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Isostatic geoid anomalies over the plateau region of Central India

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Summary

Central India plateaus (i.e. Ajanta, Satpura and Malwa) are a product of rifting associated magmatism and eruption of flood basalt. The plateaus are at maximum topography at 800 m with lateral variation from north to south. These variations are also related to gravity anomalies. The Bouguer gravity anomalies are -80 mGal over the Ajanta plateau and vary to -30 mGal over the Satpura plateau. Here we have used free-air gravity data and topography data to study the correlation of geoid and topography variation (N and h) over the plateau regions characterized of the highlands in central India. For each plateau mean value of N and h data compared to theoretical correlation for Pratt and Airy models. We find the good correlation between the geoid (N) and topography (h) over the Malwa plateau which is substantially compensated whereas over the Ajanta and Satpura plateau having insignificant correlation.

Introduction

The present study focuses on three important plateau regions of Central India i.e. Ajanta, Satpura and Malwa plateau. It falls between longitude 72^0 to78^0 E and latitude 20^0 to 24^0 N (Fig. 1) and has considerable variation in their topographic relief which aligned predominantly in the east-west direction. The topography map (Fig. 2) clearly shows the plateau uplifts that form a regional topographic high with respect to areas around the periphery of the uplift. The region is subjected to series of compression and extensional tectonic events during the course of their evolution. Narmada-Tapti and Cambay rifts appear to control the tectonics of these regions. The central India region has involved in Phanerozoic events such as the Gondwana crustal distensions and basin development and Deccan basalt magmatism. Tectonically, these events are extensional in nature and therefore can effect changes in the relative thickness of the upper and lower crust depending on the degrees of distension. The ENE-WSW trending Narmada-Son Lineament (NSL) is a major tectonic feature through Central India (Fig. 1) widely considered as a paleo-rift, which evolved during mid-late Archaean and reactivated several times in geological past.

Investigations in terms of regional crustal structure of plateau region using gravity anomalies have been carried out by many researchers (Singh et al., 1998; Mishra et al., 1998). Qureshy and Warsi, 1980 interpreted the N-S trending long wavelength negative gravity gradient due to thickening of the crust caused by isostatic compensation which also shows the inverse correlation with topography. Integrated analyses by paleo-magnetic, geochemical, gravity and magnetic study suggests rocks of mafic/ultramafic component having deep seated origin with high bulk density and susceptibility for all the plugs and favorable continental tectonic setting for their emplacement (Chandrasekhar et al., 2002). Receiver function analysis of teleseismic earthquake waveform data by Kennett and Widiyantoro (1999), Ravi Kumar et al. (2005) depicted the low velocity upper mantle centered over the north of the Gulf of Cambay and extend over the southwest and Central India. These low velocity anomalies, lie below the earliest alkaline magmatic events that preceded the main Deccan basalt eruption.

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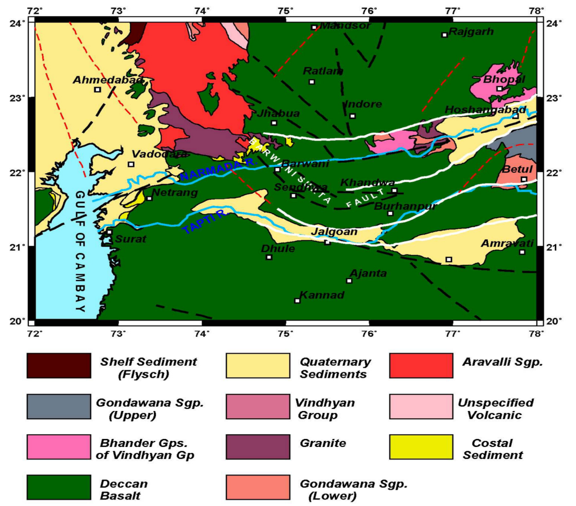

Figure 1: Geological map of the Central India with major tectonic fault (white line), minor fault (black dashed line) and major lineament (dashed red line) (modified from GSI map, 1993).

The Earth has a tendency to deform its surface in order to reach an equilibrium state. The phenomenon of land-uplift in the study area is thought to be a process of this kind. Since the free-air gravity and geoid anomalies are directly related to surface topography of any region, the relationship between present day topography of the plateau verses geoid anomalies have been utilized to provide direct constraints on the mechanism, and perhaps indirect constraints on uplift. Crustal thickening and/or decreases in mantle density inferred from modelling may provide the buoyancy required for the uplift. These two modes have very different tectonic implications, and result in quite different average depths of the compensating mass deficits, potentially detectable with geoid anomalies. Hence, isostatic compensation of the plateau was examined by means of geoidal undulation. The geoid to topography relation has been analyzed in space domain. The information related to isostatic anomalies retained in the geoid and topography signal is compared to gravity and elevation. Spectral method employing the relationship between geoid and topography was utilized to investigate the compensation of uplifted structures and to determine if the anomalous depths are dynamically maintained (McKenzie and Bowin, 1976; McNutt, 1983).

