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Research paper

Crustal structure of the western Indian shield: Model based on regional gravity and magnetic data

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A R T I C L E I N F O

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A B S T R A C T

Regional surface gravity data and global satellite magnetic data have been utilized to generate a preliminary model of the crustal structure along a southwest–northeast profile (Gadra–Fatehpur) through western Rajasthan. The study area represents the western part of the Indian continental landmass which has undergone several major episodes of repeated subduction/collision, plume traces and rifting from Archaean to recent times. The temporal and spatial relationship between the various geotectonic provinces is quite complex, thereby limiting the emergence of a suitable crustal structure model for this region. Exposures of the Malani Igneous Suite (MIS), a product of bimodal volcanism (~780 Ma), and considered to be the third largest felsic magmatic province of the world, is evident along the profile and also to the southwest of the study area. The easternmost part of the profile is close to the DAFB (Delhi Aravalli Fold Belt), a Proterozoic orogenic belt.

This study probes the geometry of the different crustal units in terms of density and susceptibility variations in order to decipher the imprints of the major tectonic processes the region has undergone. In order to decipher the crustal geometry of the Gadra–Fatehpur profile, two NW–SE gravity and magnetic profile vertical sections (A–A′ in the south and B–B′ in the north) are modelled on the basis of the constraints provided from previous seismic models. The crustal model of the Gadra–Fatehpur profile is composed of alluvium, Tertiary sediments, MIS, Marwar Supergroup, low-density layers (LDLs) and the middle–lower crustal layers, with a distinct change in configuration from the southwest to northeast. The Moho dips from SW to NE, the MIS in the SW gives way to the thick pile of the Marwar Supergroup to the NE. The evolution of MIS has been suggested to have occurred as a consequence of delamination of the upper mantle. LDLs are incorporated in Gadra–Fatehpur model. In the SW, LDL (2550 kg/m^3) lies below the MIS in the NE, another LDL (2604 kg/m^3) is depicted below the mid-crustal layer.

1. Introduction

The western part of the Indian shield comprises the Marwar craton in the west and the Bundelkhand craton in the east, welded along the Delhi Aravalli Fold Belt (DAFB) during the Paleoproterozoic (Sinha-Roy et al., 1998). This seems to be a plate collision boundary as supported by the geophysical data (Vijaya Rao et al., 2000) which is used to explain the tectonic evolution of the DAFB. Naganjaneyulu and Santosh (2011), based on 3D gravity models have shown the existence of continental amalgamation in NW India. The Malani Igneous Suite (MIS) spreads over a large area (~50,000 km^2) of the northwestern part of the Marwar craton, and outcrops to the south of the craton (Fig. 1). It is dominantly made up of felsic (rhyolitic) lava flows and granitic plutons, with subordinate mafic lavas, and felsic and mafic dykes (~780 Ma; Rathore, 1995). Dharma Rao et al. (2012) found Cryogenian ages (765–768 Ma) from the SHRIMP U-Pb of analysis zircons in the basalts and associated rhyolites of the Sindreth Group. This suggests the presence of an arc setting associated with Neoproterozoic subduction prior to the final amalgamation of the Gondwana supercontinent.

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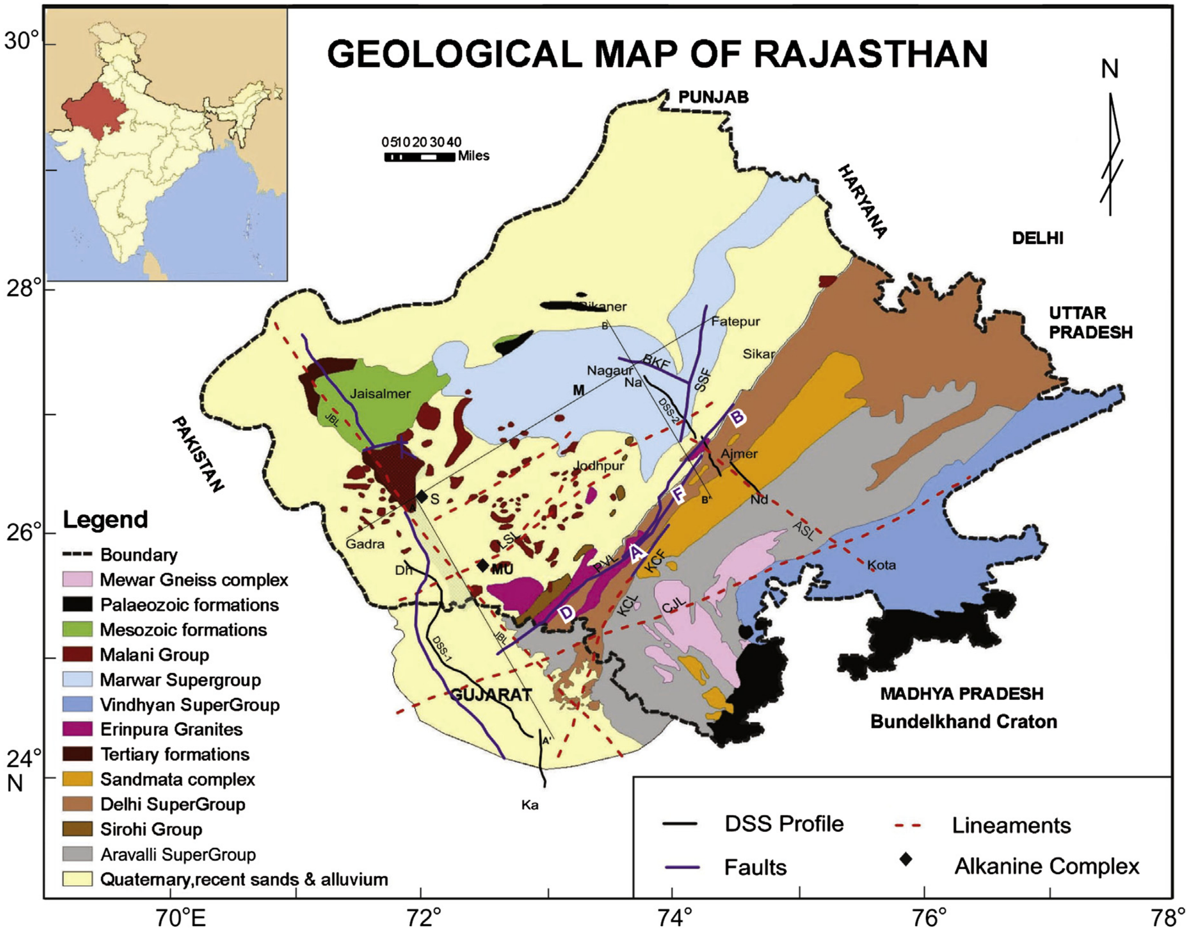

Figure 1. Geologic and tectonic map of Rajasthan. LSL: Luni–Sukri Lineament; JBL: Jaisalmer–Barwani Lineament; KCL: Kishangarh–Chipri Lineament; CJL: Chambal–Jamnagar Lineament; ASL: Ajmer–Sadia Lineament; SSF: Sardhar Shahar Fault; BKF: Bhagu–Kathu Fault; PVL: Pisangan–Vadnagar Lineament; DSS: Deepseismic sounding profiles; S: Sarnu dandali; MU: Mundawara; DAFB: Delhi Aravalli Fold Belt; M: Marwar Basin; Dh: Dharimanna; Ka: Khatana; Na: Nagaur; Nd: Nandsi.

The Malani province represents a large, intraplate, anorogenic felsic event, which is why some workers have ascribed it to an early mantle plume (Sharma, 2003). In the southern part of the craton, at Sarnu Dandali and Mundwara, evidences of intrusions predating the Deccan event around 68.5 Ma have been found (Ray and Pandey, 1999). Signatures of pericontinental rifting that lead to the formation of the Barmer basin between early Jurassic and Tertiary are also evident (Biswas, 1982). Sinha-Roy et al. (1995) suggested the evolution of MIS as a result of low-angle subduction of the Delhi crust (oceanic?) from DAFB beneath the western Rajasthan craton. It is pertinent that the collision which was responsible for DAFB must have been driven by slab-pull or by ridge-push over the entire plate in question and hence it may be expected that the alterations in the crustal structure due to emplacement of the MIS would show different signatures in the vicinity of the DAFB.

Geophysical evidences are sparse in the western part of Rajasthan (Marwar craton) in the trans-Aravalli area because the crustal structure due to the MIS must have been altered in the vicinity of DAFB. This points to the evidence of the presence of MIS as the low Bouguer anomaly of this region in an engulfed high. Seismic imaging of the crust along the 400 km Nagaur–Jhalawar deep seismic reflection profile has provided information on the broad crustal structure of the orogenic region (DAFB) and part of the Marwar Supergroup, which covers a part of the present study region (Tewari et al., 1997). Satyavani et al. (2004) showed the presence of a Low Velocity Layer (LVL) in the Marwar basin and underplating all along the Naguar–Nandsi sub profile of Naguar–Jhalawar profile. Another seismic profile (Dharimanna–Kathana) in the south of the study area provides vital seismic velocity information for constraining density values (Kaila et al., 1990). The thickness of the magnetic crust in this area estimated from the MAGSAT data for the DAFB is around 36–40 km (Mishra, 1987).

In the present study, an attempt is made to examine the prominent anomalies in the regional gravity and magnetic data (Figs. 2 and 4) for deciphering the subsurface geology, which dominates the southwestern part of the craton and fades out to the north and northeast, apparently getting obliterated over the expanse of the Marwar basin. Two NW–SE gravity and magnetic profile vertical sections (A–A′ in the south and B–B′ in the north) are modelled on the basis of constraints provided from the previous seismic models (Figs. 5 and 6). These seismic data were obtained from deep seismic sounding profiles in western Rajasthan (Kaila et al., 1990; Tewari et al., 1997; Satyavani et al., 2004). These sections subsequently serve to constrain a crustal model along an SW–NE profile (Gadra–Fatehpur), running across the western part of the Marwar craton, sub-parallel to the DAFB. It is constructed on the basis of existing geological knowledge as well as the Bouguer gravity anomalies (GSI-NGRI, 2006) and the global magnetic model (Maus et al., 2009). The model reveals the nature of interaction between the different crustal units associated with the various tectonic episodes of the past, and further sheds light on the probable dynamics of collision, origin of felsic magmatism, formation of

Marwar basin, Reunion plume traces and neotectonic activities that have manifested as lineaments in the study area.

