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Anisotropy in the flexural response of the Indian Shield

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ABSTRACT

We seek to determine the strain field which has accumulated in the Indian Shield due to the continental drift of Gondwanaland. We have used a method which involves the calculation of the 2D isostatic coherence response function between Bouguer gravity and topography as a function of azimuth by way of multispectrogram analysis. The average coherence is maximum consistently in the Indian Shield in a direction, which is at an angle of 45° to the major trend of suture zones within the shield, a result which is in good agreement with the strain inferred from absolute plate motion (APM) in a hot spot reference frame. This directionality of mechanical plate weakness suggests that all paleostress fields were erased due to the movement of the Indian plate during the Himalayan orogeny.

1. Introduction

Mechanical anisotropy can be detected in the response of the lithosphere to long-term load emplaced as topography. The integrated mechanical strength of the plate is expressed as an effective elastic thickness (Te) (Audet and Mareschal, 2004; Braitenberg et al., 2003; Burov and Diament, 1995; Forsyth, 1985; Pérez-Gussinyé et al., 2004; Simons and van der Hilst, 2003; Watts, 2001). The continental lithosphere is old in contrast to oceanic lithosphere. It has multilayer rheology and its effective elastic thickness does not depend on a single controlling mechanism nor its thermal age, but is an integrated effect of a number of other factors that include the geotherm, crustal thickness, composition, and its variability with azimuthal direction, or look-angle, which depends on its stress/strain distribution. (McNutt et al., 1988; Watts, 1992; Watts and Burov, 2003).

Previous coherence estimates for Te in cratonic regions that allow for both surface and subsurface loads are 65–120 km, which are comparable to those obtained from forward models of rift and foreland basins (Djomani et al., 1995; Ebinger et al., 1989; Pérez-Gussinyé et al., 2009). In the context of the Indian peninsular shield, the earlier estimates based on different methods show variations ranging from 10 to 110 km (Jordan and Watts, 2005; Karner and Watts, 1983; Lyon-Caen and Molnar, 1985; McKenzie and Fairhead, 1997; Rajesh and Mishra, 2004; Tiwari and Mishra, 1999). Lyon-Caen and Molnar (1983) and Karner and Watts (1983) used forward modeling techniques and showed that Bouguer gravity anomaly over the Ganges basin could be explained by the flexure of the Indian continental lithosphere. The estimated Te value of the continental lithosphere was in the range of 80–110 km. McKenzie and Fairhead (1997) questioned the validity of continental Te values >25 km, especially those based on the Bouguer coherence spectral technique (Bechtel et al., 1990; Ussami et al., 1993; Zuber et al., 1989) and estimated Te value of 24 km (for the Indian Peninsula) and 42 km (for profiles across the Himalayan foredeep) respectively, using spectral estimates of the free-air admittance and a non-spectral free-air gravity anomaly profile shape fitting technique. Tiwari and Mishra (1999) estimated Te to be 10 ± 2 km under the Deccan Volcanic Province based on admittance and coherence between the gravity field and topography and concluded that the value estimated from Bouguer coherence and free-air admittance gave almost same Te for the region but a considerable change in the compensation depth was noticed. Rajesh and Mishra (2004) considered the possibility of spatial variations in rigidity and found Te values ranging between 11 and 16 km for the Indian cratonic region by a robust coherence method based on multitaper spectral analysis on overlapping windows of equal size. Further, in this context of the India–Eurasia collisional system, Jordan and Watts (2005) estimated a high Te value of 70 km in the central region and a range of 30–50 km in the east and west. Their study employed forward modeling and results were verified with a 2-D non-spectral modeling technique using Bouguer gravity anomaly and topography data. According to Forsyth (1985), a flexural isostatic model must include both the surface as well as subsurface loads in order to accurately estimate Te. The coherence method based on Bouguer gravity yields an estimate of Te that is less biased by the presence of subsurface load than the free-air admittance method. In other words, it enables us to incorporate the effects of subsurface loading, though it is well known that coherence is not overly sensitive to the

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precise ratio or relative importance of those loads at either interface (Forsyth, 1985). Some of the previous works which investigated anisotropic mechanical response of lithosphere using spectral methods include Simons et al. (2003), Audet and Mareschal (2004), Stephen et al. (2003) and Rajesh et al. (2003). Audet and Mareschal (2004) estimated the anisotropy of flexural response of the lithosphere in the Canadian Shield using the multitaper method and obtained results that show average coherence, a proxy for plate weakness, increasing in the direction perpendicular to the main tectonic boundaries. Their inference, based on correlation with seismic fast axes, was that anisotropy reflects the same stress field possibly due to the last tectonic event. Stephen et al. (2003) estimated coherence anisotropy in the South Indian Shield using only the Slepian multitaper method and could capture only little mechanical anisotropy. Using large window sizes based on Slepian functions, Rajesh et al. (2003) obtained anisotropy in Eastern Himalayas aligned with maximum compression direction. Simons et al. (2003) computed the mechanical anisotropy of the Australian shield by calculating the coherence function between topography and Bouguer gravity anomalies. This procedure ensures spectral leakage control and spatial selectivity on the coherence estimation was provided using Hermite multitapers. Nair et al. (2010) estimated the mechanical strength of the Indonesian active continental margin by applying azimuthally averaged coherence measurements between Bouguer gravity and topography using a multitaper method with Hermite tapers. Simons et al. (2003) compared the merits of Slepian wavelets and Hermite windows by their average Wigner-Ville transformation and concluded that the symmetry and smoothness of the Hermite function kernels make them attractive for use in coherence analysis. In the context of the above studies, coherence estimation between Bouguer gravity anomaly and topography using the orthonormalized multispectogram method with Hermite circular function remains our method of choice. The geology and some major tectonic features are shown in Fig. 1. Topography (m) and Bouguer gravity (mGal) map of the Indian Shield, used in this study, is shown in Figs. 2(a) and (b) respectively.

