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Insights into crustal structure of Aravalli-Delhi Fold Belt and adjoining Bundelkhand craton-Marwar block from gravity models: Significance for Precambrian tectonics in NW India

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ABSTRACT

The 2.5D crustal density structure is modelled using complete Bouguer anomaly along two W-E profiles across the Marwar block, Aravalli-Delhi Fold Belt (ADFB), and the Bundelkhand craton, constituting the north-western edge of the Indian Shield. The rock density closely mimics the litho-tectonic units that preserve the Archean-Proterozoic evolutionary history. The Bouguer anomaly along the profiles, corresponds to significant variation in crustal structure, with Moho depth varying from 34 to 40 km under the Marwar block, ~45 km under high-relief ADFB and <42 km under the Bundelkhand craton. A high-density (2.78 g/cm^3) 6-8 km thick sill in the upper crust and a 10-12 km thick high-density (3.05 g/cm^3) body as the mantle underplating at the Moho, represent the source conduit of the Neoproterozoic Malani Igneous Suite in the Marwar block. The significant lithological variation within the 8-10 km thick upper crust with a 12-13 km thick elongated high-density (3.05 g/cm^3) basaltic body with a diffused Moho signature, possibly representing the mantle underplating due to orogenic root delamination under the ADFB. The lateral variation in the crustal structure across the craton suggests the orogenic reworking during the early-mid Proterozoic and mantle upwelling in an extensional regime during the Neoproterozoic in the ADFB and Marwar lock.

Keywords: Northwestern India, 2.5D Gravity modelling, Crustal density structures, Geodynamics, Aravalli-Delhi Fold Belt, Bundelkhand craton

INTRODUCTION

The Aravalli-Delhi Fold Belt (ADFB) together with the adjoining Bundelkhand craton towards the east and Marwar block towards the west, represents the north-western edge of the Indian shield (Figure 1), possessing a reasonably well-conserved rock record of nearly three billion years (~3.6 to ~0.75 Ga) of earth's evolutionary history (Deb and Sarkar, 1990; Bhushan, 1995; Sharma, 2009; Sharma and Mondal, 2019; Jain et al., 2020). The overlapping rock records, cryptic domain boundaries, and overprinted magmatic events make their spatiotemporal disposition enigmatic. Based on the accretion and reworking over time, the Precambrian tectonics and the crustal growth of the ADFB and adjoining regions are preserved. A knowledge of the crustal structure and reconstruction of spatiotemporal tectono-magmatic events enables detailed comparisons between models and observations. Some investigations using seismic (Rao et al., 2000; Krishna and Rao, 2010; Mandal et al., 2014, 2018), magnetic (Bansal and Dimri, 2005), and gravity methods (Mishra et al., 2000; Porwal et al., 2006; Naganjaneyulu and Santosh, 2012; Dwivedi et al., 2019**)** have been made to delineate the deep crustal structure across the central and northern part of the ADFB to speculate on the geodynamic evolution of northwestern India. In the southeastern part, the ADFB is bordered by the Bundelkhand massif basement, which is overlain by a sedimentary sequence of the Proterozoic Vindhyan Super Group. In certain parts, this sequence is covered by extensive Late Cretaceous Deccan volcanics. Whereas towards the west of ADFB, lies the Late Proterozoic Marwar Supergroup sequence of acidic volcanics, sedimentary succession, and the Mesozoic Jaisalmer sediments deposited in an extensional rift setting. The amalgamation of the complex geological setup is illuminated by pronounced seismicity, which is feeble in the central part and extensive towards the northern part of the ADFB **(**Figure 1**).** Unlike the central and northern parts, the southern part of the ADFB and its adjoining region lacks regional geophysical modelling of the crustal structure to understand the tectonic juxtaposition of syn- to post-tectonic orogenic events and, therefore, was chosen for the present study.

Unlike the seismic method, gravity models do not provide a unique solution. However, when constrained by seismic and other geophysical data, they yield a robust crustal structure that may represent a better litho-tectonic setup. We therefore modelled the high-resolution gravity data with constraints for the seismic structures that have been used to derive 2.5D density models of the deep crustal geometry of the southern ADFB and bordering geological units (Figure 1). We modelled the density structure of the crust across ADFB along two gravity profiles, where Profile 1 is constrained by the seismic structure of the region (Tewari et al., 1997; Krishna and Rao, 2010; Mandal et al., 2014, 2018). The crustal density structure along Profile 2 has been extended based on regional structures and the density interface from Profile 1. We aim to provide (i) a detailed 2.5D crustal density structure across the three tectonic domains, and examine a possible evolutionary and geodynamic link between the mafic and ultramafic rocks on the surface as well as in the deep crust.

