Resolving sub-basalt Geology from Joint Analysis of Gravity and Magnetic Data over the Deccan Trap of Central India

B. Nageswara Rao, Bijendra Singh*, A. P. Singh, and V.M. Tiwari
CSIR-National geophysical Research Institute, Uppal Road, Hyderabad-500007
**Corresponding Author: bsingh_ngri@yahoo.co.in*

Abstract

Deccan basalts which cover a large part of the central India poses a severe constrain on the use of conventional techniques to image the sub-trappean sedimentary basins for hydrocarbon exploration. Gravity and magnetic investigation is conducted in part of the Deccan Syneclise in Central India to delineate the Mesozoic sediments hidden beneath the Deccan volcanic cover through joint analysis and modelling of the gravity and magnetic data. This integrated approach has brought out a series of asymmetric half-grabens oriented in the E-W direction. Presence of high- density mafic intrusive bodies at shallow crustal depths of 4-6 km appears to be the characteristic feature of the Narmada-Tapti rift zone in the Deccan volcanic province, which might represent secondary magma chambers for the feeder dykes of the Deccan flood basalts. The pre-existing faults probably guided their ascent in the Deccan syneclise of central India.

Introduction

The Mesozoic prospects currently hold nearly half of the world's hydrocarbon reserves. In India, very little efforts have been put to explore this stratigraphic sequence for hydrocarbon resources particularly because the major part of the Mesozoic sediments is underlying the Deccan Traps. Detection and mapping of sub-basalt geology including the Mesozoic sediments has been a long-standing complex geophysical problem facing the oil industry (Kumar et al., 2004; Satpal et al., 2006; Pandey et al., 2009; Leveille et al., 2011) partly because the vast sheet of volcanic cover acts as a geophysical shield and inhibits the effective use of conventional geophysical techniques (Whithers et al., 1994). However, integration of results from different proxies of geophysical methods has provided more reliable models of subsurface geology (Rao and Reddy, 2005; Chakravarthi et al., 2007; Singh and Arora, 2008).

Gravity and magnetic (G & M) methods have been used extensively as a reconnaissance tool for the delineation of basin configuration in hydrocarbon exploration. Restrictions are often imposed on the application of these methods due to intrinsic ambiguity and non-uniqueness in the determination of the source parameters. Several processing and modelling approaches have been proposed to overcome these limitations; for example Euler deconvolution provides geometry and the depth of the gravity and/or magnetic sources without apriori information about the source parameters (Li, 2003; Nabighian et al., 2005). Joint modelling schemes reduce the number of possible solutions and increase the geologic reality of the geophysical model. Its integration with other proxies of individual geophysical methods further allows us to resolve the rift and intrabasement source geometries in complex geological settings such as in the Deccan syneclise in central India.

Geological Setting

The E-W trending Narmada-Tapti region constitutes the Deccan syneclise of central India (Fig. 1). Most of the region is covered by thick pile of Late Cretaceous Deccan lava flows except for a few places where thin Tertiary sediments are seen. Field and geochemical relations, and age (67-64 Ma) similarities of many mafic dikes and Deccan flood basalts, indicate their comagmatic nature and establish many rift-oriented mafic dikes as the primary feeders. Geochemical and petrological evidences further indicate that the majority of the lower Deccan tholeiites evolved in local and multiple magma chambers close to the surface up to a depth of 7 km (Bhattacharji et al., 1996; Ju et al., 2013). Evidences of the presence of Mesozoic sediments occur throughout the western part of the Narmada valley as both inliers and outliers which appear to have been deposited during Cretaceous times in a depression between the Satpura and the Vindhyan range (Murthy and Sharad, 1981). These sediments were uplifted, faulted, intruded, and finally covered by the Deccan basalts. The presence of C1-C5 hydrocarbons in the adsorbed soil gases in samples collected from parts of the Deccan syneclise indicates that hydrocarbon generation has taken place in the Deccan syneclise and gases are derived from a thermogenic source (Vardhan et al., 2008; Satish Kumar et al., 2013).
Analysis of Gravity and Magnetic Data.