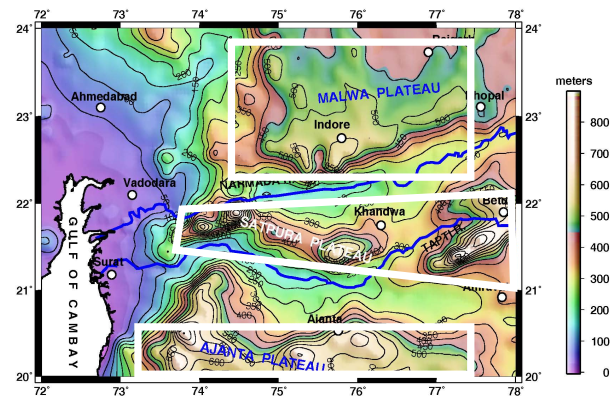

Figure 2: Topography map of Central India region. The three rectangle (White colors) drawn shows the maximum topography of the region chosen for isostatic geoid computation.

Geoidal Anomaly map

The medium wavelength geoid anomalies over the Central India region are studies with special reference to three main well known plateaus (i.e. Satpura, Malwa and Ajanta). Using the least square collocation technique the gravimetric geoid at different wavelength of harmonic coefficients has been computed. Figure 3 shows the geoid undulation at harmonic degree 360 ^{o}. The most significant feature of the geoid undulation map reveals increasing order of a long wavelength circular anomaly at different harmonic level over the part of Cambay basin (Prajapati et al, 2009). The geoid undulation map for harmonic degree 360 over Central India region is characterized by an E-W trending high over Satpura range which is bounded by low on either side. On the other hand, geoid at low harmonic degree shows a significant high over Malwa plateau.

Isostatic Geoid Anomalies

Haxby and Turcotte (1978) have used equation to obtain the relationship between anomalous topography and geoid anomalies when topography is compensated by crustal thickening (Airy Isostasy), lateral density variation (Pratt Isostasy), and thermal anomalies (thermal Isostasy).

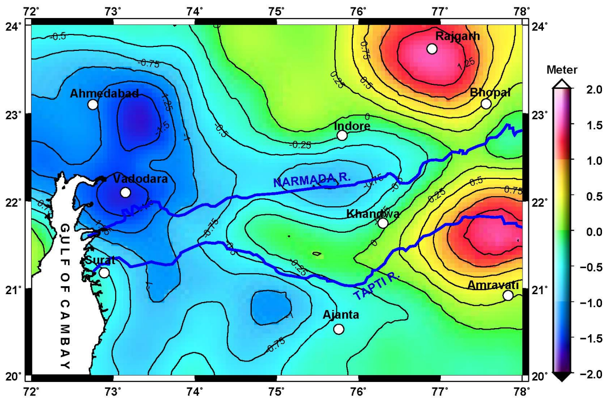

Figure 3: Residual geoid undulation map of the Central India, obtained by subtracting EGM96 geopotential model at 360 degree.

In case of isostatic compensation the integral of density anomalies with depth of any column is zero. The geoid anomaly however is nonzero and proportional to the moment of density distribution (Ockendon & Turcotte, 1977). The isostatic geoid anomaly ΔN in a long wavelength approximation is given by

$$\Delta N = \frac{-2\pi G}{g} \int_{-h}^{H} Z \Delta\rho\,(x, y, z)\,dz \quad (36)$$

Where G is the Gravitational constant, g the gravity acceleration, $\Delta\rho(x,y,z)$ is the three dimensional density anomaly distributions.

In case of Pratt Isostasy, the above equation reduce to (Haxby and Turcotte, 1978)

$$\Delta N = \frac{\pi G}{g} \rho_0 W h$$

For topography below the sea level, ρ_0 has to replace by $(\rho_0 - \rho_w)$.