2. Geotectonic history

The geology of Rajasthan has been studied by many experts over decades and the different major geological units and prominent faults and lineaments of this region are shown in Fig. 1. The crust of the northwestern Indian craton in Rajasthan comprises the Archaean Banded Gneissic Complex (BGC) forming the basement, overlain by the Proterozoic Delhi Aravalli Fold Belts of Delhi and Malani Igneous Suite, most of which are covered by the Tertiary and Quaternary sediments (Sinha-Roy et al., 1995). Studies by Gopalan et al. (1990) have provided constraints on the ages of the pre-Aravalli basement rocks. Detailed geological mapping by Roy and Jakhar (2002) suggests a wide variation in the spatial and temporal evolution of the region through different geodynamic processes.

West of the Aravallis, the surface geology is dominated by the Marwar formation to the north and by a more complex interplay of granites, volcanics, Tertiary formations, mafics and ultramafics to the south. The craton boundary possibly extends into the political boundary of Pakistan, ending at the N–S running Suleiman–Kirthar Himalaya ranges. The Sirohi and Erinpura granites and associated pegmatites and aplites, which are exposed in a number of patches at the southwestern edge of the DAFB, are considered to be the results of the protracted event of diastrophism and deformation, related to the Delhi orogeny around 1000–850 Ma (Choudhary et al., 1984; Volpe and Macdougall, 1990; Dasgupta et al., 2011; Pandit et al., 2011). In the subsequent phase of Neoproterozoic crustal building, this region has witnessed bimodal volcanism (Bose, 1989; Bhushan, 1995) in the form of Malani volcanics or Malani Igneous Suite, determined to be of 780 Ma by Rb-Sr dating (Rathore, 1995). These rocks occur as an unconformity bounded sequence occupying a large area ($\sim$50,000 km^2) of the northwestern Indian shield. Felsic (rhyolitic) lava flows, granitic plutons, with subordinate mafic lavas with felsic and mafic dykes, show evidence of at least four episodes of magmatism spread over 100 million years (Stern and Hedge,1985; Santosh and Yoshida, 1992; Rathore et al., 1999). Stern (2008) believed that increased explosive volcanism could be the main cause of such worldwide activities during the Neoproterozoic. Surface geological observations indicate that Malani volcanism occurred along parallel crustal fractures that developed as a result of extensional tectonics, indicating an intracratonic rift setting, which may or may not be associated with plume tectonics (Bhushan, 2000; Sharma, 2003).

The southern part of the Marwar craton is cut across by the oil producing Barmer and Jaisalmer rift basins formed during different stages of India–Gondwanaland separation throughout the Phanerozoic (Torsvik et al., 2005). During the early Tertiary and upper Cretaceous, magmatic activities pertaining to the Deccan Trap emplacement affected the southern part of the region which is evident from intrusives of alkaline magmatic origin at the southern edge of the study region. Such magmatism has been associated with the mantle plume interaction during the Cretaceous–Tertiary period (Ray and Pandey, 1999).

The Phanerozoic stratigraphy of the Marwar Supergroup in the north and central parts of the Marwar craton on the other hand, has remained mostly unaffected by tectonic deformation, metamorphism and migmatization. Phanerozoic formations of the Marwar Supergroup rest unconformably over the MIS and is overlain by early Permian rocks (Rathore et al., 1999; Torsvik et al., 2001). The Marwar Supergroup of lower Cambrian age (Kumar and Pandey, 2010), composed of shallow water sediments, makes up the earliest succession. This is marked by the presence of evaporite sequence with possible connections with the phosphorite horizons of Krol belt in Lesser Himalaya, Hazara in Salt Range of Pakistan and Birmania formations in western Rajasthan (Banerjee and Mazumdar, 1999). Fluvial sedimentation occurred during mid-Jurassic to Cretaceous when the Indus basin at the westernmost edge of the craton saw a major uplift and withdrawal of the sea (Sharma, 2007). Repeated transgressions and regressions are inferred in the western and southern parts during the Tertiary indicating the instability of the Indian shield prior to Himalayan collision. Continental deposition occurred only during the Quaternary; the resultant alluvial formations are seen both in the south and north (Dasgupta, 1975, 1977; Sinha-Roy et al., 1998).

Several major lineaments and faults have been traced from geological studies, which are marked in Fig. 1. These lineaments have basically controlled the neotectonic activities of this region (mostly referred to as the Thar Desert). LSL (Luni–Sukri Lineament) is a composite lineament system comprising a set of sub-parallel curvilinear lineaments, oriented east–west from Rann of Kachchh through the NE–SW trending Luni river and extending to the northeast of Ajmer. The CJL (Chambal–Jamnagar Lineament) is a NW–SE trending large scale lineament which follows the Precambrian tectonic boundaries. JBL (Jaisalmer–Barwani Lineament) is a part of the 1000-km-long ESE–WNW trending lineament which passes northeast of Gadra and appears as a boundary between the Paleoproterozoic Aravalli cover and the reconstructed basement. There are large scale lineaments which can be traced for hundreds of kilometres in the area (Roy and Jakhar, 2002). The NNE–SSW trending KCL (Kishangarh–Chipri Lineament) is a major tectonostratigraphic boundary between the Delhi Supergroup to the west and the pre-Delhi rocks to the east. The lineament forms a contact between the Delhi rocks and the Sandmata complex. ASL (Ajmer–Sadia Lineament) occurs as two sub-parallel lineaments in the Ajmer sector along the intersection of which the Aravalli mountains are dissected and dismembered. SSF (Sardarsahar Fault) is aligned in the N–S to NNE–SSW direction, with a confined downthrow of over 400 m in the west. In the Quaternary sediments, subsurface investigations show a downthrow of 700 m. BKF (Bhagu–Kathu Fault) is aligned NNW–SSE and runs perpendicular to the Sardarshar Fault.

In general, though much is known about the different aspects of geological evolution of the study area particulars of the present subsurface geometry and constitution can only be deciphered on the basis of geophysical data from the region. This in turn would corroborate geological understanding and provide clues as to how successive episodes of tectonic activity affected the formations sequentially such as alluvium, MIS and Marwar Supergroup. With this backdrop, the Gadra–Fatehpur profile ($\sim$480 km long) which crosses major gravity and magnetic anomalies and some important geological features such as Malani Igneous Suite (MIS) and the Marwar Supergroup has been selected to understand the evolution of this region.

3. Gravity data

The Bouguer anomaly map, adopted from the GSI-NGRI (2006) is presented in Fig. 2. The digitized data was available from the data bank of National Geophysical Research Institute (NGRI), Hyderabad. The Bouguer gravity anomalies (terrain-corrected) show a large variation of about 300 mGal. On examination, the map shows positive gravity anomalies of about 100 mGal in the western part of Rajasthan, trending NNW–SSE. These anomalies continue southward into Gujarat and do not have any correlation with surface geology, which consists primarily of Quaternary alluvium. The Barmer and Jaisalmer basins are reflected as gravity lows but the Cambay basin at the southern edge of the study area is located over a positive gravity anomaly. In the central and eastern parts the