The Bouguer anomaly map (Fig. 2) used for the present investigation is based on about 8000 new observations collected by CSIR-National Geophysical Research Institute as part of integrated geophysical studies for hydrocarbon exploration in the Deccan Syneclise, central India. All gravity observations were processed with reference to IGSN 71 datum and gravity anomalies were calculated using GRS80 international gravity formula. The standard crustal density of 2670 kg m^{-3} was used for Bouguer slab corrections and terrain corrections were calculated up to Hayford zone O2 (167 km), using the

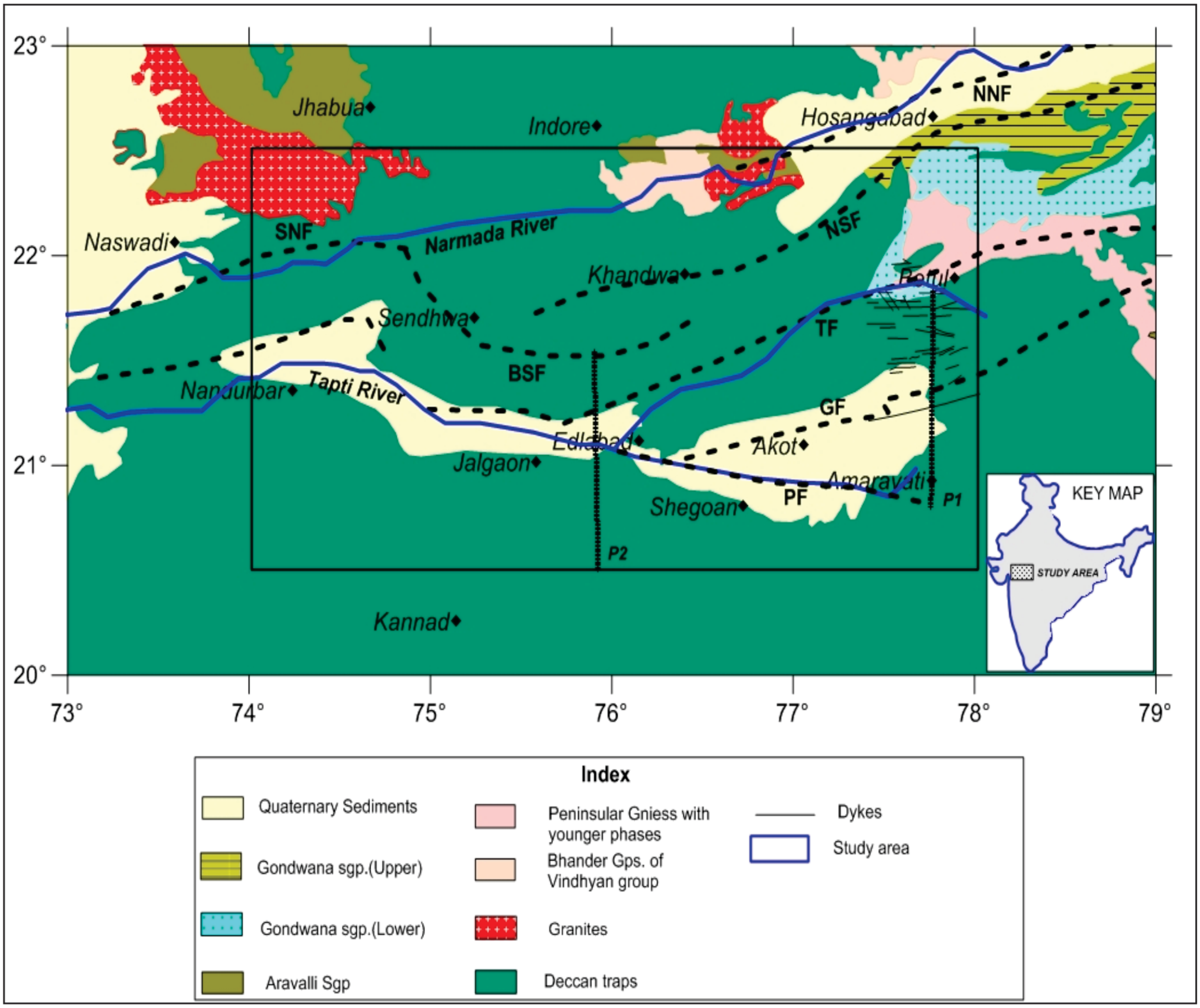

Fig. 1: Generalised geological map with major faults and dykes of Deccan Syneclise (modified after GSI, 1998). BSF: Barwani Sukta Fault;GF:Gavligarh Fault; KF: KaddamFault;NNF:Narmada North Fault,NSF:Narmada South Fault; PF: Purna Fault; SNF: SonNarmada Fault; TF:Tapti Fault.

digital elevation model with a 30m grid (GMSI, 2006). The complete Bouguer anomaly so calculated is referred hereafter as Bouguer anomaly (BA).

