Journal of Asian Earth Sciences 129 (2016) 1–12

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Full length Article

Towards sub-lithospheric stress determination from seismic Moho, topographic heights and GOCE data

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ARTICLE INFO

Article history:
Received 22 April 2016
Received in revised form 7 July 2016
Accepted 20 July 2016
Available online 21 July 2016

Keywords:
Regularisation
Tectonic boundaries
Satellite gradiometry
Isostasy
Earthquakes
Stress function

ABSTRACT

Sub-lithospheric stresses can be estimated by analysis of gravity field measurements. Depending on the measured gravimetric quantity, different methods can be employed to estimate those sub-lithospheric stresses. Here, we further develop the Runcorn's theory for estimation of mantle stresses (1967) such that a Moho model and full topographic information are used to recover the function from which the stress can be computed by taking derivatives northwards and eastwards. We develop new integral equations for such a purpose and recover this function by solving those integral equations locally over the Indo-Pak (India-Pakistan) region from (1) a gravimetric Moho model computed from the SRTM (Shuttle Radar Topography Mission) and the Earth gravity model EGM2008, (2) SRTM and the seismic Moho model of CRUST1.0 and (3) data and measurements of the GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission. Finally, we perform a joint inversion of seismic and GOCE data for the same purpose. The numerical results show that the use of a seismic Moho model recovers information about the stress field which is not seen in the results derived from a gravimetric Moho model. A combination of the seismic Moho model, SRTM and GOCE yields a better stress field than that of either the seismic and/or gravimetric data alone. The magnitudes of the sub-lithospheric stress are computed from the shear stress components over the area and good agreement is seen between the recovered combined stress field, the regional tectonic boundaries and the seismicity of the World Stress Map 2008 database.

1. Introduction

The estimation of sub-lithospheric stress due to mantle convection is a challenging and important issue for the geoscience community. The primary goal is to extract sub-surface information from seismic and gravity measurements. The gravity field of the Earth is a signature of the Earth's interior structures and it can be used for studying stresses such as those due to mantle convection, which is important for geophysical interpretation of the seismicity, volcanism, kimberlite magmatism, ore concentration and magnetic and tectonic features (Liu, 1977). The implication of gravimetric, seismic and gradiometric data for the purpose of stress field recovery is a new topic addressed here.

The convection process inside the Earth's mantle results in plate motions and stresses the lithosphere above. This stress has a direct relation to the mantle convection pattern, viscosity and the physical and geometrical properties of the lithosphere and the mantle. Significant efforts have been made to improve convection models in order to advance our understanding of lithospheric stresses. Runcorn (1962, 1963, 1964) investigated mantle convection currents and their determination from satellite gravity measurements. Runcorn (1967) simplified the Navier-Stokes equation to determine the direct connection between the geoid and the sub-lithospheric stress due to mantle convection. He presented this stress field in terms of spherical harmonics (SHs) of the Earth's gravity field. McKenzie (1967) studied heat flow using gravity anomalies and concluded that the long wavelength harmonics of the external gravity field cannot be supported by the strength of the lithosphere. Waltzer (1970) presented a simple and symmetric model for the convection currents in the Earth's mantle by assuming that the mantle becomes more and more homogenous downward. Artyushkov (1973) studied the lithospheric stress caused by crustal thickness inhomogeneities. Marsh and Marsh (1976) investigated a two-dimensional mantle convection model based on the global gravity anomalies. Liu (1977) presented the convection pattern and stress system below the African plate and

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http://dx.doi.org/10.1016/j.jseaes.2016.07.024
1367-9120/