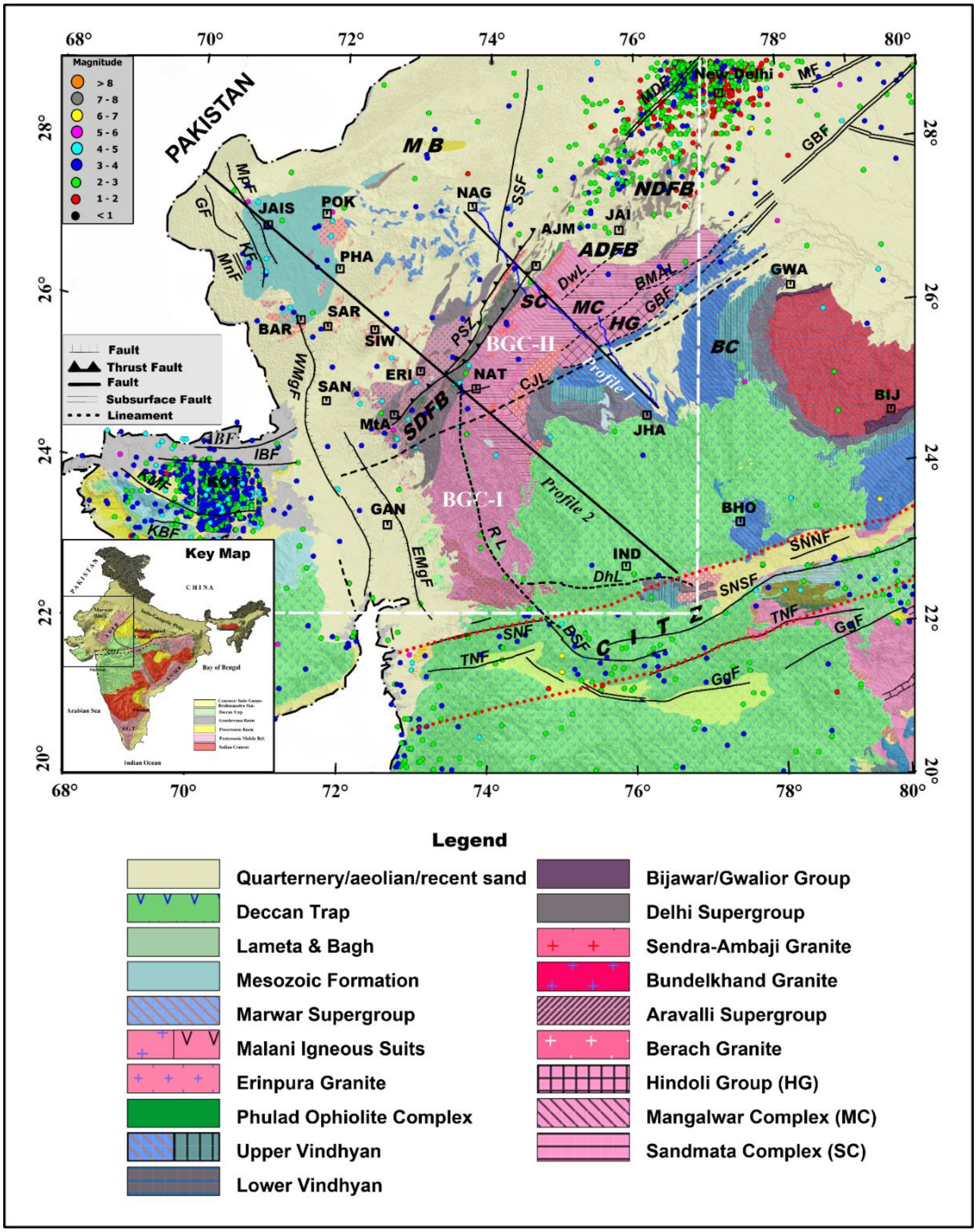

Figure 1. Generalised geology (GSI, 1998) and tectonic map (GSI, 2000) of north-western India encompassing Bundelkhand craton, Aravalli-Delhi Fold Belt, and Marwar block. Location of the seismic line (in blue) along with two gravity profiles selected for 2.5D density modelling across the ADFB (Figs. 4 and 5) is also shown. White dashed lines mark the study area. Abbreviations used for places are AJM: Ajmer, BAR: Barmer, BHO: Bhopal, BIJ: Bijawar; ERI: Erinpura; GAN: Gandhi Nagar, GWA: Gwalior, IND: Indore, JAI: Jaipur, JAIS: Jaisalmer, JHA: Jhalawar, KUT: Kutch, MtA: Mount Abu; NAG: Nagaur, NAT: Nathdwara, PHA: Phalsund, POK: Pokharan, SAN: Sanchore, SAR: Saranu, SAU: Saurashtra. Abbreviations used for geological/tectonic provinces are ADFB: Aravalli-Delhi Fold Belt; BC: Bundelkhand craton; CITZ: Central Indian Tectonic Zone; HG: Hindoli Group of rocks; MB: Marwar block; MC: Mangalwar Complex; NDFB: North Delhi Fold Belt; SDFB: South Delhi Fold Belt. BGC-I and BGC-II are the Banded Gneissic Complex of ADFB. Abbreviations used for faults and lineaments are ABF: Allah Bund Fault, BMAL: Bharatpur-Mount Abu Lineament, CJL: Chambal-Jahazpur Lineament; BSF: Barwani Sukta Fault, DhL: Dhar Lineament, DwL: Delwara Lineament, EMgF: Eastern Marginal Fault, GBF: Great Boundary Fault, GF: Ghotaro Fault, GgF: Gawaligarh Fault, IBF: Island Belt Fault, KBF: Katrot Bhuj Fault; KF: Kantli Fault, KMF: Kutch Mainland Fault; KF: Konoi Fault, MDF: Mahendragarh-Dehradun Fault, MnF: Manshuriyan Fault, MpF: Manpiya Fault, PSZ: Phulad Shear Zone, RL: Rakhabdev Lineament, SNF: Son-Narmada Fault, SNNF: Son-Narmada Narth Fault, SNSF: Son-Narmada South Fault, WMgF: Western Marginal Fault. Igneous rocks are the Deccan Traps, Malani Igneous Suite, Rakhabdev Ultramafic Suite, and Phulad Ophiolite Complex.

REGIONAL GEOLOGY

The North-western Indian craton is a collage of three tectonic domains, namely the Bundelkhand craton, the Marwar block and the Aravalli-Delhi Fold Belt (Figure 1), all of which preserve the records of crustal evolution from Archaean to Neoproterozoic that involved multiple accretion and syn- to post-tectonic magmatic events (Sharma, 2009; Sharma and Mondal, 2019; Pandey, 2020).

Bundelkhand craton