In case of Airy model we get

$$\Delta N = \frac{\pi G}{g} \rho_c \left\{ 2 Z_m h + \frac{\rho_m}{\rho_m - \rho_c} h^2 \right\}$$

Because of complex tectonic & short wavelength topography which is unlikely to be locally compensated of the study regions, we would not expect the geoid-topography correlation technique to yield meaningful results when applied directly to the whole region (Central India). The short wavelength topography would have to be filter out. To avoid the complication, the study is restricted to the only elevated part of the plateau. It is also assume the anomalous topography is partially compensated by crustal thickening and in part by anomalous underlying layer of mantle. Scrutton (1972), using refraction study on the Rockall plateau also indicates thickened crust overlaying an anomalous low density layer. Seismic, MT and gravity results already indicate a thickened crust beneath the Central India region but could not indicated the record of mantle refraction over the selected profiles.

To perform the Isostatic study, we assumed the following physical parameter and its value for computation (Table 1). Both models (Airy & Pratt) are regarded the flexure strength of the lithosphere is not taken into account.

ρ_0	Crustal density at zero elevation	2700 kg/m^3
ρ_c	Crustal density	2900 kg/m^3
ρ_m	Mantle density	3300 kg/m^3
g	Gravity acceleration	10 m/s^2
Z_m	Depth of compensation (Airy)	35 km
W	Depth of compensation (Pratt)	50 km

Table 1: Physical parameters for isostatic geoid computation for Airy and Pratt compensation models.

The isostatic geoid undulation for different harmonic degree (L= 100, 200, 360) are calculated. The chosen area for computation extending from (i) 73.00° to77.50°E & 20.00°to 20.60°N, (ii) 73.50° to 78.00°E & 21.20° to22.25°N, (iii) 74.20° to77.50°& 22.25° to23.90° N (i.e. over Malwa, Satpura and Ajanta plateau, Fig. 2) in Central India region. The observed geoidal versus topography for all harmonic degree together with geoid against topography curves computed for Air and Pratt model are shown in Fig. 4, 5 and 6.

Over the Satpura range, the geoid/topography ratio (GTR) is too low and insignificant and hence can not explain any of the simple compensation models. The low GTR features require large crustal thickness larger than the estimated from the crustal modeling. Interpretation of this curve is of course non-unique as uncompensated thin or thick crust could yield a low GTR. The compensation in terms of low GTR is considered to be consistent with the dynamic cause. Over the Malwa plateau, to the north of the Narmada rift basin a very good correlation is found between the geoid and topography at different harmonic degree with compensation depth for Airy model of 50 km but over a part of topography. Small geoid/topography ratio (GTR) in the region of compensated low amplitude topography considered the component of thermal effect partly and also observed over the continental flood basalt region of the world (i.e. Parana, Columbia, Ethiopian CFBs) (Sandwell and Mackenzie, 1989). As the calculation of Isostatic geoidal anomalies over the Ajanta plateau i.e. south of Narmada son lineament does not able to explain any deep source for different harmonic degree at all depths of compensation. The observed signal over the Ajanta plateau indicates that signal related to topography is too weak. The cause of weak signal is mostly due to very small density variation in lithospheric mantle (Marquart et al., 1992).

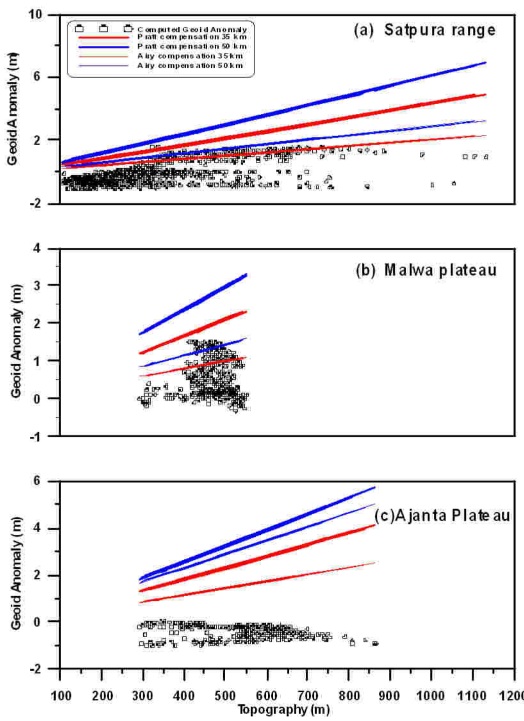

Figure 4: Geoid Anomalies verus topographys in meters for (a) Satpura Range (b) Malwa Plateau (c) Ajanta Plateau. Curves are the theoretical geoid (360°x360°) veruse topography for Airy type compensation and Pratt model witrh 35,50 km depth.

