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Lithospheric stress and uppermantle dynamics in mainland China due to mantle flow based on combination of global- and regional-scale seismic tomography

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ABSTRACT

In order to explore the importance of mantle flow to lithospheric stress field in mainland China, seismic tomography_based mantle flow models are used to predict the most compressive principal horizontal stress directions (MCPHSDs). Considered that regional-scale seismic tomography models have higher horizontal resolution to map the mantle structure, while global-scale models can present the information out of the imaging domains of regional-scale models although this information has relatively poor horizontal resolution, the combined global- and regional-scale seismic tomography_based mantle flow models (hereafter called combined models) are mainly used in this paper. After the comparison of the observed and our predicted MCPHSDs, it is suggested that (1) a combined model, compared with a only global-scale seismic tomography_based model, could improve greatly the predictions in some regions of mainland China such as Sichuan-Yunnan, South China and North China blocks; (2) the mantle flow model driven by both plate motions and mantle density heterogeneity (hereafter called plate-density-driven model), compared with the flow model driven only by mantle density heterogeneity (hereafter called density-driven model), has much better predictions in the eastern China; (3) the presence of density variations above 250 km could better dramatically the predictions in the eastern China; and (4) sublithospheric mantle flow causes the lithosphere under compression in mainland China, and plays an important role in forming the lithospheric stress in Alashan, Qaidam, western Tibetan and eastern Tarim blocks as well as the east of the eastern China.

1. Introduction

The state of lithospheric stress has been one of the important issues in geosciences because it is of significance to earthquake occurrence and tectonic deformation. It could be due to both local forces such as stress concentrations due to structure heterogeneities, crustal loading and unloading, asthenospheric thermal anomalies (e.g., Bott and Dean, 1972; Artyuskov, 1973; Fleitout and Froidevaux, 1982; Sonder, 1990; Assumpcao, 1992) and regional forces such as ridge-push, negative buoyancy of the subducted slab, continental collision force, viscous shear forces at the base of the lithosphere due to mantle flow and trench suction or buoyancy due to thick crust and/or thinned lithosphere (e.g., Molnar and Deng, 1984; Froidevaux and Isacks, 1984; Adams and Bell, 1991; Richardson and Reding, 1991; Zoback and Zoback, 1991; Stefanick and Jurdy, 1992; Xu et al., 1992). Mainland China is located in the east of Eurasian plate and has complex geotectonic settings. Its stress field has thought to be dominated by the strong NE-SW or NNE-SSW compressive stress due to India-Eurasian collision to its southwest in the western China bounded by about 100°E and the ENE-WSW or WNW-ESE compressive stress due to subduction of Pacific plate to its east and subduction of Philippine plate to its southeast (e.g., Molnar and Tapponier, 1975; Molnar and Deng, 1984; England and Houseman, 1989; Xu et al., 1992). A number of studies have agreed with this opinion, but yet some studies, even though relatively limited, have shown that the viscous shear forces at the base of the lithosphere due to mantle flow is a possible important cause of lithospheric stress in the regions far from the collision and subduction belts. For instance, Fu and Huang (1992) evaluated the lithospheric basal shear stress due to geopotential_based mantle flow and the force system along plate boundaries, and then concluded that the former has almost equal importance of the latter to form the lithospheric stress in China.

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Steinberger et al. (2001) obtained a good match to the observations from World Stress Map (Bird and Li, 1996) in the eastern China based on a global-scale seismic tomography_based mantle flow model. However, their mantle flow models do not consider lateral viscosity variations (LVVs) and heat transfer. LVVs could be up to 2–4 orders in the upper and lower mantle and 1–2 orders in the middle mantle (Ranalli, 2001) and has probably great effects on mantle flow patterns, phase change dynamics, the earth's thermal structure and plate dynamics (e.g., Oliver and Booker, 1983; Zhong and Gurnis, 1994; Stemmer et al., 2006; Yoshida and Nakakuki, 2009), and then on geoid anomaly and topography (e.g., Richards and Hager, 1989; Bunge and Richards, 1996; Wang and Wu, 2006). Heat energy is huge in the earth's interior and transferred mainly by mantle flow (e.g., Jaupart et al., 2015). Therefore, consideration of LVVs and heat transfer in a mantle flow model should be more realistic for our planet and is expected to improve the predictions of MCPHSDs.

In this paper, seismic tomography_based mantle flow model by Steinberger et al. (2001) is applied to predict MCPHSDs in mainland China. In addition to LVVs and heat transfer, considered that regional-scale seismic models have higher horizontal resolution in mapping the mantle structure and global-scale models can present the information out of the imaging domains of regional-scale models although this information has relatively poor horizontal resolution, they are combined to derive mantle density heterogeneities and then lateral temperature variations (LTVs) in this study. Our models and also their predictions are obviously improved compared with those of Steinberger et al. (2001) (Comparisons in Section 3.1). As a result, our results are believed to be more helpful to probe the importance of mantle flow to lithospheric stress and deformation in mainland China and also provide the more reasonable constraints on simulations of crustal dynamics (e.g., Molnar and Tapponier, 1975; Ichimura et al., 2013).