The most conspicuous feature of the anomaly map is the relative gravity high (H1), aligned in the E-W to ENE-WSW direction, between the rivers Narmada and Tapti. This large amplitude relative gravity high associated with the Satpura Mountains was interpreted to be due to a thick 10-15 km mafic body at the base of the crust that finds support from deep seismic sounding studies along Ujjain-Mahan profile (Singh and Meissner, 1995; Reddy et al., 1997, Singh, 1998). The other prominent features on the map are the relative gravity lows (L1 and L2) towards south of the Tapti and north of Narmada Rivers, which show inverse correlation with topography of Ajanta mountains and Malava plateau suggesting deficit of mass at deeper level due to isostatic compensation. Nearly ENE-WSW trending small wavelength gravity lows (L3, L4 & L5) may be attributed to large thickness of sub-trappean Mesozoic sediments. Circular gravity highs (H2, H3) may be attributed to high density intrusive.

Total magnetic intensity anomaly (TMIA) map obtained after the removal of International geomagnetic Reference Field (IGRF) from the diurnally corrected magnetic observations is presented in Fig.3, which shows large variation in the anomaly amplitudes - a typical signature of volcanic terrains. The most significant feature of the anomaly map is an E-W to ENE-WSW trending magnetic high (H) associated with low (L) in the north in the central part of the map. Presence of large amplitude high associated with medium amplitude low to the north at low latitudes, like the present study; suggest predominance of remanace magnetization in the causative source. It also depicts short wavelength highs and lows distributed randomly over the entire region which indicates large variation in the magnetization of the Deccan basalts.

In hydrocarbon exploration we are interested in shallow crustal investigation, therefore the Bouguer anomaly map which represents the total sum of gravitational effects of

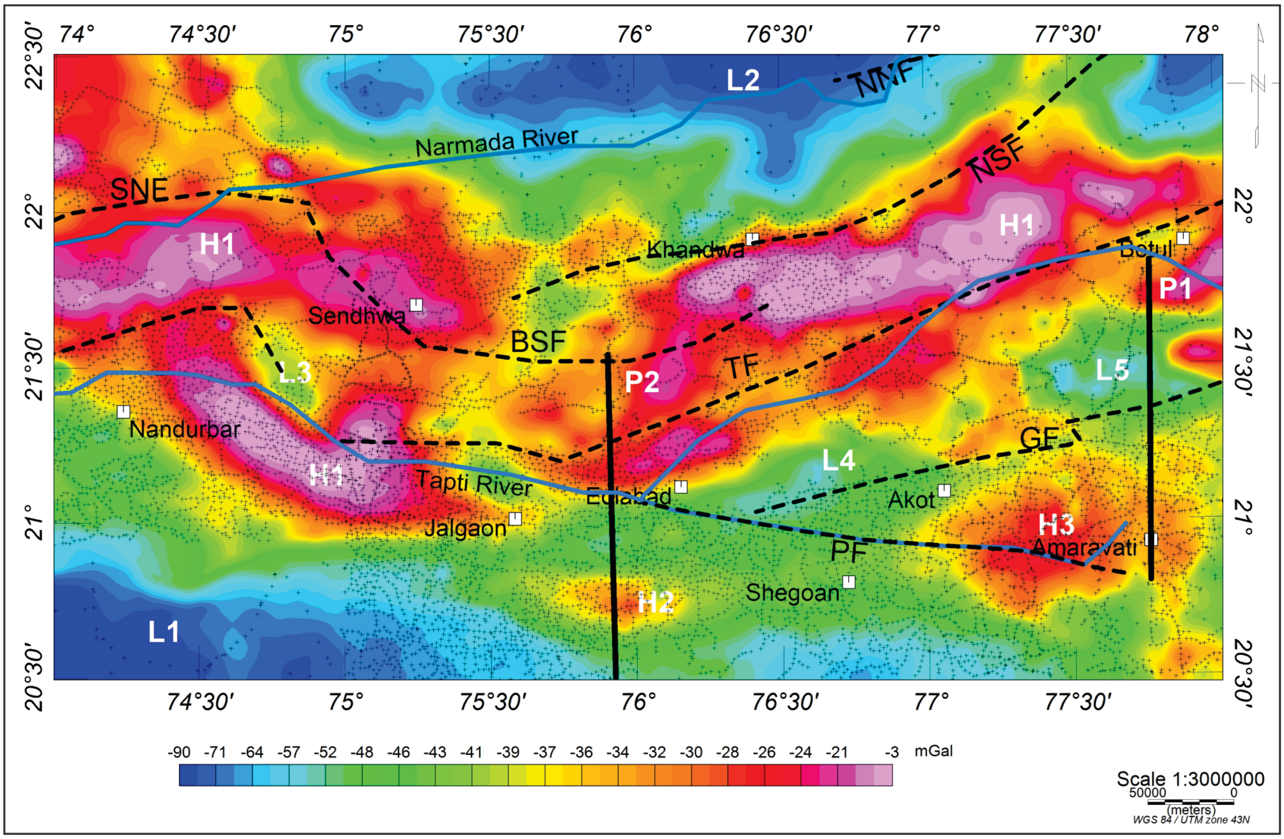

Fig. 2: Bouguer anomaly map for the study region with contour intervals of 5 mGal. Solid dots indicate the data distribution in the study region. Abbreviations for faults are as per Fig.1.