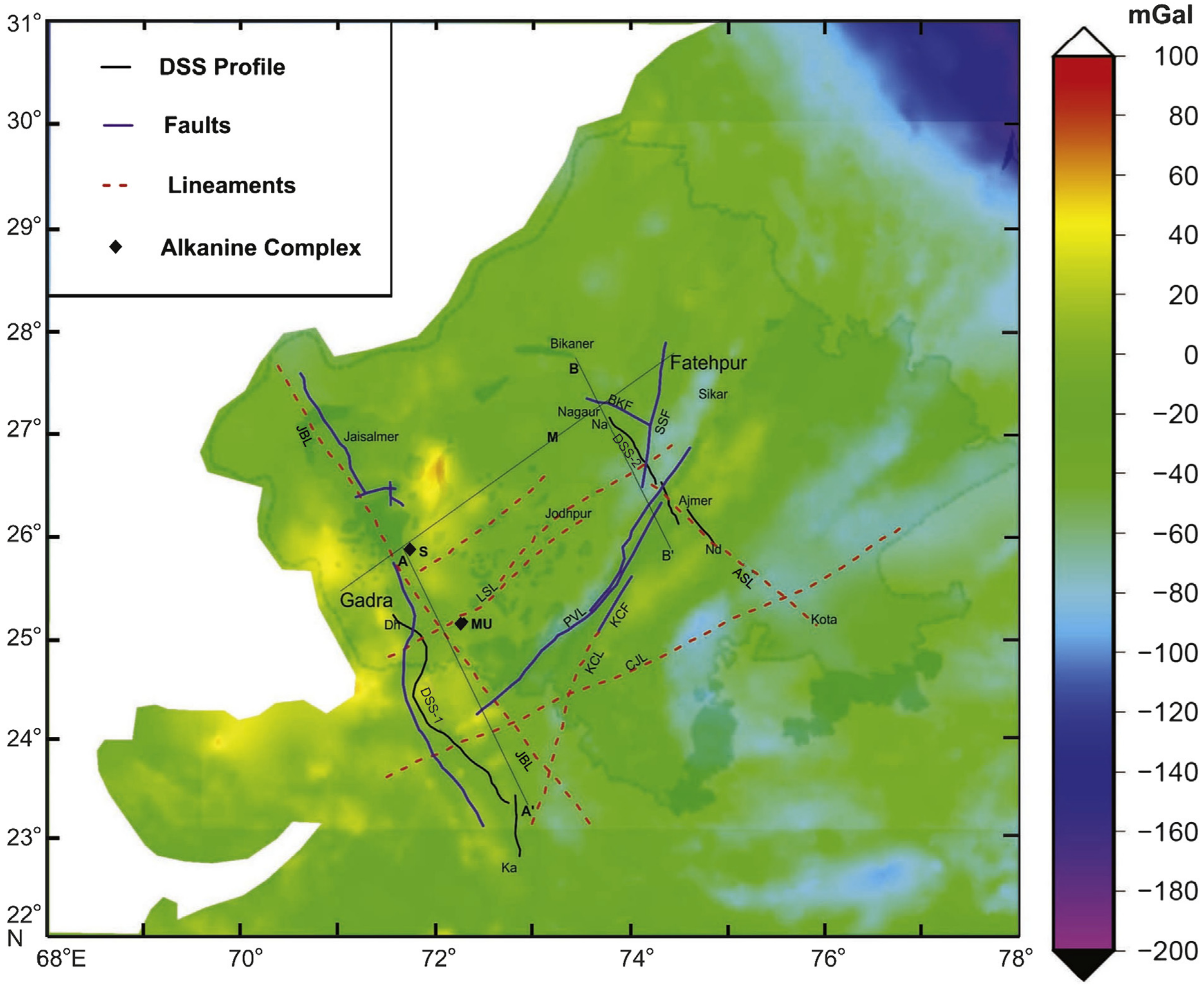

Figure 2. Gravity Bouguer anomaly map of Rajasthan with geology. LSL: Luni–Sukri Lineament; JBL: Jaisalmer–Barwani Lineament; KCL: Kishangarh–Chipri Lineament; CJL: Chambal–Jamnagar Lineament; ASL: Ajmer–Sadia Lineament; SSF: Sardhar Shahar Fault; BKF: Bhagu–Kathu Fault; PVL: Pisangan–Vadnagar Lineament; DSS: Deepseismic sounding profiles; S: Sarnu dandali; MU: Mundawara; M: Marwar Basin; Dh: Dharimanna; Ka: Khatana; Na: Nagaur; Nd: Nandsi.

gravity anomalies trend NE–SW following the trend of the DAFB and possibly marking the zone of amalgamation between the Marwar and Bundelkhand cratons.

4. Topography

Gravity being closely linked with topography, the elevation map is presented in Fig. 3. The gravity highs in the west are consistent with low relief regions; this trend continues into Gujarat. The topography is linear along the DAFB in the central portion of the map, where the highest point is greater than 1000 m above mean sea level. This is associated with the NE–SW trending paired gravity anomalies. In the east, this topography gives way to the Indo-Gangetic Plains possibly controlled by the extensions of topographic ridges and valleys below the alluvium (Gupta and Jindal, 2000). In the Bouguer anomaly map this is reflected as a series of gravity lows along the eastern flanks of the relief.

5. Magnetic data

The use of regional magnetic anomalies for the interpretation of crustal configuration is gaining strength as observational and computational techniques have received a fresh impetus in recent times. Joint inversion of regional gravity and magnetic anomalies, leading to delineation of collision zones which have resulted in thermal demagnetization, have been published by Zheng and Arkani-Hamed (1998). Hemant and Maus (2005) have provided examples of cases where prominent regional magnetic anomalies have been modelled to understand crustal structure and its deformation in Greenland, Africa and Siberia. Structure of the Indian offshore from satellite derived magnetic data has been interpreted by Rajaram et al. (pers. comm.).

In the quest for parallel geophysical evidences to reduce ambiguities of interpretation, we attempt to extract information on crustal configuration, based on magnetic data. In the earlier studies, surface magnetic data along the Nagaur–Jhalawar DSS profile across the DAFB has been analysed by Mishra et al. (1995) and Bansal and Dimri (2005). Depths of about 1.5–2.8 km for the magnetic sources have been suggested by them. Aeromagnetic data is available over the known areas of mineralization in the southern parts of the DAFB (Porwal et al., 2006) which however does not cover the present study area. Since the above data does not cover the entire region of study, data for the current study is derived from the global magnetic anomaly models derived from the CHAMP satellite as well as available surface data. The EMAG2 global model (Fig. 4) (Maus et al., 2009) is compiled from satellite, marine, aeromagnetic and ground magnetic survey with inclusion of additional grid and track line data both over the land and the

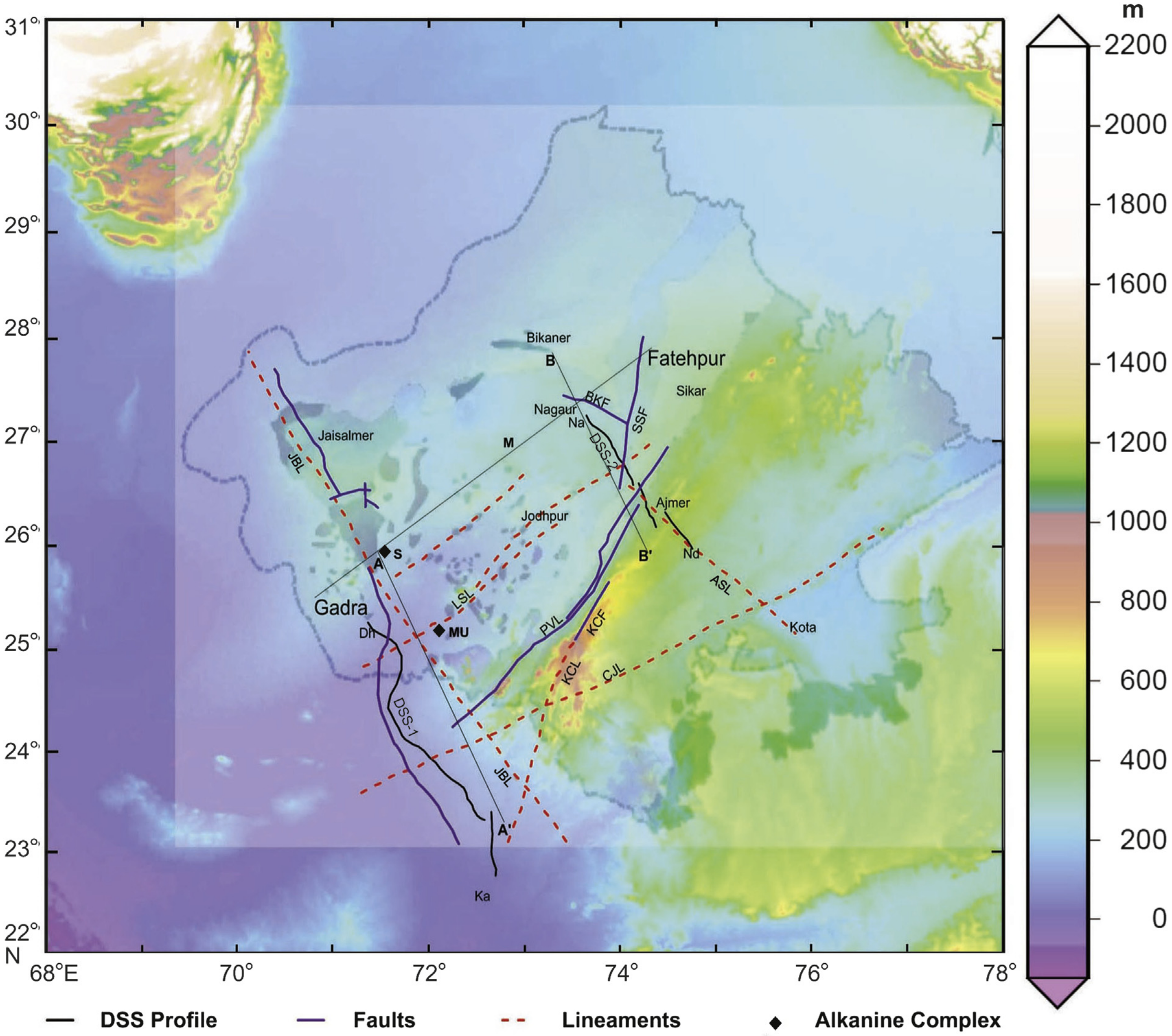

Figure 3. Elevation map of Rajasthan with geology. LSL: Luni–Sukri Lineament; JBL: Jaisalmer–Barwani Lineament; KCL: Kishangarh–Chipri Lineament; CJL: Chambal– Jamnagar Lineament; ASL: Ajmer–Sadia Lineament; SSF: Sardhar Shahar Fault; BKF: Bhagu–Kathu Fault; PVL: Pisangan–Vadnagar Lineament; DSS: Deepseismic sounding profiles; S: Sarnu dandali; MU: Mundawara; M: Marwar Basin; Dh: Dharimanna; Ka: Khatana; Na: Nagaur; Nd: Nandsi.

oceans and has a resolution of 2 arc minutes. Such regional anomalies reflect magnetic signatures of deep-seated crustal sources of significant susceptibility contrasts.

The magnetic data, presented in Fig. 4, corresponding to the gravity highs (Fig. 2) in the western part of Rajasthan, show a major magnetic high along with a low further west. Smaller positive magnetic anomalies correlate with gravity highs at the westernmost edge of the map. The gravity signatures of the DAFB show no corresponding reflections in the total intensity anomaly map. On the other hand, in the eastern part of the map, over the Ganga Plains (east of DAFB), several prominent magnetic highs and lows represent peculiarities of the subsurface structure. Unlike the prominent pair in the west, which lies along the continuation of JBL, the anomalies to the east do not exhibit a clear correlation with any faults or lineaments.

6. Constraining information for modelling along the Gadra–Fatehpur profile

The variations of density and susceptibility along a 480-km-long profile from Gadra to Fatehpur crustal architecture are modelled on the basis of the prominent regional gravity and magnetic anomalies. This profile runs across the northwestern part of the craton and is chosen so that it intersects the most prominent gravity and magnetic anomalies. In order to further reduce ambiguities inherent in potential field modelling, two vertical sections (A–A′ and B–B′) perpendicular to the Gadra–Fatehpur profile and cutting it at the south and north ends have been modelled on the basis of two Deep Seismic Sounding (DSS) profiles in the region: the Dharimanna–Kathana (Dh–Ka) profile to the south (DSS-1) and the Nagaur–Nandsi (Na–Nd) profile to the north (DSS-2) (Fig. 1). Dharimanna (DSS-1) is the nearest location from Gadra and Nagaur is the nearest location from Fatehpur (DSS-2). It has been suggested that the Marwar Supergroup rests unconformably over the MIS or Paleoproterozoic Aravalli/Delhi metamorphics from the DSS-2 profile (Prasad et al., 2010).