Discussion and Conclusion

The tectonic of Western and Central India reveals a complex pattern of rifting and associated magmatism. Gravity studies carried out in the region played an important role in the delineation of shallow and deep crustal structures beneath the Deccan trap. It is well known that large-scale features of the earth's surface, such as mountains and ocean basins are in a state of isostatic equilibrium. On the other hand, nature of isostasy of medium scale topographic features, such as plateau and sedimentary basins, show departures from local isostatic balance. Since the surface elevation is intimately related to the crustal structure through phenomenon of isostasy, the relationship between the surface elevation, density distribution and crustal structure is best manifested in the geoidal undulation.

The geoid undulation maps at different harmonic degrees work like a filter and reveal the density distribution at different depth. Geoid undulation map for harmonic degree 360 over Central India region is characterized by an E-W trending high over Satpura range bounded by low on either side which indicates shallow density heterogeneity in the upper crust. On the other hand, geoid at low harmonic degree shows a significant high over Malwa plateau which probably suggests thick lithosphere beneath the Bundelkhand craton. The isostatic geoid anomaly computed for the local compensation models (Airy and Pratt) have been compared with the observed geoid and topography ratio (GTR) and it is found that over the Satpura plateau, GTR is insignificant suggesting lack of local isostatic compensation which might be due to addition of high density magmatic material at the base of the crust at the time of rifting.

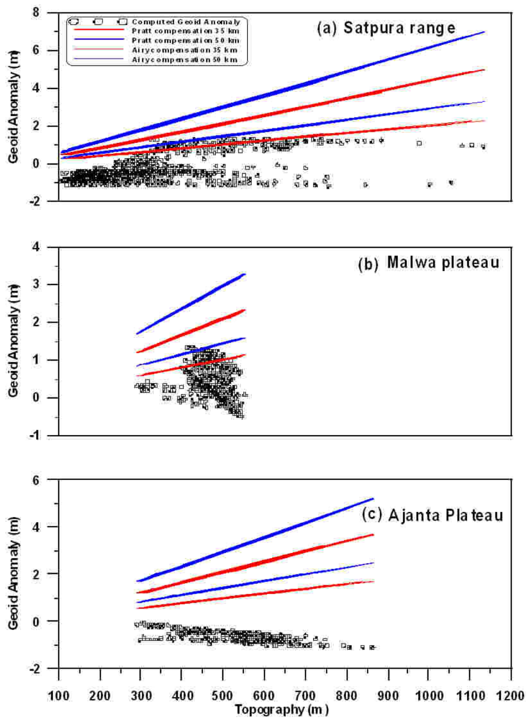

Figure 5: Geoid Anomalies verus topographys in meters for (a) Satpura Range (b) Malwa Plateau (c) Ajanta Plateau. Curves are the theoretical geoid (200°x200°)veruse topography for Airy type compensation and Pratt model witrh 35,50 km depth.

Geoid undulations which can sense deeper information more effectively than the gravity filed can be utilized to map the sub-crustal heterogeneities in the lithosphere. Therefore, density model based on forward and inverse modelling of gravity and geoid data will improve the image of the lithosphere. Further, gravity, geoid and topographic data can be used to map the variation of lithosphere mechanical strength based on numerical modelling. Such analysis can greatly improve our understanding about dynamic process responsible for tectonic evolution.

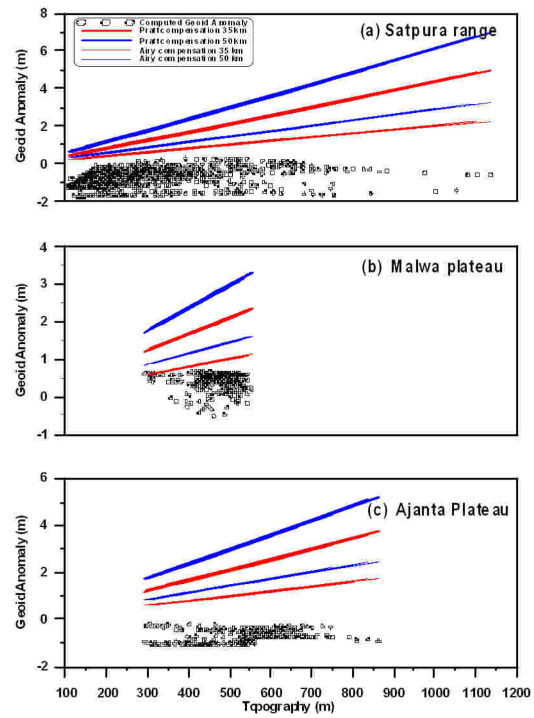

Figure 6: Geoid Anomalies verus topographys in meters for (a) Satpura Range (b) Malwa Plateau (c) Ajanta Plateau. Curves are the theoretical geoid (100°x100°)veruse topography for Airy type compensation and Pratt model witrh 35,50 km depth.

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