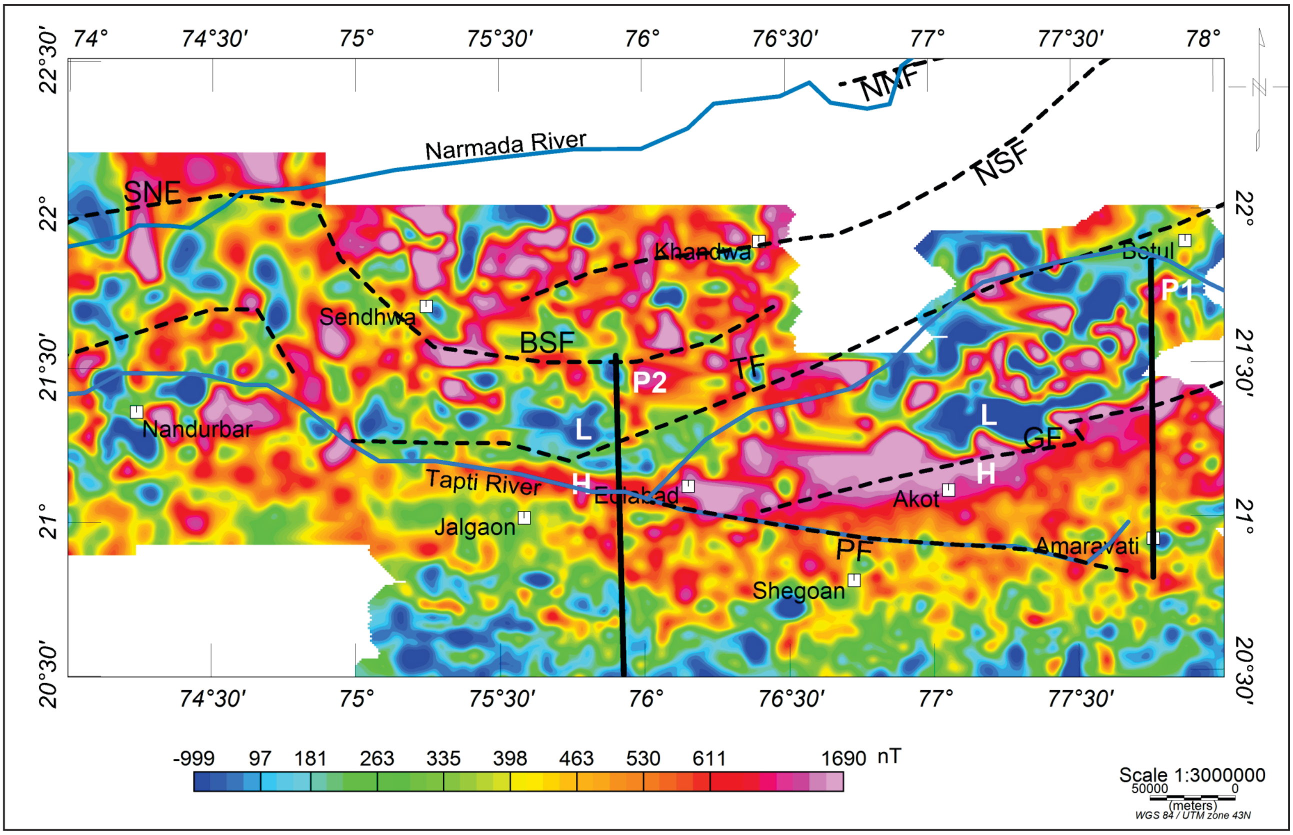

Fig. 3: Total Magnetic Intensity anomaly map of the study area. Abbreviations for faults are as per Fig.1. Lines P1 and P2 are used for G-M modelling.