Liu (1978) performed a similar study over Asia. Later, Liu (1979) presented a theory about the sub-lithospheric stress concentration and its relation to the seismogenic model of the Tangshan earthquake of 1976. Lux et al. (1979) studied the movements of the lithospheric plates due to mantle convection. Liu (1980) studied the convection-generated stress field and intra-plate volcanism while Runcorn (1980) proposed that the geoid determined by satellite observations is a direct consequence of convective upwelling and downward currents in the mantle. McNutt (1980) implemented the regional gravity field for studying stress in the crust and upper mantle and determined that the stresses implied in the regional compensation scheme are an order of magnitude larger than those corresponding to the local stress. Jacoby and Seidler (1981) studied the relation between plate kinematics and the gravity field. Hager and O'Connell (1981) presented a simple global model of plate dynamics. Dahlen (1982) investigated isostatic geoid anomalies on the sphere, based on the Haxby and Turcotte (1978) results, and hypothesised that the stress in the crust influences the long wavelength structure of the geoid. Huang and Fu (1982) and Fu and Huang (1983) used the satellite-derived gravitational harmonics to model the global stress field in the lithosphere based on an elastic earth model and solutions of the elastic equations in spherical regions by Love (1944). Hager (1983) studied global isostatic geoid anomalies for plate and boundary layer models of the lithosphere. Souriau and Souriau (1983) investigated global tectonics using a geoid model derived from the gravimetric data. Ricard et al. (1984) investigated the connection between the lithospheric stress and geoid height. Richards and Hager (1984) combined different types of data in order to improve our understanding the structure of the viscosity of the mantle. Fu (1986) considered that the mantle is an isoviscous, Newtonian liquid shell with a uniform distribution of heat sources, and considered the boundary between the core and mantle in formulating the stress. Forte and Peltier (1987) investigated plate kinematics and mantle convection. Pick and Charvatova-Jakubkova (1988) modified Runcorn's formulae to reduce the contribution of the far-zone gravity anomaly and geoid height for local applications. Ricard et al. (1988) presented a model relating the geoid and global plate motions. Hager and Richards (1989) investigated the long wavelength variations on Earth's geoid and presented physical models and dynamical implications for those variations. Fu (1989) investigated mantle convection based on a thermal-convection model and concluded that the absolute motion of the rigid plates are correlated with that mantle thermal convection and associated with the geoid. Fu and Huang (1990, 1992) presented a global stress pattern constrained by deep mantle flow and tectonic features and investigated the drag force caused by mantle flow and the force system along the plate boundaries to form the stress field in the lithosphere. Nataf (1991) considered the relation between mantle convection, plate motion and hotspots. Davies and Richards (1990) also investigated this process and the associated models. Pick (1994) presented closed-form formulae for the kernel of the integral involving the gravity anomaly and geoid height in order to model the stress below crust. Monnereau and Quere (2001) further developed convection models by considering spherical shells. Fu et al. (2003) presented a new convection model constrained by seismic tomography data. Naliboff et al. (2012) investigated the relationship between the lithospheric thickness and density structure on Earth's stress field. Eshagh (2014a) developed the Runcorn (1967) formulae in such a way that satellite gradiometry data can be used for determining the sub-crustal stress and Eshagh (2015) derived the mathematical model between the sub-crustal stress and a gravimetrically-determined Moho model by Vening Meinesz-Moritz (VMM) theory (Sjöberg, 2009). Later on, Eshagh and Tenzer (2015) applied this method for sub-lithospheric stress determination in certain places with special geophysical properties, and interpreted those results. Tenzer and Eshagh (2015) studied the stress in subduction zones in Taiwan based on the gravimetric data and Tenzer et al. (2015) investigated the stress field over Mars. Eshagh and Romeshkani (2015) employed GOCE gradiometric data (ESA, 1999) over Iran to estimate the sub-lithospheric stress due to mantle convection. Eshagh (2016) developed integral approaches for determination of sub-lithospheric stress from terrestrial gravimetric data over the same area and found good agreement between the stress field recovered from the gravimetric data and the active earthquake locations of the World Stress Map 2008 (WSM08) database (Heidbach et al., 2008).

In this study, we extend the results of Eshagh (2015) for relating the Moho and sub-crustal stress. Eshagh (2015) used the VMM theory, in which the Bouguer gravity anomaly correction was used to model the Moho, whilst in this paper we consider the full topographic information. The sub-lithospheric stress components or stress function (SF), are derived by taking the northward and eastward derivatives. Here, our emphasis is on recovering this SF from a combination of density contrast information over continents and oceans as well as the seismic Moho model of CRUST1.0 (Laske et al., 2013). To do so, two new integral equations are presented and applied to the Indo-Pak region. In addition, actual GOCE gradiometric data are used to recover this SF. Subsequently the GOCE data, topographic information from SRTM (Farr et al., 2007) and the seismic Moho model of CRUST1.0 are jointly inverted to recover the SF over the aforementioned area. Geophysical results are interpreted from the produced SF and stress maps.

2. Runcorn's solution for sub-lithospheric stress

Amongst the efforts to model the Earth's interior structures and mechanisms to regenerate a gravity field discussed above, Runcorn (1967) gave a simplified solution for the Navier-Stokes equation for modelling the sub-lithospheric stress due to the mantle convection. He assumed that the density and viscosity of the mantle are constant and the lithosphere is a thin shell. Under these assumptions, he derived the following simple mathematical relation between the SH coefficients of the disturbing potential (T_{nm}) and the shear stresses beneath the lithospheric shell:

$$S_x\mathbf{e}_\theta + S_y\mathbf{e}_\lambda = \kappa\sum_{n=2}^{N} v_n \sum_{m=-n}^{n} T_{nm}\mathrm{X}^2_{nm}(\theta,\lambda) \tag{1}$$

where S_x and S_y are horizontal shear stress components with their corresponding unit vectors $\mathbf{e}_\theta$ and $\mathbf{e}_\lambda$ towards the north and east, respectively. In fact, the frame used for taking the derivatives is local and north-oriented, which means that the x-axis is pointing towards the north and y-axis to the east. In this case the z-axis will be upwards along the plumb-line. κ and v_n in Eq. (1) are defined by:

$$\kappa = \frac{Mg}{4\pi(R-D)^2} \text{ and } v_n = \frac{1}{s^{n+1}}\frac{2n+1}{n+1} \text{ where, } s = \frac{R-D}{R}.$$

where D and R, respectively, stand for the mean lithospheric depth and the mean Earth's radius. M is the average mass of the Earth and g is the gravitational acceleration. N stands for the maximum degree of SH expansion. As the series is not convergent we have to limit the series to a maximum degree; see Eshagh (2015) for a discussion of the degree of the convergence of such series. Colatitude and longitude are denoted by θ and λ, respectively. $X^2_{nm}(\theta,\lambda)$ is the fully-normalised surface vector SHs of degree n and order m and has the following relation with the ordinary SHs $\mathrm{X}^1_{nm}(\theta,\lambda)$:

$$\mathrm{X}^2_{nm}(\theta,\lambda) = \frac{\partial \mathrm{X}^1_{nm}(\theta,\lambda)}{\partial\theta}\mathbf{e}_\theta + \frac{\partial \mathrm{X}^1_{nm}(\theta,\lambda)}{\sin\theta\partial\lambda}\mathbf{e}_\lambda. \tag{2}$$