The density, susceptibility parameters as well as the depth estimates of the subsurface formations derived from these DSS profiles were incorporated as constraints for modelling the Gadra–Fatehpur profile. Many exploratory wells have been drilled by India's national oil companies (OIL and ONGC) close to this region. Thus this region assumes importance from the economic point of view.

Velocity information through reinterpretations of the Nagaur–Nandsi DSS profile (Tewari et al., 1997) by Satyavani et al.

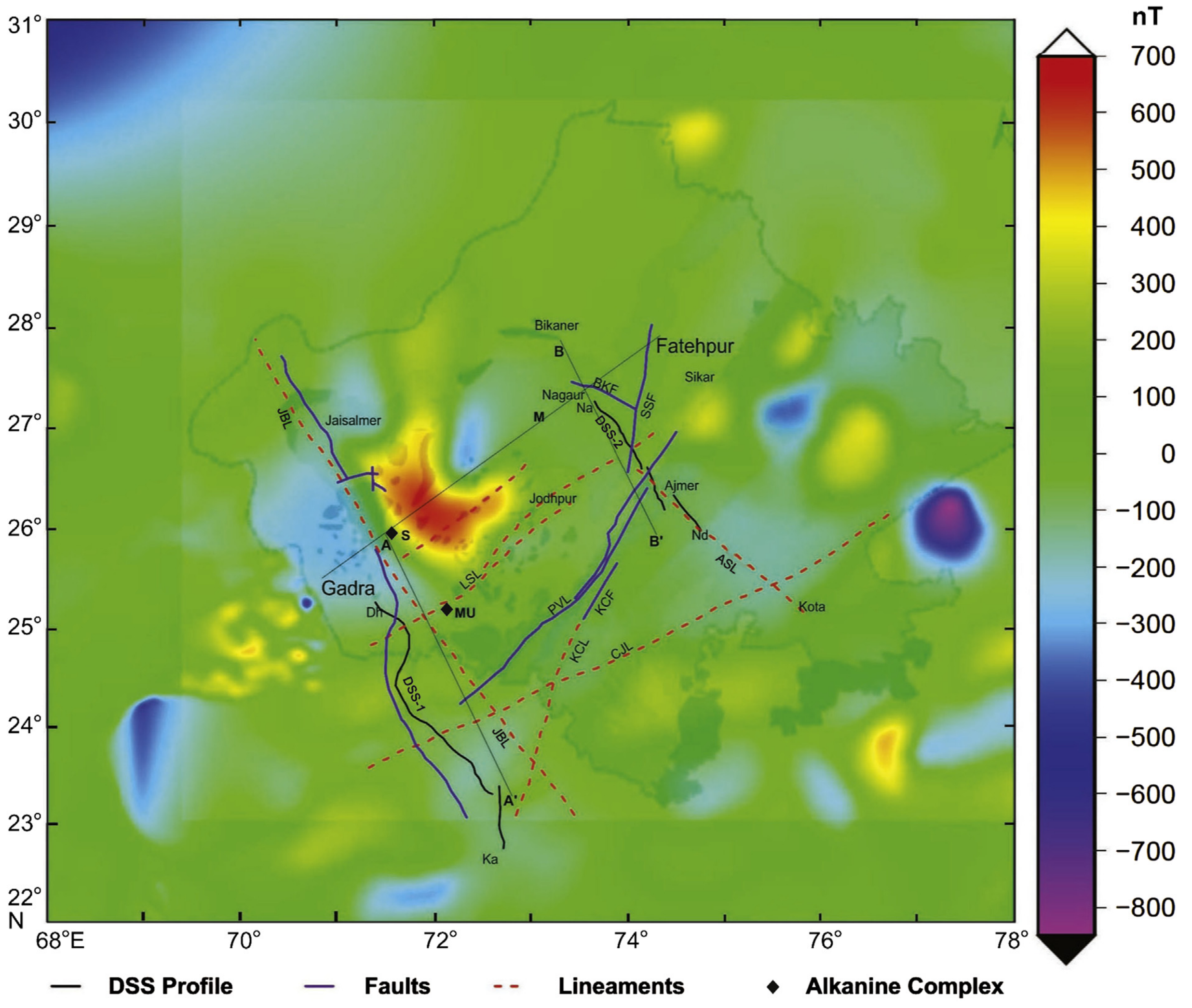

Figure 4. Satellite magnetic contour map of Rajasthan with geology. LSL: Luni–Sukri Lineament; JBL: Jaisalmer–Barwani Lineament; KCL: Kishangarh–Chipri Lineament; CJL: Chambal–Jamnagar Lineament; ASL: Ajmer–Sadia Lineament; SSF: Sardhar Shahar Fault; BKF: Bhagu–Kathu Fault; PVL: Pisangan–Vadnagar Lineament; DSS: Deepseismic sounding profiles; S: Sarnu dandali; MU: Mundawara; M: Marwar Basin; Dh: Dharimanna; Ka: Khatana; Na: Nagaur; Nd: Nandsi.

(2004) has been used to constrain the initial model, especially at the northeastern end where three prominent faults are traceable. The velocity–depth section shows a distinct upwarp of all the layers, right from the upper crust to the lower crust. Presence of a mid-crustal LVL in the Nagaur–Rian sector with velocities appreciably different from the LVL detected in the DSS-1 profile makes it an interesting observation, which indicates that the crustal structure of this region is tectonically complex. The depth and velocity information, derived from the two seismic profiles, which are used in our model are summarized in Table 1. Density values have been assigned to the corresponding geological units (based on the velocities) on the basis of the results in Ludwig et al. (1970), Barton (1986), and the two seismic profiles in the region.

In order to account for the long-wavelength magnetic anomalies derived from the combined magnetic model, the concept of Vertically Integrated Susceptibility (VIS) from Hemant and Maus (2005) has been used in the present study. Depending upon the known rock types of the region, they are assigned a standard susceptibility value and using the Crust 2.1 seismic crustal structure, a VIS model is computed at each point of the region. The crust is thin in

Table 1
Summary of geological formations and geophysical parameters.

Dharimanna–Khatana profile			Formation	Nagaur–Nandsi profile			Formation
Velocity (km/s)	Density (kg/m^3)	Susceptibility (nT)		Velocity (km/s)	Density (kg/m^3)	Susceptibility (nT)	
2.1	1800	0	Alluvium	–	1800	0	Alluvium
3.2	2200	0	Tertiary	4.6–4.8	2495	0	Granitic rock
4.3–4.5	2400	0	Tertiary sediments	5.5	2560	0	Marwar Group
5.9–6.0	2600	0	MIS/granitic rock	5.5–6.1	2565–2780	0	Granitic rock
5.5	2550	0	Low density layer	6.0	2604	0	Low density layer
6.6–6.7	2800	0	Middle crust	6.5	2800	0	Middle crust
7.2–7.4	2900	0.006–0.093	Lower crust	6.8–7.2	2900–2950	0-0.032-0.1	Lower crust
8.0–8.1	3300	0	Upper mantle	8.0	3300	0	Upper mantle

comparison to the altitude of satellite. Hence, satellite magnetic maps are incapable of resolving individually the parameters viz., depth and susceptibility distribution, which are responsible for the crustal anomalies. Hence, only bulk susceptibilities, susceptibility of lower crustal formations multiplied by the thickness of the crust at each point of the globe, can be inferred irrespective of the position of the magnetic body in that vertical column. This method is adopted in the current model computation and the susceptibility is assigned only to the lower crustal rocks.

7. Interpretation of gravity and magnetic data

The subsurface geology of Gadra–Fatehpur profile is modelled by representing lithological layers as equi-density and/or equi-susceptibility layers and/or blocks. The units are defined by contrast boundaries of the layers/blocks. For 2.5D modelling, the third dimension '*y*' (in and out of the plane of the profile) is approximated by one or more given distances, thus generating a quasi-3D model. To obtain consistency between observed and compared gravity and magnetic data, physical parameters observed from measured seismic velocity are constrained and the layer dimensions are changed in an iterative manner. The best fit between observed and computed anomalies for both the gravity and magnetic data was obtained by interactively modifying the configuration of the assumed bodies.

7.1. Subsurface model along A–A′

This profile, as already mentioned, has been modelled basically to provide constraints to the Gadra–Fatehpur profile, particularly for the end regions of the profile. Fig. 5 depicts the crustal configuration along the 330 km (A–A′ section), constrained by seismic inputs from the Dharimanna–Kathana deep seismic investigations (Kaila et al., 1990). The consistency between the observed data and computed magnetic and gravity responses of the model are shown in the two top panels. The bottom panel depicts the model geometry, about 330 km in length and 60 km in depth. The extent of the surface formations has been matched with the exposed lithology from geological maps. The bottom panel is a magnified image of the top 10 km of the near surface features, which lack clarity in the full model due to limitations of the vertical scale.