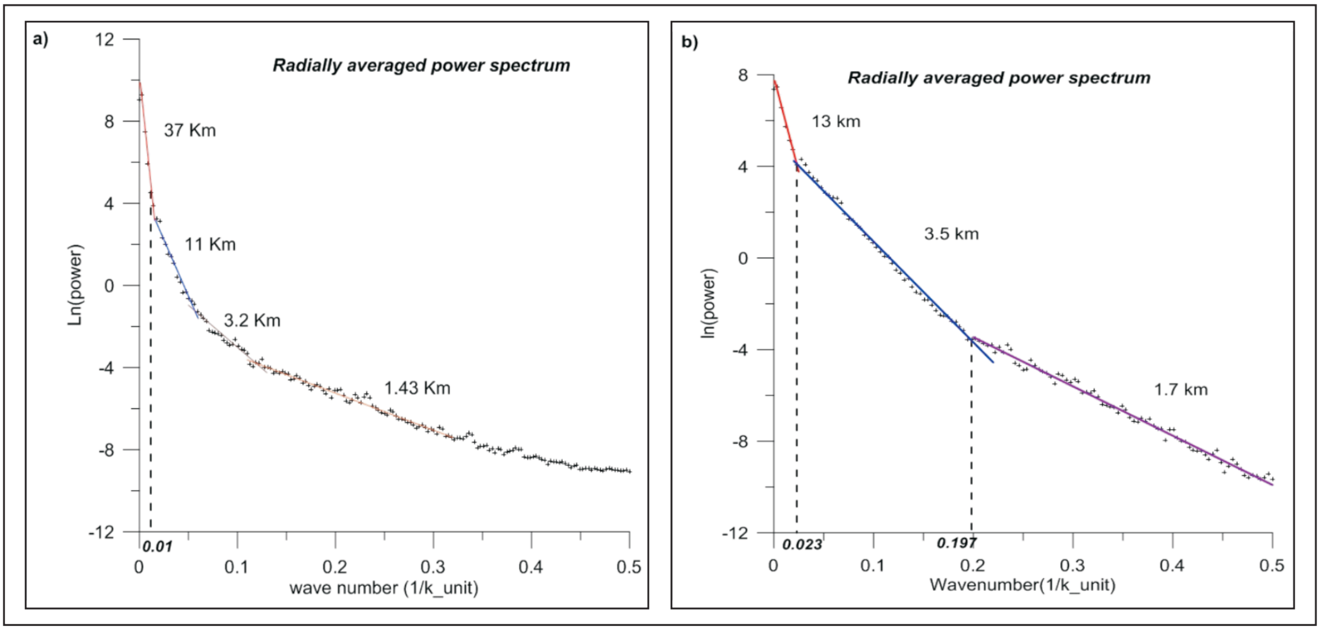

Fig. 4: Radially averaged power spectrum of a) complete Bouguer anomaly, and b) Total Magnetic Intensity anomaly of the study region.

sources from various depths; need to be decomposed into its component parts using frequency filtering based on power spectrum analysis of G-M data. Thus, the estimate of causative source depths can be obtained by transforming the spatial domain gravity/magnetic data in the frequency domain and calculating the power spectrum assuming that deeper sources are indicated by the lower-frequency components of an anomaly. Figure 4a shows the power spectrum of the Bouguer anomalies, which indicates distinct segments corresponding to sources at depths of 37.0, 11.0, 3.2, 1.43 km. Similarly, the radial power spectrum of TMIA shows all the three at shallower depths at 13, 3.5 and 1.7 km except one at deeper depth of 37 km. Thus a broad correlation exists between causative sources of TMIA and BA.

Wavelength filtering

The cut-off wave number corresponding to different linear segments on the power spectrum plot can be judiciously used in the filter operator to filter the different frequency contents present in the observed data leading to regional and residual maps. In order to decompose the observed gravity fields into different components, low and high pass filters were applied corresponding to cut-off wave numbers as shown in Figure 4. Since our interest in hydrocarbon exploration lies in the shallow targets, contributions from deep seated sources (~37 km) are removed employing a high pass Butterworth filter with a cut-off wave number of 0.01 (wavelength = 100 km) to the Bouguer anomaly map (Fig. 2). The resultant residual map (Fig. 5) shows anomalies that are attributed to the mass inhomogeneity coming from shallower depths (from surface to ~12 km depth). The map shows medium amplitude and medium wavelength gravity anomalies associated with basement structures and probably represent pre-basalt extensional tectonics. Gravity lows may be attributed due to sediment fill and highs may be caused due to basement up warp or due to mafic intrusive which cannot be resolved by joint interpretation of G-M anomalies not by gravity alone. The most significant feature of the map is the NW-SE trending low bounded by Tapti and Barwani Sukta fault in the west. This feature appears to continue as E-W to ENE-WSW trending lows in the east south of Edlabad and near Akot. This low is bounded by highs on either side. This low gravity anomaly may be attributed due to presence of subtrappean Mesozoic sedimentary basin which is bounded by faults along which Deccan magma appears to have intruded causing highs on the margins. It is observed that the linear magnetic high and low in the central part of magnetic anomaly map seems to have genetic relation with the residual gravity highs and lows suggesting presence of mafic intrusive in the basement along the faulted contact of the thick Mesozoic basin in the Tapti rift zone.