Seismic anisotropy is mainly produced due to the lattice preferred orientation (LPO) of olivine mineral as a result of plate deformation aided by increased melt production within the upper mantle; at the edges of fault-bounded rift valleys. Seismic anisotropy can be due to the alignment of inclusions such as crack-like melt inclusions (Kaminski, 2006, Kendall et al., 2005, 2006). The asthenospheric flow in the direction of absolute plate motion (APM) and the flow in oceanic ridges can be responsible for induced lattice preferred orientation (Kaminski and Ribe, 2001; Kendall et al., 2005; Ribe, 1989). For isotropic media, seismic SKS waves should exhibit linear particle motion. However, in case of anisotropy, this phase splits into a fast and slow shear-wave and produces elliptical particle motion. The hypothesis of upwelling mantle material beneath hotspots predicts that the ascending hot material is deflected as well as sheared by the lithosphere. This phenomenon is apparent in shear-wave splitting studies (Walker et al. (2005). Surface wave studies indicate that the lithospheric thickness of the Indian subcontinent varies between 160 and 280 km (Pasyanos, 2008). The analysis of SKS splitting can be used for the study of upper mantle anisotropy (Savage, 1999; Silver, 1996). The review of the relationship between elastic thickness estimates and their relationship to that of the seismogenic layer is not consistent. Therefore, much controversy still exists on whether elastic thickness represents only the crustal strength. Kendall et al. (2005, 2006) presented the evidence of anisotropy in the upper mantle of the Northern Ethiopian Rift using shear-wave splitting in the teleseismic phases, SKS, SKKS and PKS. Their results indicate that the magnitude of SKS splitting correlates with the degree of magmatism along the rift valley, and that, for the uppermost 75 km, it is primarily due to melt alignment. Although away from the rift valley, the anisotropy is due to the pre-existing lithospheric fabric. However Burov and Watts (2006) used a numerical thermo mechanical model and argued that irrespective of

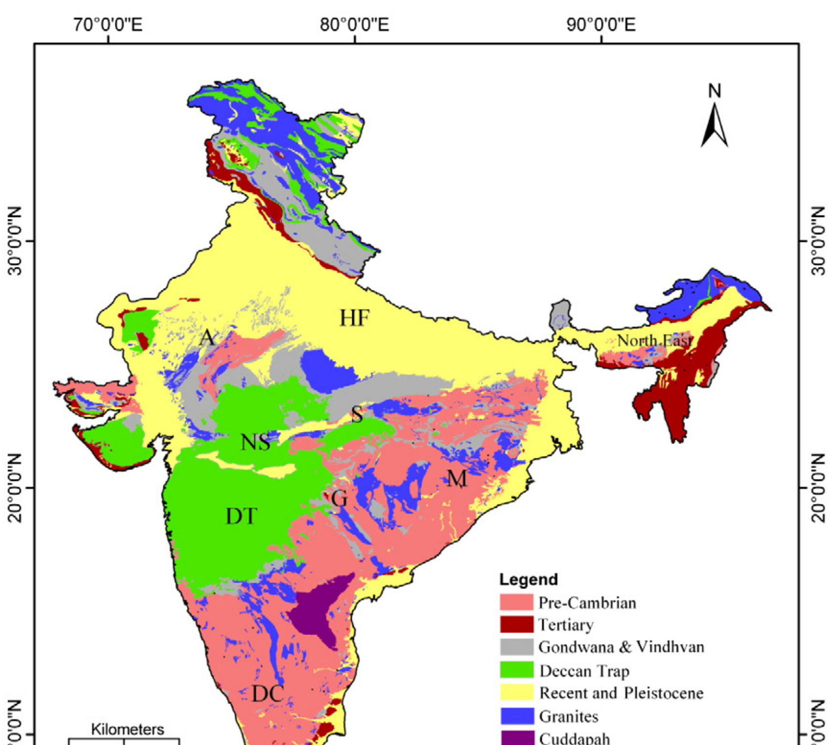

Fig. 1. Map of Indian Shield showing different geological formations with some major tectonic features, viz., Aravalli Range(A), Dharwar Craton(DC), Deccan Trap(DT), Himalayan Front(HF), Godavri Rift(G), Narmada–Son Rift(NS), Mahanadi Rift(M) and Satpura Range(S). The geology of the Indian subcontinent is from Dasgupta et al. (2000).