2. Model setup

In order to determine the lithospheric stress and deformation in mainland China due to mantle flow, the 3-D spherical finite element code for mantle convection, CitcomS (Zhong et al., 2000; Tan et al., 2006), is used. The code solves for an incompressible Newtonian fluid within a spherical mantle shell and has been benchmarked extensively (e.g., Moresi et al., 1996; Zhong et al., 2000, 2008). Our models, following Zhong et al. (2008), adopt the Boussinesq approximation for an incompressible fluid, assume entirely basal heating (*i.e.*, no internal heat generation) and constant material properties except for viscosity (*i.e.*, no compositional heterogeneities), and include the effects of self-gravitation. Table 1 lists the basic model parameters used in this study.

2.1. Mesh parameters

Our study area covers the range of 35° (20–55°N) and 60° (74–134°E) in latitude × longitude (Fig. 1). Our models adopt different meshes for different goals, but they cover the same physical domain of 180° (−90°S to 90°N), 360° (−180°W to 180°E) and 2900 km in latitude, longitude and depth. For the determination of the most suitable depth-dependent effective viscosity (Section 2.3) as well as global-scale seismic tomography model (Section 2.4.1), the mean mesh with 385 × 385 × 65 nodes in latitude × longitude × depth is adopted. For the determination of regional-scale seismic tomography model (Section 2.4.2) and our final computations, an irregular mesh both in depth and horizontal directions is adopted. The used mesh has 577 × 577 × 129 nodes in latitude × longitude × depth. It is arranged as the interval of 100 km from 0 to 100 km, 10 km from 100 km to 670 km, 20 km from 670 km to 1070 km and 36.6 km from 1070 km to 2900 km in depth, and has the grid resolution of 0.25° (in latitude) × 0.25° (in longitude) in the region of (10–60°N) × (65–145°E) and of ∼0.33 × ∼1.09° in the rest region in horizontal directions. Other meshes with higher horizontal grid resolutions of 0.15° × 0.15° and 0.2° × 0.2° in the region of (10–60°N) × (65–145°E) are also tested and it is suggested that there are little differences between their predictions.

Table 1
Summay of model parameters.

Parameter	Symbol	Value
Radius of the earth	R_E	6371 km
Gravitational acceleration	g	9.81 m s^{-2}
Reference mantle density	ρ_0	3340 kg m^{-3}
Reference mantle viscosity	η_0	10^{21} Pa s
Thermal diffusivity	κ	10^{-6} m^2 s^{-1}
Temperature contrast across the whole mantle	ΔT	3500 K
Surface temperature	T_s	273 K
Gas constant	R	8.31 J mol^{-1}

2.2. Rheology

Both depth- and temperature-dependent viscosity is used. The dimensionless form, following Huang and Zhong (2005) or Korenaga (2009), could be expressed as

$$(r,T) = (r)\exp\left(\frac{E}{T+T_0} - \frac{E}{1+T_0}\right) \tag{1}$$

where $\eta(r)$ is a depth-dependent effective viscosity and is normalized by reference mantle viscosity η_0, E is non-dimensional activation energy and is related to activation energy E^* as $E = E^*/(R\Delta T)$ with $E^* = 120$ kJ/mol (Watts and Zhong, 2000), $T = (T^* - T_s)/\Delta T$ and T^* is the dimensional temperature split up into laterally averaged part T_r which only depends on radius r and LTV δT, and $T_0 = T_s/\Delta T$. In the present paper, except for special explanation, LTVs are converted from thermally-induced density perturbations $\delta\rho$ (Section 2.4), and $\delta\rho$ are imposed to be zero above 250 km in order to ignore the effects of chemical heterogeneity in the "continental tectosphere" (e.g., Jordan, 1975, 1978; Shapiro et al., 1999; Forte and Perry, 2000) and are derived from anomalies of seismic velocity via a constant velocity-to-density conversion factor R_{ρ/V_s} or R_{ρ/V_p} (the subscripts s and p indicate S and P wave; hereinafter the same) below this depth because the maximum lithospheric thickness is thinner than 250 km in mainland China (Conrad and Lithgow-Bertelloni, 2006; Fig. 1). The presence of δT leads to large amplitude LVVs which will be superimposed on the depth-dependent effective viscosity $\eta(r)$.

2.3. Determination of effective viscosity structure

An effective viscosity structure could be derived geodynamically from many kinds of data (Fig. 2). In order to choose the most suitable effective viscosity structure used in the present study, the observed large-scale geoid anomalies and these predicted by global-scale mantle flow models under different effective viscosity structures shown in Fig. 2 are compared. The flow model is based on an updated seismic tomography model of Grand (2002), TX2011 (the reason of selecting this model presented in Section 2.4.1), with free-slip top and bottom boundaries and the mean mesh with 385 × 385 × 65 nodes in latitude × longitude × depth (Model I). The observed geoid anomalies (Fig. 3a) are calculated from the isostatically corrected gravity anomalies of WGM2012 (Bonvalot et al., 2012; Balmino et al., 2011) based on EGM2008 (Pavlis et al., 2008) and are transferred from relative

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