As per the Dharimanna–Kathana seismic profile (Kaila et al., 1990), the crust is more or less horizontally layered with the crust–mantle boundary at about 33 km depth. Under such constraints, a crustal configuration from the gravity anomalies is attributed mainly to changes in the geometries of the near surface layers of alluvium (1800 kg/m^3), Tertiary (2200 kg/m^3) and another formation (?) belonging to 4.5 km/s (2400 kg/m^3). This formation is assumed to be denser and formed during the early Tertiary with the intrusion of the Deccan Traps (?), since Sarnu is close to the 'A' (A–A′ profile) which is the site of Deccan magmatism. The lower crust happens to be the underplated layer with density of 2900 kg/m^3. This assumption was necessitated because the shallow seismic structure of the seismic profile was not mapped because of the logistical difficulties in the DSS surveys. The western end of the section runs along the gravity and magnetic anomalies instead of across them and hence modelling becomes subjective. Nonetheless the gravity low in the west is attributed to the increased thickness of alluvium and the high at the junction of PVL and JBL, is explained by an upwarp of the upper crustal layers and the absence of

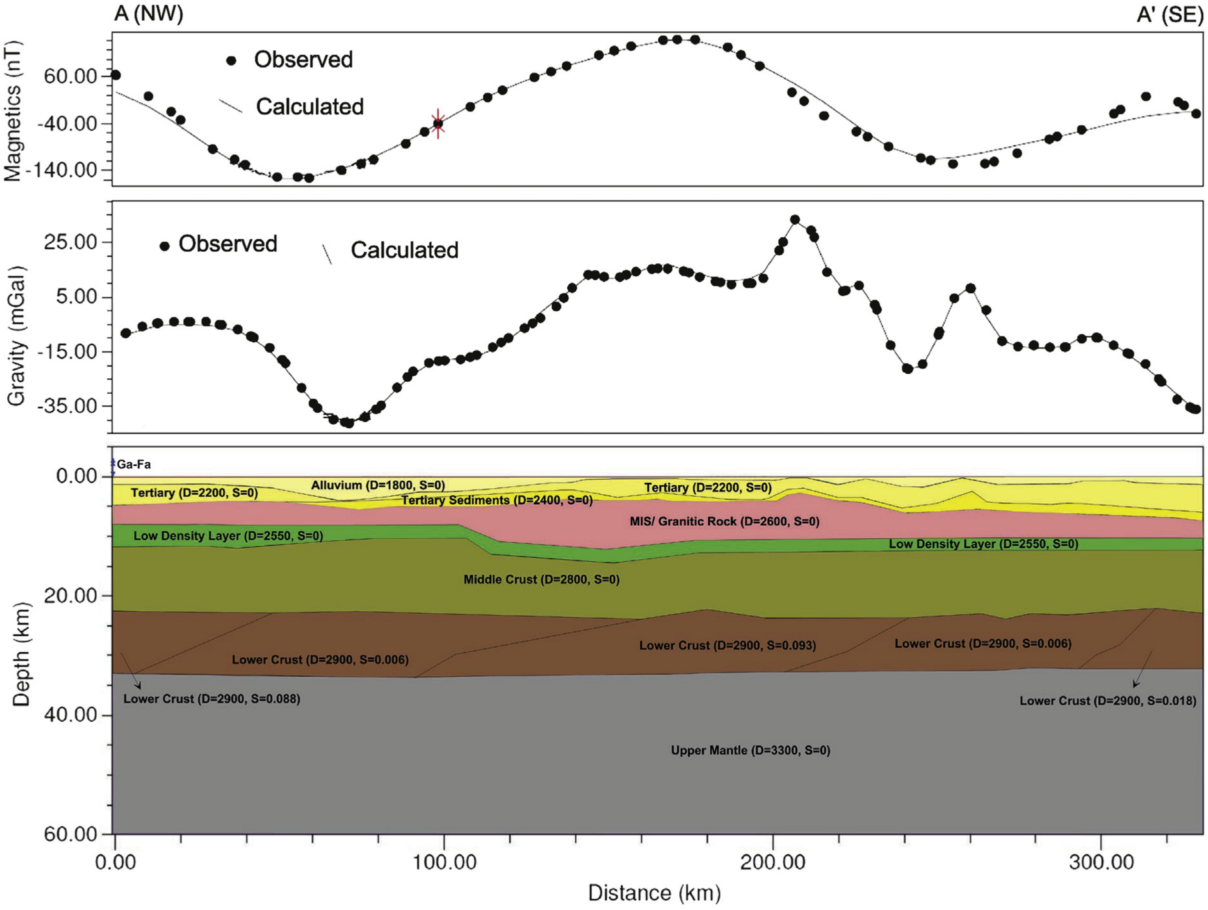

Figure 5. Crustal model along A–A′ profile.

alluvium. The prominent magnetic anomaly is explained by a large susceptibility (0.093 SI units) observed in the lower crust of the central part of the profile and which is distinctly lower on both the flanks.

7.2. Subsurface model along B–B′

The crustal structure along the 245 km B–B′ (Fig. 6) section is constrained by inputs from the Nagaur–Nandsi profile (Satyavani et al., 2004). From the west to east this section depicts clear change in the nature of the crust; the crust appears to be sub-horizontally layered in the west and becomes faulted and disturbed to the east where it is proximal to the DAFB, marked by the presence of a distinct positive anomaly. The crust–mantle boundary in the crust is at the depth of 40 km in the west while it is at 46 km in the east. The lower crust happens to be the underplated layer with density 2900 kg/m^3. The magnetic anomalies along this section are not so prominent and the lower crustal rocks are ascribed gentle susceptibility contrasts, until the beginning of the DAFB region, where the value is clearly lower compared to the rest of the profile.

7.3. Subsurface model along the Gadra–Fatehpur profile

The geometry of the subsurface along the 480 km long Gadra–Fatehpur profile, obtained from combined modelling of observed gravity and magnetic anomalies is presented in Fig. 7. The laterally projected positions of intersection of this profile with the earlier discussed DSS lines (A–A′ and B–B′) are represented by two vertical pseudo-logs indicating the interpreted depths from the seismic data and marked as A–A′ and B–B′ at the surface. The ‘S’ marks the projected position of exposures of alkaline magmatism at Sarnu Dandali, about 5 km to the north.

From the southwest to the northeast, for the first 180 km, the gravity and magnetic signatures along the profile depict very prominent anomalies: a regional high in the gravity field (about 25 mGal) is punctuated by two lows and a low-high pair in the magnetic field. The subsurface model geometry, guided by velocity information from the DSS-1 profile, depicts a layer of surface alluvium of maximum depth of 2 km corresponding to the Barmer basin, tapering off to both sides. In the area of the Barmer basin, this is underlain by the Tertiary sedimentary formations of average thickness of 1.5 km. This is followed by the MIS ($D = 2600$ kg/m^3) of thickness ranging between 3 and 7 km. The extent of substantial quantities of the MIS computed from this model ends at the boundary of the surface exposures of the Marwar formations. This coincides with the presence of the prominent positive magnetic anomaly of about 700 nT. A low density layer of 2550 kg/m^3 and thickness of 4 km extends from the southwest extremity, below the Marwar formations at depths of 13 km. This is followed by normal middle crustal rocks ($D = 2800$ kg/m^3). The lower crust, however, shows sharp variations in susceptibility. Towards A–A′, VIS value is about 0.088, corresponding to 0.0027 SI units, which is ascribed to metavolcanics. Farther to the east, the contrast in VIS is sharp with a value of 0.315, corresponding to lower crustal susceptibility of 0.0091 SI units, which may be ascribed to igneous rocks, having

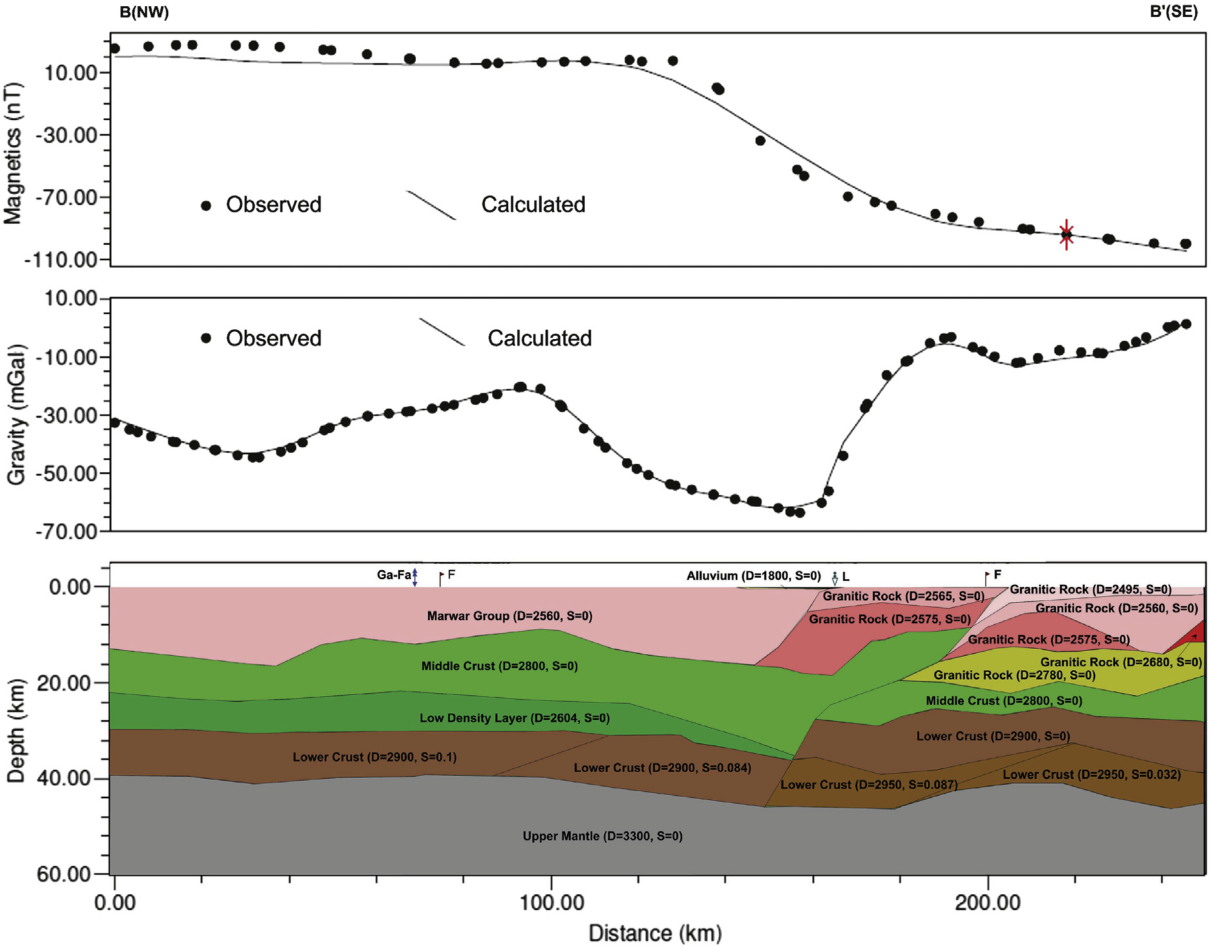

Figure 6. Crustal model along B–B′ profile.