Modelling and interpretation

Gravity modelling in isolation is inherently non-unique particularly in a trap-covered area where knowledge of subtrappean stratigraphy as well as the basement architecture is inadequate. This inevitable non-uniqueness of the gravity modelling is overcome by the available depth section from other geophysical methods like MT and seismic. However, in a volcanic terrain like the present study area, joint modelling of gravity and magnetic anomalies incorporating depth constraints from power spectrum and Euler's estimates reduces the uncertainty in model geometry. The physical properties (density, susceptibility and remanant magnetization) for the constituent layers i.e. Mesozoic sediment and Deccan basalt overlying the gneissic basement were adopted from published literature (Chandrasekhar et al. 2002, NGRI tech Report-2009, Singh et al. 2013). Palaeomagnetic measurements on tholeiitic flows of the Deccan basalts indicated normal-reverse-normal (N2-R1-N1) polarity sequence with predomination of middle reverse

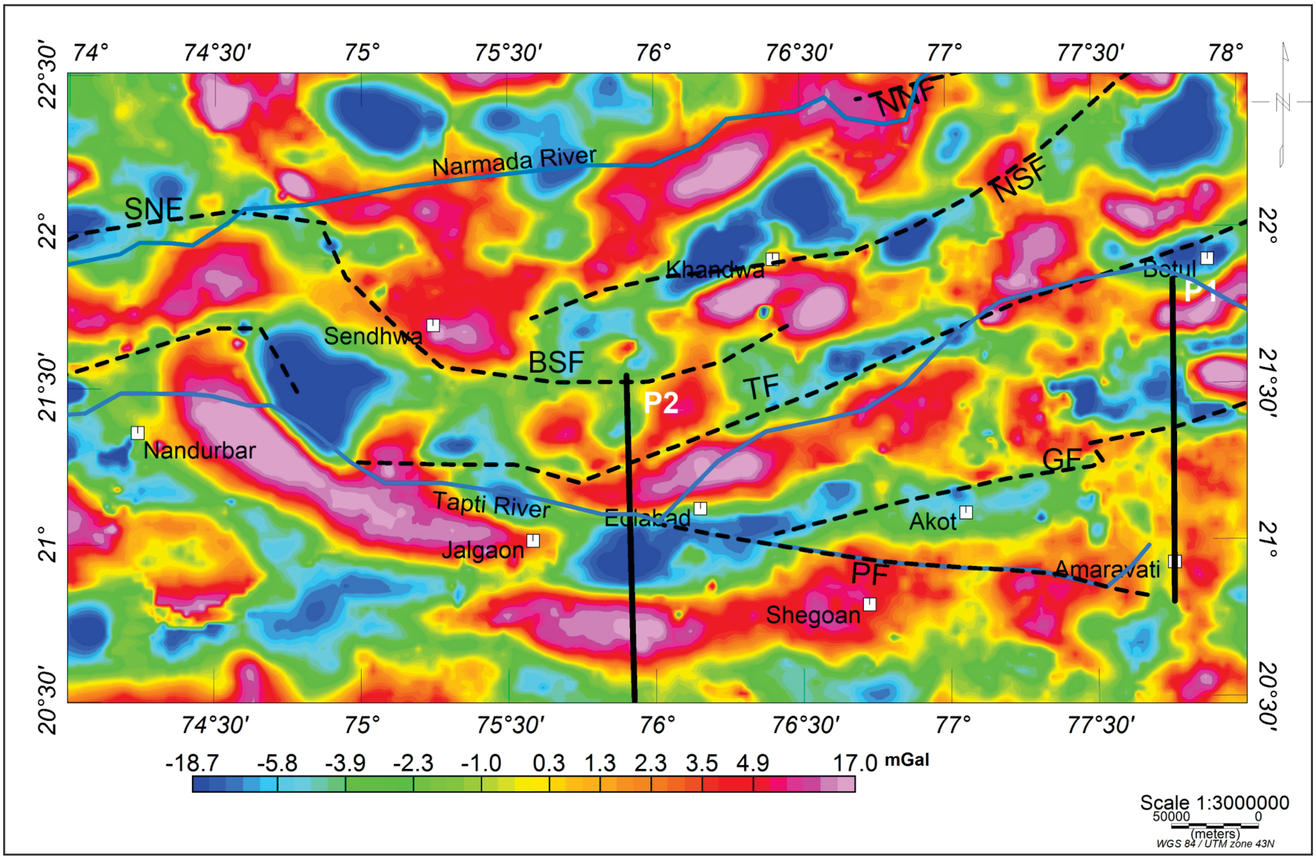

Fig. 5: Residual gravity anomaly map of the study area. Abbreviations for faults are as per Fig.1.