The Bundelkhand craton, also known as the Bundelkhand Granite Massif or Bundelkhand Granitoid Complex, comprises granitic gneiss complexes of Archaean age (Figure 1). The craton is divided into three discrete litho-tectonic units: (i) ~3.5 Ga highly deformed gneiss-greenstone assemblages; (ii) ~2.5 Ga undeformed multiphase granitoid plutons; and (iii) mafic dyke swarms and other intrusions (Basu, 1986; Sharma and Rahman, 2000). The Bundelkhand craton is traversed by younger mafic dykes trending NW-SE, ENE-WSW, and NE-SW directions (Pati and Singh, 2020). The Bijawar and Gwalior basins (1.8-1.9 Ga) represent two isolated and narrow peripheral basins, where sediment deposition occurred over the Bundelkhand cratonic basement. The extensive Proterozoic sedimentation over the Bundelkhand craton continued with two distinct sequences of the Lower (1.6-1.9 Ga) and the Upper Vindhyan Supergroups (0.9-1.075 Ga) (Deb et al., 2002), which are unconformably overlain by the Neogene Himalayan foreland alluvium of the Ganga basin towards the north and the Deccan volcanics towards the southwest. The Great Boundary Fault separates the Bundelkhand craton from the ADFB (**Figure 1**) (Naqvi and Rogers, 1987; Sinha-Roy, 2000).

Aravalli-Delhi Fold Belt

Aravalli-Delhi Fold Belt (ADFB), extending between the Son-Narmada graben and the Central Indian Tectonic Zone to the Indo-Gangetic plain, is a collage of three Proterozoic fold belts with distinct evolutionary history (Figure 1). The Archaean Aravalli Complex towards the east and the Meso-Neoproterozoic Delhi Complex towards the west (Mondal, 2019; Jain et al., 2020; Ghosh et al., 2023). The Aravalli Supergroup is subdivided into Banded Gneissic Complex-I (BGC-I) towards the east and southeast and BGC-II towards the north of the Nathdwara. BGC-II is constituted of the Sandamata Complex towards the west and the Mangalwar Complex towards the east (Ahmad et al., 2018). The Archaean Sandamata Complex is situated in the middle of the ADFB, flanked by the Paleoproterozoic Mangalwar Complex towards the east and the Meso-Neoproterozoic Delhi Complex towards the west (Mondal, 2019; Jain et al., 2020). The western contact of the Sandamata Complex with the Delhi Complex is distinguished by an NNE-SSW trending sub-vertical to steeply southeast-dipping Mylonitic tectonic mélange zone, whereas the eastern contact with the Mangalwar Complex is marked by the Delwara dislocation (shear) zone (Sinha-Roy and Malhotra, 1989).