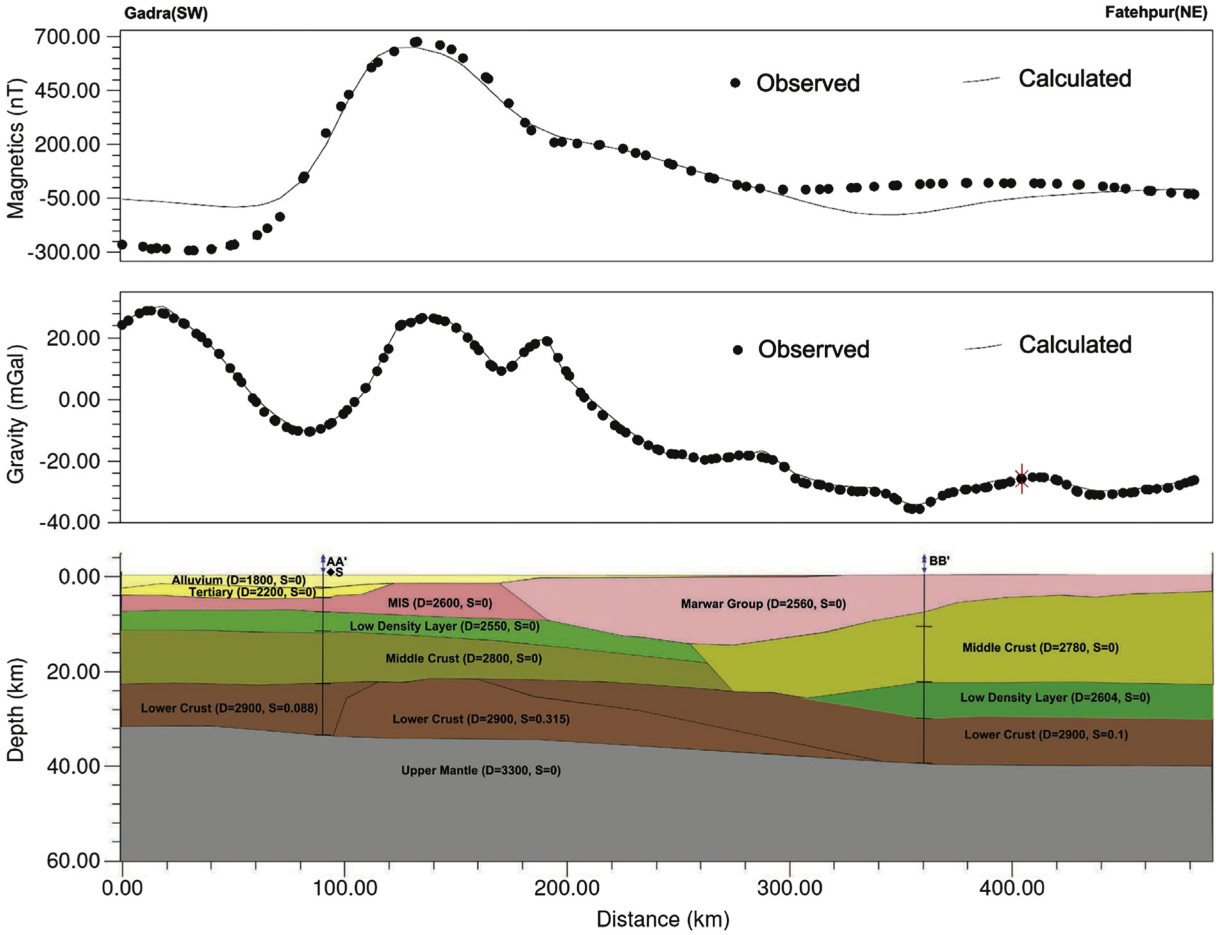

Figure 7. Crustal model along Gadra–Fatehpur profile.

largest thickness below the MIS and to the east VIS value is 0.1, corresponding to 0.0025 SI units.

The northeastern part of the profile, though closer to the DAFB, shows no significant anomalies either in the gravity or magnetic field. Here the surface exposures of the Marwar Supergroup extend to depths of about 14 km, below which the mid-crustal rocks dip in the westerly direction. Below the mid-crustal rocks a low density layer with a density of 2604 kg/m^3 is delineated, based on the constraints from the B–B′ section.

The crust–mantle boundary along the entire profile shows a gentle gradient from 32 km in the southwest to 40 km in the northeast. The shallowing of Moho across the Cambay basin modelled by Tewari et al. (1991) is corroborated by our own modelling results, close to the Barmer basin.

8. Discussion and conclusions

The region under study has a long and complex geological history. The model of subsurface configuration, brought out in Fig. 7, represents a first order result of geophysical investigations, guided by available seismic and geological information, which contributes to the understanding of the imprints in the crustal structure that different geodynamic processes have left behind. The Gadra–Fatehpur profile runs roughly sub-parallel to the axis of the DAFB. The major tectonic perturbations in DAFB was summarized and a 3D gravity model was presented by Naganjaneyulu and Santosh (2011), wherein they explained the architecture of crustal structure in the DAFB region beneath the DSS profile.

The model configuration (Fig. 7) suggests that the crust of the northeastern part predominantly retains the signatures of the Proterozoic plate tectonics pertaining to the DAFB formation, whereas in the southwest the signatures of volcanic activity extending over the region have overprinted the earlier geometry of the crust to a large extent.

Admittedly the seismic controls used are quite regional in nature and consequently the models may see significant modifications in the details, with the availability of new data in the future. The configuration of the Gadra–Fatehpur model suggests the following inferences:

(1) There is a change in crustal regime from the southwest to northeast within the Marwar craton, obviously wrought by different tectono-thermal processes viz., plate collision, delamination, plume impact, rifting and faulting patterns from Proterozoic to recent, influencing the different parts of the profile.
(2) The Proterozoic collision-related orogenies resulted include the making of the DAFB due to the amalgamation of the Marwar and Bundelkhand cratons (Vijaya Rao et al., 2000; Naganjaneyulu and Santosh, 2011). The complexities of the DAFB are beyond the scope of this paper. However, the tectono-thermal processes in the making of DAFB must have altered the crustal configuration in the study region in a very subtle way. Beyond the collision zone to the northwest, the formation of a broad flexural basin is likely to have formed in which sedimentation took place in several phases depending on the

transgression and regression of the sea, possibly from the west and south (Kumar et al., 1997). These are presently seen in the form of Marwar group of rocks. The formation of the Marwar Supergroup, derived from late Neoproterozoic to early Cambrian sediments, is dated at 620–540 Ma (Kumar et al., 1997). The basin is west of the Delhi Fold Belt and consists of flat undeformed clay evaporate sequences. According to Sinha-Roy et al. (1995), the Erinpura granites (850 Ma) and Malani Igneous Suite (850–740 Ma) form its basement, however our model is not able to confirm or reject this idea, on the basis of density and velocity. We believe that the Marwar Supergroup directly rests over the middle crust in the NE region where as it rests over LVL in the NW region of the profile (Fig. 7). The maximum depth of Marwar Supergroup extends to depths of 14 km which is too high (pers. comm., Sinha-Roy). In the absence of seismic constrains in this region, it is possible that Marwar Supergroup may be resting over the MIS and it may continue in the subsurface level further northeast.

(3) The long-wavelength gravity and magnetic fields around the DAFB do not show conspicuous anomalies, leading us to infer that the lithospheric section is in a state of compensation and also that the lower crustal layer does not include rocks of high susceptibility. This prompts us to speculate that delamination and slab breakup, possibly in Meso- and Neoproterozoic times, may have been the mechanism whereby isostatic compensation was achieved. Without more constraints and 3D computations, it is not possible to estimate the location where delamination may have taken place, but it is logical to deduce that this process would modify the crust in the form of crustal-scale faulting and/or underplating (Grover and Wortel, 1993; Zantd and Ammon, 1995). The present model agrees with the underplating model as proposed from both velocity models (Kaila et al., 1990; Satyavani et al., 2004). In such a situation, ductile lower crustal mechanism governed by pressure-driven lateral flow (Block and Royden, 1990) must have played a vital role, whereby the Moho remains flat and extension disturbs the upper and middle crust only. Depletion of material from the lithosphere would result in shallowing of the Curie isotherm, which may lead to demagnetization. Thus traces of magnetic substances would also be obliterated to a large extent. Since Moho in Nagaur sector (northwest) appears as moderate, discontinuous reflections, the strong reflection bands in the southeast part (Tewari et al., 1995) suggest effects of metamorphism and different degrees of magmatism.

(4) The end of the Mesoproterozoic and the beginning of the Neoproterozoic era is recognized as the time period for the breakup of the Rodinia supercontinent, followed by the assembly of Gondwana. The formation of the Malani Igneous Suite is suggested to have occurred during this period (Torsvik et al., 2001; Gregory et al., 2009; Pradhan et al., 2010). The mechanism for its formation still attracts controversy, and various mechanisms, ranging from a plume below the Archaean basement to Delhi orogeny-led extensional tectonics of crust (Choudhary et al., 1984; Bhushan, 2000) have been proposed. An intra-cratonic rift setting has also been suggested, while the presence of a deep mantle plume has been objected to (Sharma, 2003). Sinha-Roy et al. (1995) suggested the evolution of the MIS (~750 Ma) as a result of low-angle subduction of the Delhi oceanic/transitional crust beneath the western Rajasthan craton (post-Delhi orogeny ~1100 Ma). The related distensional tectonics during Neoproterozoic time along with reactivation of orthogonal deep faults and fractures were crafted onto the Marwar craton during the Delhi orogeny (Sinha-Roy et al., 1995). We opine that delamination related magmatism was primarily responsible for providing sediments and water, resulting in MIS/granitic magmatism (~750 Ma), which intruded through the upper crust through shear zones and faults, which themselves were the outcome of the delamination process (Müntener and Hermann, 2001). As a consequence of delamination, upper mantle lava would flow into the crust along weak zones, which would serve as mafic/ultramafic conduits, possibly responsible for felsic composition in the crust. The seismic receiver function analysis (Jagadeesh and Rai, 2008) also reveals the felsic crust in the northwest Indian craton. This is accompanied by alteration in the crust, which probably led to the formation of the felsic Erinpura granites in the study region (Nelson, 1992).