(R1) polarity (Vandamme et al., 1991). Whereas, palaeomagnetism of igneous intrusion associated with the Deccan basalts has revealed normal and reversed magnetic directions (Chandrasekhar et al., 2002). In general, the direction of magnetization with reverse and normal polarity varies over a wide range. For example, inclination (I) and declination (D) of the reverse polarity shows I=$50^{0}\pm20^{0}$ and D=$152^{0}\pm25^{0}$where as normal polarity shows I=$-45^{0}\pm20^{0}$ and D=$335^{0}\pm25^{0}$ (Vandamme et al., 1991). We have carried out 2D joint G-M modelling along two N-S profiles; one located in eastern part (P1) close to the seismic traverse and other (P2) located in the central part of the study area. These profiles cut across the major tectonic elements present in the area.

2D shallow crustal model along Profile P1 &P2.

Figure 6 presents the gravity and magnetic anomalies along profile P1 in the upper panel along with geological section arrived from interactive joint modelling of G-M anomalies. The G-M anomaly profile shows prominent highs on either side of a low in the central part of the profile. In modelling the gravity and magnetic anomalies, density and magnetic properties of the Deccan traps, sub-trappean Mesozoic sediments and basement of a three layer section is predetermined while thickness of trap and sediments are changed to match the anomalies without deviating much from the basement depth obtained from seismic results. The calculated response of the initial basement model is compared with observed anomalies and the difference in the

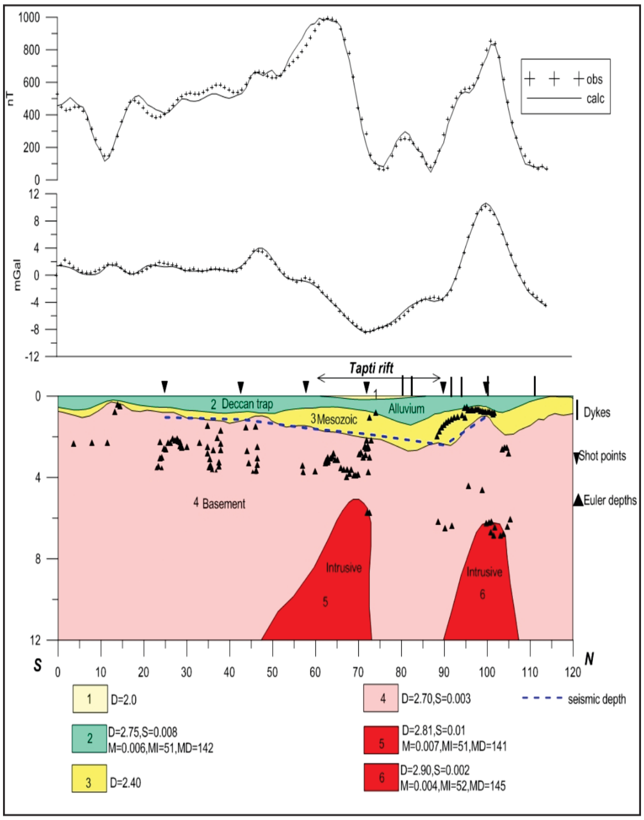

Fig. 6: Sub-basalt geology derived from joint modelling of gravity and magnetic data along profile P1. Solid triangles in the depth section indicate Euler depth from magnetic data.

observed and calculated responses is reduced by changing the model geometry. However, this has not produced satisfactory match between the observed and calculated response. In order to achieve the best fit, two high density intrusive bodies are incorporated in the basement to minimise the major departures. Final model with optimum curve fits is shown in Fig. 6 which amply justifies the efficacy of our integrated approach adopted for the delineation of sub-basalt geology.