The prevailing rock records encapsulated in these three major blocks of ADFB have a distinct history of evolution and mineralisation (Bhowmik and Dasgupta, 2012; Fareeduddin and Banerjee, 2020). The ADFB evolved out of episodic oceanic crust-continent interactions within the craton under ensialic regimes from the Early Archaean (ca. ~3.5 Ga) to Neoproterozoic (ca. ~0.75 Ga) (Sinha-Roy et al., 1995; Sharma, 2009; Bhowmik and Dasgupta, 2012). The evolution of the Proterozoic ADFB started with a phase of extension at about 2.15 Ga ago and was completed following the accretion of crustal blocks by 1.15 Ga ago (Sinha-Roy, 1988; Roy, 1990; Sugden et al., 1990; Sharma, 2009; Bhowmik and Dasgupta, 2012).

Marwar block

The volcano-sedimentary sequence of the Marwar block is constituted of the silicic lavas (sporadically bimodal at the base), granite, and felsic and mafic dykes of the Neoproterozoic Malani Igneous Suite, which rest unconformably on the Delhi Supergroup (Pandit et al., 1999; Bhushan, 2000). The Phulad Shear Zone represents the suture along which patchily deformed Neoproterozoic granitoids of the Marwar block accreted to the ADFB (Chatterjee et al., 2017). The epilogue of the tectonic evolution was marked by profuse granitic activity at 1015 ± 4.4 Ma and 966 ± 3.5 Ma, especially around Erinpura and Mt. Abu along the junction of the Marwar block-south Delhi Fold Belt (Dharma Rao et al., 2013). The Pokharan boulder bed of the Vendian age and the Ediacaran to Cambrian Marwar Supergroup red-bed and evaporitic sequences were deposited over the Malani Igneous Suite rocks after a hiatus (Torsvik et al., 2001). The Mesozoic Gondwana fragmentation led to the development of the Jaisalmer, Barmer, and Bikaner-Nagaur basins during the Jurassic, which are now covered by widespread Quaternary sediments and wind-blown dunes of the Thar Desert (Figure 1).

Tectonic evolution

The evolution and accretionary history of the crustal growth of various micro-blocks of the northwestern Indian craton (Marwar-ADFB-Bundelkhand) is variously debated (Bhowmik and Dasgupta, 2012; Fareeduddin and Banerjee, 2020). The notable tectono-magmatic and metamorphic episodes in the ADFB are typified by the Banded Gneissic Complex (BGC) (ca. 3.0 Ga), the Aravalli orogeny (ca. 1.8 Ga) towards the east, the Delhi orogeny (ca. 1.1 Ga) towards the west, and post-Delhi silicic magmatism (ca. 0.85-0.75 Ga) of

Malani Igneous Suite (Dharma Rao et al., 2013). The Neoproterozoic time interval (1.1-0.9 Ga) represents the amalgamation of the Rodinia supercontinent, which broke up 0.75-0.63 Ga ago (Meert et al., 2013). The Phulad granite is considered as a stitching pluton during this suturing at 0.81-0.82 Ga (Chatterjee et al., 2020). The post-tectonic bimodal magmatic event, namely the Malani Igneous Suite in the Marwar block, took place about 0.77-0.75 Ga ago (Gregory et al., 2009; Ashwal et al., 2013; de Wall et al., 2018; Wang et al., 2018). The intervening granites have yielded an age of ~0.735 Ga, indicating a brief magmatic event in the region.

GRAVITY DATA

For the understanding of the Proterozoic tectono-magmatic signatures, a complete Bouguer anomaly map of the region has been prepared from 8504-station data at ~5 km intervals (which was used to prepare the gravity map series of India, GSI-NGRI, 2006), 441 gravity data recorded at a station interval of about 1 km along the Nagaur-Jhalawar profile (Profile 1) (Mishra et al., 2000), and an additional 2525 station gravity data acquired at an interval of about 2-3 km over the Malani Igneous Suite (Prakash et al., 2020) (Figure 2). Gravity readings of all three data sets were tied to an available absolute gravity base at Sheo (Qureshy and Warsi, 1972), and the Geodetic Reference System 1980 was used to compute normal (theoretical) gravity in the procedure to reduce the observed gravity data to Bouguer anomalies. A crustal density of 2.67 g/cm^3 was used for the Bouguer and terrain corrections (Hinze et al., 2013).

The amplitude of the Bouguer anomaly ranges from +52 to -92 mGal in the studied regions, with a long linear gravity 'high' (+5 mGal) seen over the high relief region of the ADFB. A positive gravity anomaly over ADFB is an unusual feature, as the elevated region is typically expected to have a negative Bouguer anomaly due to isostatic compensation of the topography. The positive Bouguer gravity anomaly was earlier interpreted as a horst-like feature in the basement at a depth of over 11 km (Reddi and Ramakrishna, 1988a, b).