(5) MIS bimodal volcanism is heterogeneous and composed of rhyolites, basalt, andesite, trachyte, welded tuff, alkali granite plutons, veins and dykes of granodiorite, aplite, dolerite and gabbro (Bhushan, 1984). The high thickness of MIS (~7 km) could be due to a mixture with the Deccan Traps. Under this situation of the MIS/granitic rocks, the depth will be reduced in the model. It may be noted that the exposed MIS are mostly low-density rhyolites, which came to the surface due to high buoyancy; occasional exposures of basic MIS could be related to very high buoyant forces during a phase of Malani magmatism. Sharma (1995) opined that the Malani granites could have a mixed crustal source and could be a partial melt product of BGC. Spera et al. (1986) demonstrated that sudden changes of eruption conditions can lead to sharp compositional variations in the outflow deposit, even when the initial composition profile of magma chamber remains continuous.

A series of intra-cratonic rift basins developed under an extensional tectonic regime from early Jurassic to Tertiary in the Barmer, Jaisalmer and Bikaner regions during the Cretaceous–Tertiary period in western Rajasthan, India. The profile cuts across the Barmer basin (~100 km in the North–South direction and ~50 km wide), which contains a sedimentary sequence of middle Jurassic to lower Eocene age; deposited under shallow marine fluvial environment (Sinha-Roy, 1998). The evolution of this basin may be related to the thermo-tectonic events of the Cambay basin of India (Tewari et al., 1991).

(6) In the southwestern end of the profile (Fig. 1), in the Sarnu Dandali and Mundwara region, the crust is intruded by the alkaline magmatic complexes of age 68.43 and 68.57 Ma (Ar-Ar). This is associated with the continental flood basalt of Deccan volcanism and the observed ^{3}He/^{3}He ratio in this region is twelve times higher than the average (Basu et al., 1993), indicating plume tectonics. Ray and Pandey (1999) also support this idea on the basis of their study. Pb loss event around 70 Ma was also reported in this region due to Reunion plume tectonics (Sivaraman and Raval, 1995). According to Sheth et al. (1997), alkaline magmatism is known from many flood-basalt provinces of the world, a natural consequence of plume head incubation. It is difficult to filter out the signatures of delamination and plume tectonics solely on the basis of gravity and magnetic data; possibly both the events are interwoven in the configuration of the crust.

(7) It is possible that the thermal perturbations due to plume activity have affected the configuration and composition of the Precambrian crust in the western Rajasthan during late Mesozoic in the form of the LDL (Fig. 5), a mid-crustal emplacement of fractionated fluids, spread throughout the region, below the MIS. This geometry can be inferred to be the product of the DAFB collision and associated flexure, where the low density layer could be a by-product of subduction-related fluids. The existence of LDL/LVZ in the crust could also be

assumed due to the mixing of rhyolitic magma with high Fe content basaltic magma, generated by plume tectonics. Since the Cambay graben in Gujarat was connected with the Rajasthan shelf through Sanchor and Barmer grabens during the late Cretaceous, lithospheric extension related to Reunion plume interaction, must have left its imprint on the crustal fabric and its chemical composition as a whole.

(8) Collision of the Asia–Eurasia plates (~57 Ma) followed by anticlockwise rotation in the Holocene led to the formation of the Thar Desert. The seismicity of Rajasthan (San and San, 1983) indicates a high-strain region. Chun (1986) shows a shear wave velocity of 4.52 km/s in the uppermost 80 km of the mantle, a signature of active tectonics. During the Quaternary, major lineaments seem to have been active which show the Precambrian structural grains and some lineaments that cross cut the Precambrian grains (Roy and Jakhar, 2002). Saline lakes, which are characteristic features of the Thar Desert seem to have a connection with neotectonics as they are bounded by these lineaments. Krishna Brahmam (1993) attempted to explain the high gravity anomaly as being due to high density rocks at shallow depths. A possible meteorite and/or asteroid impact has also been ascribed as the source of the magnetic anomaly of this region (Tripathi et al., 2010). The cause for thickening of upper crust/middle crust in the eastern side of the profile along with deepening of the Moho is attributed to the flexure of the crust and other thermo-tectonic activity possibly associated with the Himalayan orogeny. This flexure affects the entire Gangetic foredeep (Bilham et al., 2003).

Thus it can be inferred that the region under the study is still undergoing deformation due to Himalayan tectonics over and above the tectonomagmatic events of earlier geological times in western Rajasthan.

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References

Banerjee, D.M., Mazumdar, A., 1999. On the late Neoproterozoic-Early Cambrian transition events in parts of east Gondwanaland. Gondwana Research 2, 199–211.

Bansal, A.R., Dimri, V.P., 2005. Depth determination from a non-stationary magnetic profile for scaling geology. Geophysical Prospecting 53, 399–410.

Barton, P.J., 1986. The relationship between seismic velocity and density in the continental crust – a useful constraint? Geophysical Journal of the Royal Astronomical Society 87, 195–208.

Basu, A.R., Renne, P.R., Dasgupta, Deb K., Teichman, F., Poreda, R.J., 1993. Early and Late Alkali Igneous pulses and a high-^{3}He plume origin of the Deccan Flood Basalts. Science 261, 902–906.

Bhushan, S.K., 1984. Classification of Malani Igneous Suite: symposium on three decades of developments in petrology, mineralogy and petrochemistry in India. Geological Survey of India Special Publication 12, 199–205.

Bhushan, S.K., 1995. Late Proterozoic continental growth: implications from geochemistry of acid magmatic events of West Indian craton, Rajasthan. Geological Society of India 34, 339–355.

Bhushan, S.K., 2000. Malani rhyolite – a review. Gondwana Research 3, 65–77.

Bilham, R., Bendick, R., Wallace, K., 2003. Flexure of the Indian plate and intraplate earthquakes. Journal of Earth System Science 112 (3), 315–329. http://dx.doi.org/10.1007/BF 02709259.

Biswas, S.K., 1982. Tectonic framework and evolution of graben basins of India. Indian Journal of Petroleum Geology 1, 276–292.

Block, L., Royden, L.H., 1990. Core complex geometries and regional scale flows in the lower crust. Tectonics 9, 557–567.

Bose, U., 1989. Correlation problems of the Proterozoic stratigraphy of Rajasthan. Indian Minerals 43, 183–193.

Choudhary, A.K., Gopalan, K., Sastry, C.A., 1984. Present status of geochronology of Precambrian rocks of Rajasthan. Tectonophysics 105, 131–140.

Chun, K.Y., 1986. Crustal block of the western Ganga basin: a fragment of oceanic affinity? Bulletin of the Seismological Society of America 76, 1687–1698.

Dasgupta, S.K., 1975. Revision of the Mesozoic-Tertiary stratigraphy of the Jaisalmer basin, Rajasthan. Indian Journal Earth Science 2, 77–94.

Dasgupta, S.K., 1977. The stratigraphy of West Rajasthan shelf. In: Proceedings of IV Colloquium on Indian Micropalaeontology and Stratigraphy. I.P.E., O.N.G.C, Dehra Dun, pp. 219–233.

Dasgupta, N., Pal, T., Sen, J., Ghosh, T., 2011. Characteristics of Pegmatoidal granite exposed near Bayalan, Ajmer district, Rajasthan. Journal of Earth System Science 120 (4), 617–626.

Dharma Rao, C.V., Santosh, M., Kim, Sung Won, 2012. Cryogenian volcanic arc in the NW Indian Shield: Zircon SHRIMP U–Pb geochronology of felsic tuffs and implications for Gondwana assembly. Gondwana Research 22, 36–53.

Gopalan, K., Macdougall, J.D., Roy, A.B., Murali, A.V., 1990. Sm-Nd evidence for 3.3 Ga old rocks in Rajasthan, northwestern India. Precambrian Research 48, 287–297.

Gregory, L.C., Meert, J.G., Bingen, B.A., Pandit, M.K., Torsvik, T.H., 2009. Paleomagentism and geochronology of the Malani igneous suite, northwest India: implications for the configuration of Rodinia and the assembly of Gondwana. Precambrian Research 170, 13–26.

Grover, R., Wortel, M.J.R., 1993. Initiation of asymmetric extension in continental lithosphere. Tectonophysics 223, 75–96.

GSI-NGRI, 2006. Gravity Map Series of India. Geological Survey of India and National Geophysical Research Institute, Hyderabad, India.

Gupta, R.P., Jindal, A.K., 2000. Influence of buried topography on surface drainage pattern. International Journal of Remote Sensing 21 (2), 209–211.

Hemant, K., Maus, S., 2005. Why no anomaly is visible over most of the continent-ocean boundary in the global crustal magnetic field. Physics of the Earth and Planetary Interiors 149, 321–333.

Jagadeesh, S., Rai, S.S., 2008. Thickness, composition, and evolution of the Indian Precambrian crust inferred from broadband seismological measurements. Precambrian Research 162, 4–15.

Kaila, K.L., Tewari., H.C., Krishna., V.G., Dixit, M.M., Sarkar, D., Reddy, M.S., 1990. Deep seismic sounding studies in the north Cambay and Sanchor Basins, India. Geophysical Journal International 103, 621–637.

Krishna Brahmam, N., 1993. Gravity and seismicity of Jaisalmer region, Rajasthan. Current Science 64 (11 and 12), 837–840.

