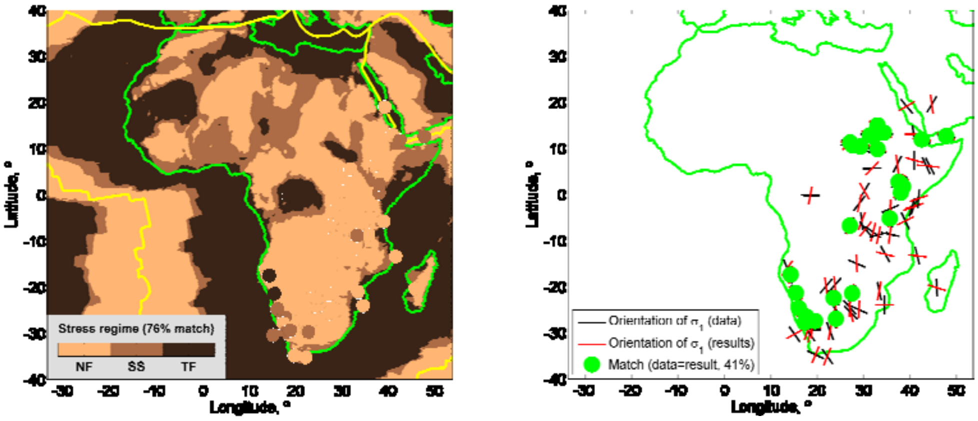

Figure 2. Results for model 3 represents typical distribution of the stress regimes with TAP (left) and orientation of maximal compressive stresses (marked as σ1 on the right panel). The results of the model are compared to observations (see text for description of data). The data represented by black markers on the left panel. Green discs cover the results with orientation within 90% confidence interval of observations on the right panel.

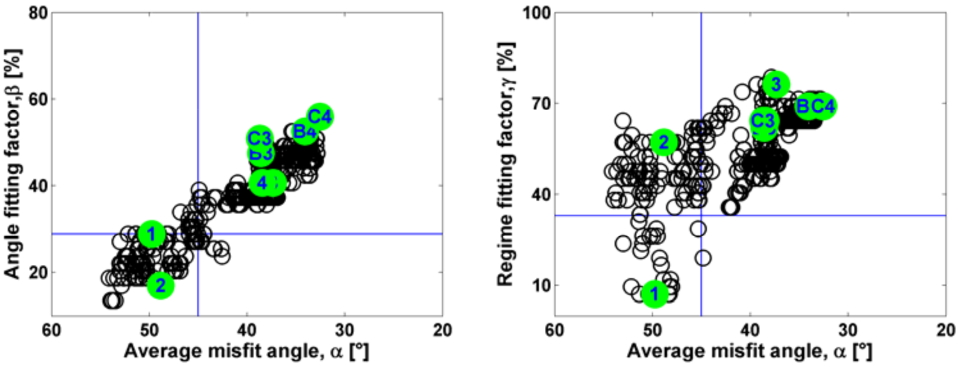

Figure 3. Illustration of variation of fitting parameters for different sets of numerical experiments. All circles represent results for different sets of parameters variations, circles filled with green represent successful representatives of each set (marker 4 covers marker for model 3 on left panel, marker C3 covers B3 and marker C4 covers C3 on the right panel). See text for description of the numerical experiments series and definitions of fitting parameters. Blue lines present random average values, the results that fall below or left from these lines represent light anti-correlation with observations.

Model results and parameters sensitivity studies

The results of base model (fig. 3, model 1) compares poorly with observations. This model presents the simplest combination of simple models and widely available data, and thus may be considered as greatly oversimplified.

One of the most significant simplifications of the model 1 is simple half-space cooling model for mantle lithosphere, which assumes that the top of the mantle lithosphere (Moho) has constant temperature. That is clear oversimplification for model of TAP, which includes mid-oceanic ridges and thick continents. The model 2 (fig. 3) assumes that the Moho temperature is proportional to the thickness of the crust above. This model, however, does not show significant improvement while compared to model 1 for variety of the coefficients of proportionality between crustal thickness and Moho temperature, ΔT.

Two previous models are based on the prescribed thickness of the crust (given by CRUST2) and model topography does not match exactly the observed topography of TAP. In model 3 we assume that the CRUST2 model is inaccurate and we stretched the thickness of the model crust so that after isostatical adjustment observed and model topography match exactly. Varying ΔT within model 3 we found that the optimal value for constant ΔT within TAP and improved significantly the match between model results and observation.

The density of mantle within models 1-3 depends only on thermal state of mantle, which in turn depends on the age and/or crustal thickness. The observations, however, point out existence of significant compositional (and thus, density) variations of the mantle beneath TAP. In model 4 we assume that part of mismatch between CRUST2-based topography and observed topography is associated with mantle density variations. That was emulated by variations of effective thermal situation, simply by assuming ΔT variable laterally. The model 4 does not show significant improvement compared to model 3.

In addition to the stresses directly resulted from GPE, we considered several additional complications of the model. In series B we considered basal drag caused by sub-mantle flow. Figure 1 (right) presents the example of the mantle flow field derived from mantle convection model. We couple this flow filed to models 3 and 4 (using coupling terms in equations similar to, e.g., Bird et al., 2006) and vary parameters of coupling. Whereas the model B3 shows little improvement compared to model 3, the basal drag with reasonable parameters of coupling improves significantly model with variable density of the lithospheric mantle (model 4 vs. model B4).

All the models considered above are based on uniform rheological properties of TAP. This is very strong simplifying assumption. In model series C we considered simplest variations of rheological properties, assigning weakening along mid-oceanic ridges. The results improve (model C4) when weakening related to young age of the ocean floor is by up to two orders of magnitude.

The models presented on figs. 2 and 3 are based on the structure of CRUST2 model for crust (Bassin et al., 2000). We also tested several other models based on different approaches, such as global density model within 3SMAC (Nataf and Ricard, 1996), Moho map from surface wave tomography of Africa (Pasyanos and Nyblade, 2007), and the crustal structure calculated from simple gravity inversion. The crustal structure inferred from the gravity inversion shows good potential in explaining stress patterns of TAP.

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