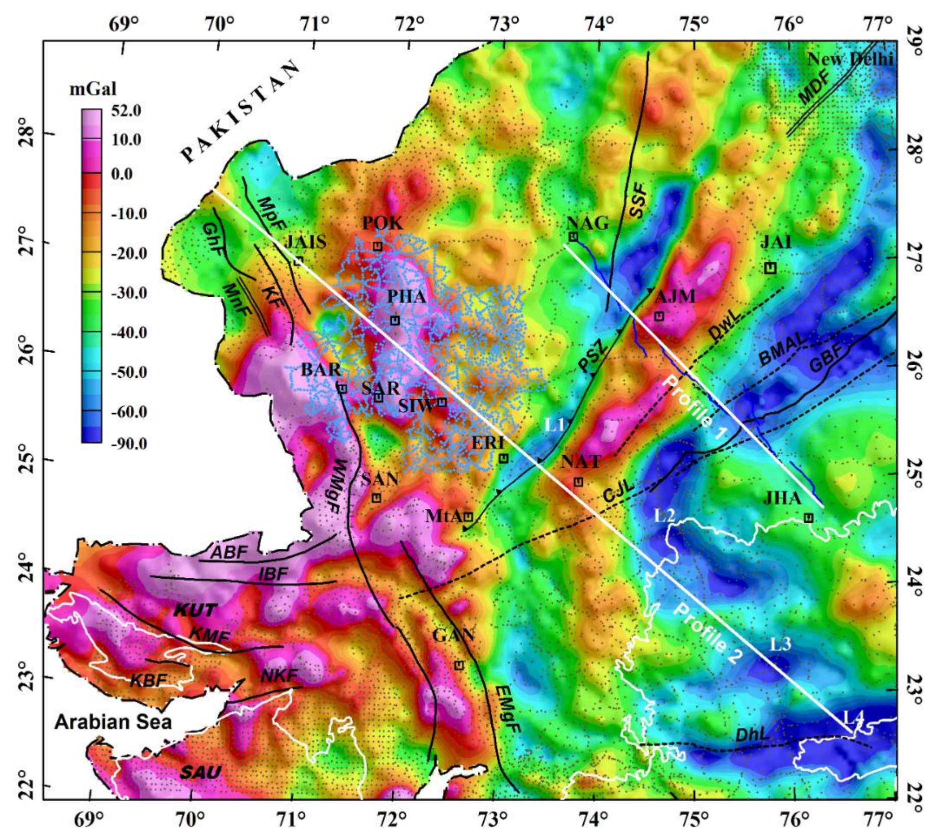

Figure 2. Complete Bouguer anomaly map (in mGal) of north-western India is based on more than 11470 terrestrial gravity station data points indicated by light black (8504 old gravity data points from GSI-NGRI 2006), dark blue (441 old gravity data points, collected along the Nagaur-Jhalawar seismic profile, from Mishra et al. 2000), and light blue stars (2525 new data points from Prakash et al. 2020). The flanking lows (L1 and L2) of -60 mGal on either side of the Aravalli-Delhi Fold Belt coincide with the Erinpura granite and Marwar supergroup towards the west and the Berach granite and Hindoli group of rocks towards the east. Gravity lows L3 and L4 are located over the trap-covered Vindhyan basin. White lines indicate profile locations along which vertical density cross-sections across the Aravalli-Delhi Fold Belt are modelled (shown in Figures 4 and 5). NKF: North Kathiawar Fault. Other abbreviations are the same as those given in **Figure 1.**

In contrast, Qureshy (1971) opined that the source of high gravity must be rooted deep in the crust, possibly in the high-density intruded mafic mantle material in the upper crust, which caused the Aravalli uplift (Qureshy, 1981). Recent seismic studies, however, rule out the possibility of a high-density inhomogeneity at shallow depths (Tewari et al., 1997; Krishna and Rao, 2010).

Based on the observed high seismic velocity (V_p=7.3 km/s), a high-density igneous body at the base of the crust was proposed as a source for the high gravity anomaly over the ADFB (Mishra et al., 2000; Kumar et al., 2020). The flanking gravity lows (L1 and L2) of amplitude -60 mGal on either side of the ADFB gravity high (Figure 2) coincide with the Ambaji/ Erinpura granite to the west and the Berach granite and Hindoli Group rocks to the east. The steep gravity gradients are interpreted to represent the deep crustal breaks, which channeled the syenites and Phulad granites in the region. According to Mishra et al. (2000), the steep gradient between the central high and the contiguous lows to either side indicates faulted contacts of the ADFB with the Marwar block to the west and the Bundelkhand craton to the east.