The interpreted section shows shallowing of the basement, and thinning of the sediments caused by the presence of small amplitude gravity high and associated magnetic low at a distance of 10 km along the profile. The gravity high near station 45km is modelled as a shallower basement than the one indicated in the seismic section. Without disturbing the seismic basement, an intrusive at a depth of 3-4 km in the basement as indicated by the Euler deconvolution would be an alternative solution to this anomaly. The gravity and magnetic highs in the northern part of the profile towards Betul are a typical example of geophysical interpretation through the integration of seismic, gravity and magnetic results, where the shallowing of the basement and a high density intrusive body of density 2.88 g/cm^3 having remanant magnetization equivalent to reverse polarity of Deccan basalt at a depth of 5 km is required to match the magnetic anomalies. Similarly, magnetic high positioned over the gradient of a broad gravity low is modelled with another intrusive body at a depth of 6 km with the reverse magnetization direction of the Deccan basalts. Thus, the model depicts large thickness of sediments beneath the Tapti rift zone which is infected by mafic intrusions of Deccan basalts along the faults at the margin.

Adopting the same modelling approach as performed along profile P1, results of joint modelling of G-M anomalies along profile P2 is presented in Fig.7. The interpreted section reveals thick Mesozoic sediments in the central part. The gravity high and associated magnetic low in the southern part is attributed due to high density intrusive having remnant magnetization direction corresponding to normal polarity of Deccan trap. However, gravity and magnetic high near station 70km is interpreted due to intrusive body at a depth of 6km having reverse polarity of remanat magnetization direction. The prominent magnetic high and associated gravity low near the northern end of the profile is caused due to thick trap and deeper basement.

Discussion and Conclusions

Integrated interpretation of the magnetic and gravity data combined with the known surface geology and seismically constrained basement provides new and useful knowledge of the sub-basalt geology of the Deccan Syneclise of central India. Results from interactive 2D joint modelling of gravity and magnetic data (Figs. 6 & 7) indicate variable thickness of Deccan Traps ranging from 0.5 to 1.5 km while the thickness of underlying Mesozoic sediments varies from less than 0.5 km to as large as 2.0 km below the Tapti rift zone. The most significant finding is the presence of mafic intrusive bodies in the upper crust at depths of 4 and 6 km below the Deccan basalts. These intrusive show a remanant magnetization direction that is the same as that of the Deccan basalt and thus favours their genetic link. Presence of E-W trending dykes of Deccan basalt exposed on the surface in the Tapti rift valley suggests that the mafic intrusive are genetically linked in some proportion at depth. Possibly the basement intrusive were emplaced along the margins of the rift zone and reached the upper levels of the crust from a large magma chamber formed at the crust mantle interface at the time of Deccan volcanism. Bhattacharji et al. (1996) and Ju et al. (2013) proposed a model for the magma chamber positions in the Deccan Volcanic Province where the plutonic rocks intruded along the Narmada-Tapti graben. They argued that this discordance allowed enough space to accommodate relatively large amounts of molten magma as secondary magma chamber close to the surface up to a depth of 7 km. The molten material further uplifted during or after the Late Cretaceous and the mafic bodies were exposed as dykes or remained close to the surface. The inferred model thus explains the origin of intrusive bodies emplaced into the upper crust of the Narmada Tapti rift zone. Thus, the model depicts large thickness of sediments beneath the Tapti rift zone which is intruded by Deccan basalts along the margin of the Tapti basin. Hence the present study amply demonstrates that efficacy of joint modelling of gravity and magnetic data to delineate the sub trappean geology.

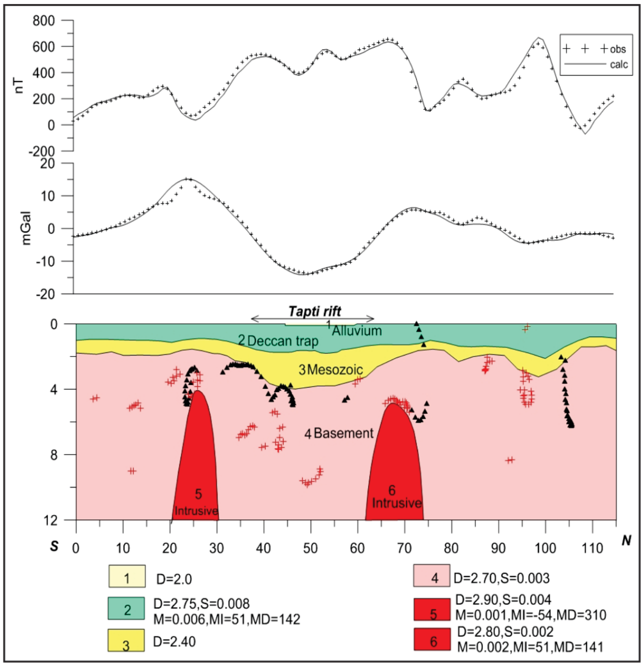

Fig. 7: Sub-basalt geology derived from joint modelling of gravity and magnetic data along profile P2. Solid triangles and plus sign in the depth section indicate depth derived from Euler and analytical signal of magnetic data respectively.

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