Kumar, S., Pandey, S.K., 2010. Trace fossils from the Nagaur Sandstone, Marwar Super group, Dulmera area, Bikaner district, Rajasthan, India. Journal of Asian Earth Sciences 38, 77–85.

Kumar, G., Shankar, R., Maith, P.K., Mathur, V.K., Bhattacharya, S.K., Jain, R.A., 1997. Terminal Proterozoic-Cambrian sequences in India: a review with special reference to Precambrian-Cambrian boundary. Palaeobotanist 46, 19–31.

Ludwig, J.W., Nafe, J.E., Drake, C.L., 1970. Seismic refraction. In: Maxwell, A.E. (Ed.), The Sea, vol. 4. Wiley Inter science, New York, pp. 53–84.

Maus, S., Barckhausen, U., Berkenbosch, H., Bournas, N., Brozena, J., Childers, V., Dostaler, F., Fairhead, J.D., Finn, C., von Frese, R.R.B., Gaina, C., Golynsky, S., Kucks, R., Lühr, H., Milligan, P., Mogren, S., Müller, D., Olesen, O., Pilkington, M., Saltus, R., Schreckenberger, B., Thébault, E., Caratori Tontini, F., 2009. EMAG2: a 2-arc-minute resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne and marine magnetic measurements. Geochemistry Geophysics Geosystems 10 (Q08005), 1–12.

Mishra, D.C., 1987. Bijawar and Vindhyan tectonics of central India from airborne magnetics and ground geophysical surveys. Geological Society of India 6, 357–367.

Mishra, D.C., Lakshman, G., Rao, M.B.S.V., Gupta, S.B., 1995. Analysis of the gravity-magnetic data around Nagaur-Jhalawar geotransect. In: Sinha-Roy, S., Gupta, K.R. (Eds.), Continental Crust of Northwestern and Central India. Geological Society of India, vol. 31, pp. 345–351.

Müntener, O., Hermann, J., 2001. The role of lower crust and continental upper mantle during formation of non-volcanic passive margins: evidence from the Alps. Geological Society, London, Special Publications 187, 267–288.

Naganjaneyulu, K., Santosh, M., 2011. Tracing the Proterozoic continental collision in NW India: a geophysical approach. Geological Journal. http://dx.doi.org/10.1002/gj.1307.

Nelson, K.D., 1992. Are crustal thickness variations in old mountain belts like the Appalachians a consequence of lithosphere delamination? Geology 20, 498–502.

Pandit, M.K., Wall, H. De, Daxberger, H., Just, J., Bestmann, M., Sharma, K.K., 2011. Mafic rocks from Erinpura gneiss terrane in the Shirohi region: possible ocean-floor remnants in the foreland of the Delhi Fold Belt, NW India. Journal of Earth System Science 120 (4), 627–641.

Porwal, A., Carranza, E.J.M., Hale, M., 2006. Tectonostratigraphy and base-metal mineralization controls, Aravalli province (western India): new interpretations from geophysical data analysis. Ore Geology Reviews 29, 287–306.

Pradhan, V.R., Meert, J.G., Pandit, M.K., Kamenov, G., Gregory, L.C., Malone, S., 2010. India's changing place in global Proterozoic reconstructions: new geochronologic constraints on key paleomagnetic poles from the Dharwar and Aravalli/Bundelkhand Cratons. Journal of Geodynamics. http://dx.doi.org/10.1016/j. jog/2009.11.08.

Prasad, B., Asher, R., Borgohai, B., 2010. Late Neoproterozoic (Ediacaran)-Early Paleozoic (Cambrian) Acritarchs from the Marwar Supergroup, Bikaner-Nagaur Basin, Rajasthan. Journal Geological Society of India 75, 415–431.

Rathore, S.S., 1995. Geochronological studies of Malani volcanic and associated igneous rocks of southwest Rajasthan, India: implications to crustal evolution. Unpublished Ph.D. thesis, M.S. University, Baroda.175p.

Rathore, S.S., Venkatesan, T.R., Srivastava, R.K., 1999. Rb-Sr isotope dating of Neoproterozoic (Malani Group) magmatism from southwest Rajasthan, India: evidence of younger Pan-African thermal event by ^{40}Ar-^{39}Ar studies. Gondwana Research 2, 271–281.

Ray, J.S., Pandey, K., 1999. Carbonatite alkaline magmatism associated with continental flood basalts at stratigraphic boundaries: cause for mass extinctions. Geophysical Research Letters 26, 1917–1920.

Roy, A.B., Jakhar, S.R., 2002. Geology of Rajasthan (Northwest India) Precambrian to Recent. Scientific Publishers, India, Jodhpur.

San, D., San, S., 1983. Post-neogene tectonics along Aravalli range, Rajasthan, India. Tectonophysics 93, 75–98.

Santosh, M., Yoshida, M., 1992. A petrologic, and fluid inclusion study of charnockites from the Lutzon-Holm Boy region, East Antarctica: evidence from fluid-rich-metamorphism in the lower crust. Lithos 29, 107–126.

Satyavani, N., Dixit, M.M., Reddy, P.R., 2004. Crustal structure of Delhi Fold Belt, India, from seismic reflection data. Current Science 86, 991–999.

Sharma, R.S., 1995. An Evolutionary Model for the Precambrian Crust of Rajasthan: Some Petrological and Geochronological Considerations. Geological Survey of India, Mem. 31, p. 91.

Sharma, K.K., 2003. Neoproterozoic Malani Magmatism, Northwestern Indian Shield: Not a Plume Product. http://www.mantleplumes.org/malani.html (accessed 06.06.04).

Sharma, K.K., 2007. K-T magmatism and basin tectonism in western Rajasthan, India, results from extensional tectonics and not from Reunion plume activity. Geological Society of America Special Paper. http://dx.doi.org/10.1130/2007.2430(35).

Sheth, H.C., Duncan, R.A., Chandrasekharam, D., Mahoney, J.J., 1997. Deccan Trap dioritic gabbros from the western Tapi–Satpura region. Current Science 72, 755–757.

Sinha-Roy, S., 1998. Precambrian of the Aravalli Mountain Rajasthan, India. Geological Society of India 7, 95–108.

Sinha-Roy, S., Malhotra, G., Guha, D.S., 1995. A transect across Rajasthan Precambrian terrain in relation to geology, tectonics and crustal evolution of south central Rajasthan. In: Sinha-Roy, S., Gupta, K.R. (Eds.), Continental Crust of Northwestern and Central India. Geological Society of India, vol. 31, pp. 63–90.

Sinha-Roy, S., Malhotra, G., Mohanty, M., 1998. Geology of Rajasthan. Geological Society of India, Bangalore, p. 278.

Sivaraman, T.V., Raval, U., 1995. U-Pb isotopic study of zircons from a few granitoids of Delhi-Aravalli belt. Journal Geological Society of India 46, 461–475.

Spera, F.G., Yuen, D.A., Greer, J.C., Sewell, G., 1986. Dynamics of Magma chamber withdrawal from stratified magma chamber. Geology 14, 723–726.

Stern, R.J., Hedge, C.E., 1985. Geochronologic and isotopic constraints on late Pre-Cambrian crustal evolution in the Eastern Desert of Egypt. American Journal of Science 285, 97–127.

Stern, Robert J., 2008. Neoproterozoic crustal growth: the solid Earth system during a critical episode of Earth history. Gondwana Research 14, 33–50.

Tewari, H.C., Dixit, M.M., Sarkar, D., Kaila, K.L., 1991. A crustal density model across the Cambay basin, India and its relationship with the Aravallis. Tectonophysics 194, 123–130.

Tewari, H.C., Vijaya Rao, V., Dixit, M.M., Rajendra Prasad, B., Rao, N.M., Venkateswarlu, N., Khare, P., Keshav Rao, G., Raju, S., Kaila, K.L., 1995. Deep reflection studies across the Delhi-Aravalli fold belt: results from the northwestern part. In: Sinha-Roy, S., Gupta, K.R. (Eds.), Continental Crust of Northwestern and Central India. Geological Society of India Memoirs, vol. 31, pp. 382–402.

Tewari, H.C., Dixit, M.M., Rao, N.M., Venkateswarlu, N., Vijaya Rao, V., 1997. Crustal thickening under the Paleo/mesoproterozoic Delhi Fold Belt in NW India: evidence from deep reflection profiling. Geophysical Journal International 129, 657–668.

Torsvik, T.H., Carter, L.M., Ashwal, L.D., Bhushan, S.K., Pandit, M.K., Jamtveit, B., 2001. Rodinia redefined or obscured: Palaeomagnetism of the Malani Igneous Suite (NW India). Precambrian Research 108, 319–333.

Torsvik, T.H., Pandit, M.K., Redfield, T.F., Ashwal, L.D., Webb, S., 2005. Remagnetizations of Mesozoic limestones from the Jaisalmer Basin, NW India. Geophysical Journal International 161, 57–64.

Tripathi, R.P., Mathur, S.C., Mathur, S., Trupthi, G., Chandrashekharam, D., 2010. Occurrence of stishovite in the Precambrian Siwana Volcanic Province, Western Rajasthan, India. Current Science 98, 30–32.

Vijaya Rao, V., Rajendra Prasad, B., Reddy, P.R., Tewari, H.C., 2000. Evolution of Proterozoic Aravalli Delhi fold belt in the northwestern Indian shield from seismic studies. Tectonophysics 327, 109–130.

Volpe, A.M., Macdougall, J.D., 1990. Geochemistry and isotopic characteristics of mafic (Phulad Ophiolite) and related rocks in the Delhi Supergroup, Rajasthan, India: implications for the rifting in the Proterozoic. Precambrian Research 48, 167–191.

Zantd, G., Ammon, J., 1995. Continental crust composition constrained by measurements of crustal Poisson's ration. Nature 374, 152.

Zheng, Y., Arkani-Hamed, J., 1998. Joint inversion of gravity and magnetic anomalies of eastern Canada. Canadian Journal of Earth Sciences 35, 832–853.