The range of Bouguer anomaly within the Marwar block varies from +52 to -60 mGal (Figure 2), indicating a broad association with the exposed litho-units (Figure 1). For example, the most notable north-south trending gravity high of peak value +52 mGal centred over the Saranu-Phalsund-Pokharan region and a gravity high of peak value +40 mGal to the west of Barmer encompassing the Malani Igneous Suite (Prakash et al., 2020). Another short-wavelength positive Bouguer anomaly attaining a peak value of +11 mGal is positioned at the eastern margin of the Siwana Ring Complex. Several dispersed gravity-high anomaly peaks, which have various trends that do not show any apparent association with the exposed geology, may be related to the basement highs or ridges (Dutta, 1983). Another interpretation is that many of these gravity highs are caused by ascending lower crust or upper mantle magmatic rocks (Krishna Brahmam, 1993; Roy, 2003). The SE-NW trending gravity low in the Sanchore-Barmer-Jaisalmer basins suggests they are interconnected with the Cambay graben to the south (Krishna Brahmam, 1993). Other significant gravity lows in the Marwar block, which descend to -20 to -25 mGal in areas where no plausible geological body is exposed, may indicate the presence of subsurface granites (Reddi and Ramakrishna, 1988a, b).

The Bouguer anomaly over the western part of the Bundelkhand craton varies from -10 to -92 mGal. The gravity high around Jhalawar and radiating in the south-west, west, and north-west directions corresponds with the ENE-WSW Central India Tectonic Zone, and Deccan Traps may be associated with sub-trappean high-density Bijawar Group (comprising meta-sediments with basic/ultra-basic intrusive) (Mishra and Ravikumar, 2014). The high gravity could also be attributed to lower Proterozoic volcanic deposits beneath the Vindhyan sediments (Qureshy and Warsi, 1975). The curvilinear gravity low (L2) encompasses the Berach granite, Hindoli Group, and the Vindhyan sediments. In contrast, the gravity lows (L3 and L4) around the Indore region may be due to subtrappean Vindhyan sediments. The geometries of various density inhomogeneities in the Bouguer anomaly map, produced by the Proterozoic tectono-magmatic events, are modelled by a 2.5D crustal density structure along two gravity profiles (Figure 2).

Density variation

The geometry, depth, and density of the causative body are the major factors that govern the inherent ambiguity in gravity modelling. The available densities of the major lithologies exposed in the study area, and their laboratory-measured densities, are listed in Table 1. The densities of the majority of the Archaean and Proterozoic formations that overlie the BGC, acting as the basement of the ADBF, are variable, ranging from 2.65 to 2.75 g/cm³. Granitic rocks on the western flanks of the ADFB, including Ambaji/ Erinpura granites, have a density of 2.62 g/cm^3. In contrast, the density of the Precambrian Phulad formation, which may represent the basic volcanic of an ophiolite mélange, is higher than the densities of other granites (Mishra et al., 2000, and references therein). Low but variable density values characterise the Siwana granite (2.57-2.77 g/cm^3), Jalore granite (2.48-2.61 g/cm^3), and Malani rhyolite (2.43-2.86 g/cm^3), whereas high-density values (2.70-2.75 g/cm^3) characterise the Siwana rhyolite (Table 1) (Prakash et al., 2020). The density variation in different granitic samples probably arises from differences in the proportion of minerals and the phase transformation of minerals during metamorphism, a common phenomenon in metamorphic processes during orogenesis. Rocks with the same chemical composition can exhibit significant variations in density due to differences in the pressure they experience.

In the Marwar block, we divide the early Oligocene deposits into the Marwar supergroup (comprising sandstone, shale, limestone, and evaporites) with a density of 2.30 g/cm^3 and an upper sand and soil unit with a density of 2.0 g/cm^3 (Prakash et al., 2020). Proterozoic sediments in the Vindhyan Basin are sub-divided into a Lower Vindhyan sequence (2.85 g/cm^3) and an Upper Vindhyan sequence (2.55 g/cm^3) in the southern part of the graben (Das et al., 2007). Due to its mafic composition, the Bijawar Group of rocks has a higher density (2.85-2.95 g/cm^3) than the sediments of the Vindhyan Supergroup (Kailasam, 1976; Das et al., 2007). The relatively thin Bagh Group of rocks in the Vindhyan Basin has a density of about

2.35-2.40 g/cm^3 (Das et al., 2007). The Deccan Trap on the surface is allocated a density of 2.78 g/cm^3 (Prasad et al., 2018, 2021). The seismic velocities observed along the Nagaur-Jhalawar Profile-I (Tewari et al., 1997; Krishna and Rao, 2010; Rao and Krishna, 2013) are used to constrain the sub-surface density distribution of associated crustal layers (Figure 3) (Barton, 1986).

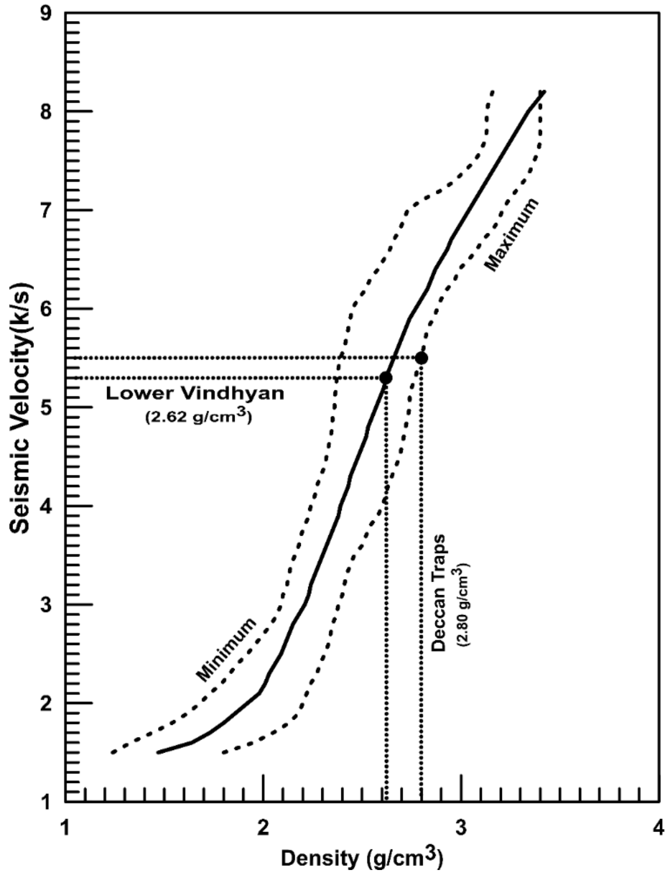

Figure 3. The relationship between seismic velocities and the densities of rocks, as given by Barton (1986).

Table 1. Measured density values of some of the intrusive rock formations. The older rock of ADFB appears to have overlapping density values. However, their histogram suggests that the maximum number of samples lies in the range of 2.65 to 2.70 g/cm^3.

Rock type	No. of sample	Density (g/cm^3)	Source	Density used (g/cm^3)
Malani rhyolite	21	2.43-2.86	Prakash et al. (2020)	2.62
ADFB granite	--	2.40-2.60	Ramakrishna and Rao (1981)	2.62
Lameta / Bagh bed	--	2.35-2.40	Das et al. (2007)	2.40
Upper Vindhyan	--	2.55	Das et al. (2007)	2.55
Lower Vindhyan	--	2.62	Barton (1986)	2.62
Erinpura granite	--	2.60-2.65	Mishra et al. (2000)	2.62
Deccan Traps	--	2.65-2.80	Prasad et al. (2018)	2.80
Bijawar	--	2.80-2.95	Das et al. (2007)	2.85
Middle crust	--	2.80	--	2.80
Lower crust	--	2.90-2.95	--	2.89
Underplated layer	--	3.0-3.1	--	3.05
Upper mantle	--	3.30	--	3.30

GRAVITY MODELLING

Nagaur-Jhalawar (Profile-I)

A wide-angle reflection seismic profile along the Nagaur-Jhalawar transect (Figures 1 and 2), which cuts across the ADFB, was acquired between 1991 and 1993 (Tewari et al., 1997). The seismic refraction/ wide-angle reflection data (Tewari et al., 1997; Krishna and Rao, 2010) imaged an imbricated crustal structure with ~38-40 km deep reflective Moho under the Marwar block (Figure 4) (Mandal et al., 2014). The Moho could not be identified beneath the ADFB due to poor reflectivity in the seismic images at the expected depth of investigations (Tewari et al., 1997; Mandal et al., 2014), and the crustal thickness was estimated to be between 45 and 50 km across the ADFB. The high-velocity (7.3 km/s) laminar lower crustal layers with a total thickness of ~10-12 km, covering both the Delhi and Sandamata complexes, are conjectured to signify the possible presence of mafic intrusions (Tewari et al., 1997; Mandal et al., 2014). The P_{MS} interface, observed at 29 km depth beneath the Ajmer broadband station, is also reported to be the top of the anomalous high-velocity layer (Ravi Kumar et al., 2001). The reprocessed seismic data, together with the synthetic seismogram modelling of the reflected phases, have delineated a lamellar structure overlying the Moho at a depth of ~ 46±1 km underneath the ADFB (Krishna and Rao, 2010), and also the crustal-scale south Delhi Thrust dipping in 25°-30° SE direction. The common reflection surface study imaged the Jahazpur Thrust under the Sandamata Complex, which becomes listric at the Moho (Mandal et al., 2014). An NW-dipping Chambal Thrust has been imaged from 9- to 30-km depth under the Bundi-Kota segment (Mandal et al., 2018). The depth-migrated seismic section delineated the Moho structure in the Vindhyan Basin reveals a crustal thickness ranging from 40 to 44 km towards the east (Mandal et al., 2018).

Projection of the seismic layers (Figure 4) onto the gravity profile extracted along a straight line from the gravity anomaly map (Figure 2) shows that the significant seismic reflectors correlate with the major gravity features (Figure 5). We completed 2.5D forward modelling of the gravity data along the reprocessed seismic section of Mandal et al. (2014, 2018). Gravity data at an equal interval of 2 km were extracted along a straight profile (Profile 1) from the composite gravity map (Figure 2). The *a priori* model geometry is extended in both directions by 10000 km to avoid the edge effects. Initially, minor modifications are made to the density and geometry of the *a priori* crustal density model. To arrive at the final crustal density model, which is similar to the seismic model and generates a response matching the observed gravity anomalies, a couple of small mafic bodies are also inserted (Figure 5).

On the western flank of the ADFB, the gravity low (L1) is partly modelled as Ambaji granite in the Delhi/ Marwar block. The Marwar block towards the west is apparently the major source of the low L1, which is modelled in terms of Quaternary sand, soil, and Oligocene Marwar supergroup (2.30 g/cm^3) near the surface, below which is the Malani Igneous Suite (2.62 g/cm^3) that lies above the Delhi Supergroup as the basement. Although the succession beneath the Erinpura/ Ambaji granite in the Marwar block is seismically transparent, gravity modelling suggests that the granites (density 2.62 g/cm^3) extend up to ~10.5 km in depth. The Delhi Supergroup, Sandmata granulitic complex, and Mangalwar complex of the ADFB also extend to a similar depth of ~10.5 km. Based on the mapped surface geology (e.g., granulites) and given tectono-magmatic events (e.g., basic volcanic of an ophiolite mélange) (Sinha-Roy et al., 1995; Mishra et al., 2000), a couple of high-density intrusive rock units are inserted in ADFB to match the short-wavelength gravity anomalies. The Hindoli Group of rocks (ρ=2.68 g/cm^3) of the ADFB is modelled as a thin tabular body reaching up to a depth of ~9 km.

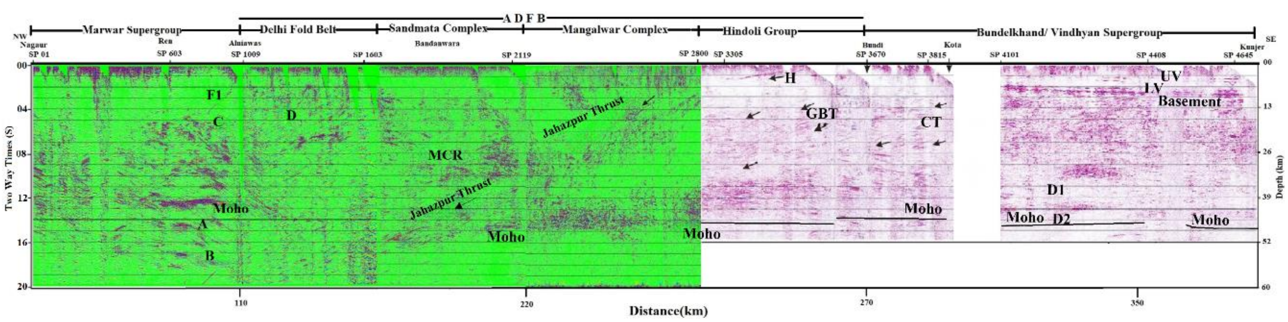

Figure 4. Common reflection surface stack section of the Marwar Basin- ADFB-Vindhyan Basin along the seismic line "Nagaur-Jhalawar Profile-I" (modified after Mandal et al., 2014, 2018). 'A' and 'B' represent the sub-crustal reflections beneath the Marwar block. MCR: mid-crustal reflectors in ADFB, GBT: Great Boundary Thrust, CT: Chambal Thrust. Moho and Jahazpur faults are also shown for ready reference; 'C' and 'D' represent oppositely dipping reflections, and F1 represents the boundary fault. 'A' and 'B' represent upper mantle reflections; UV = Upper Vindhyan sediments (650-1100 Ma); LV = Lower Vindhyan sediments (1100-1700 Ma); D1 and D2 are two diffraction tails; Shallow reflector-H represents the basement for the Hindoli group of rocks.

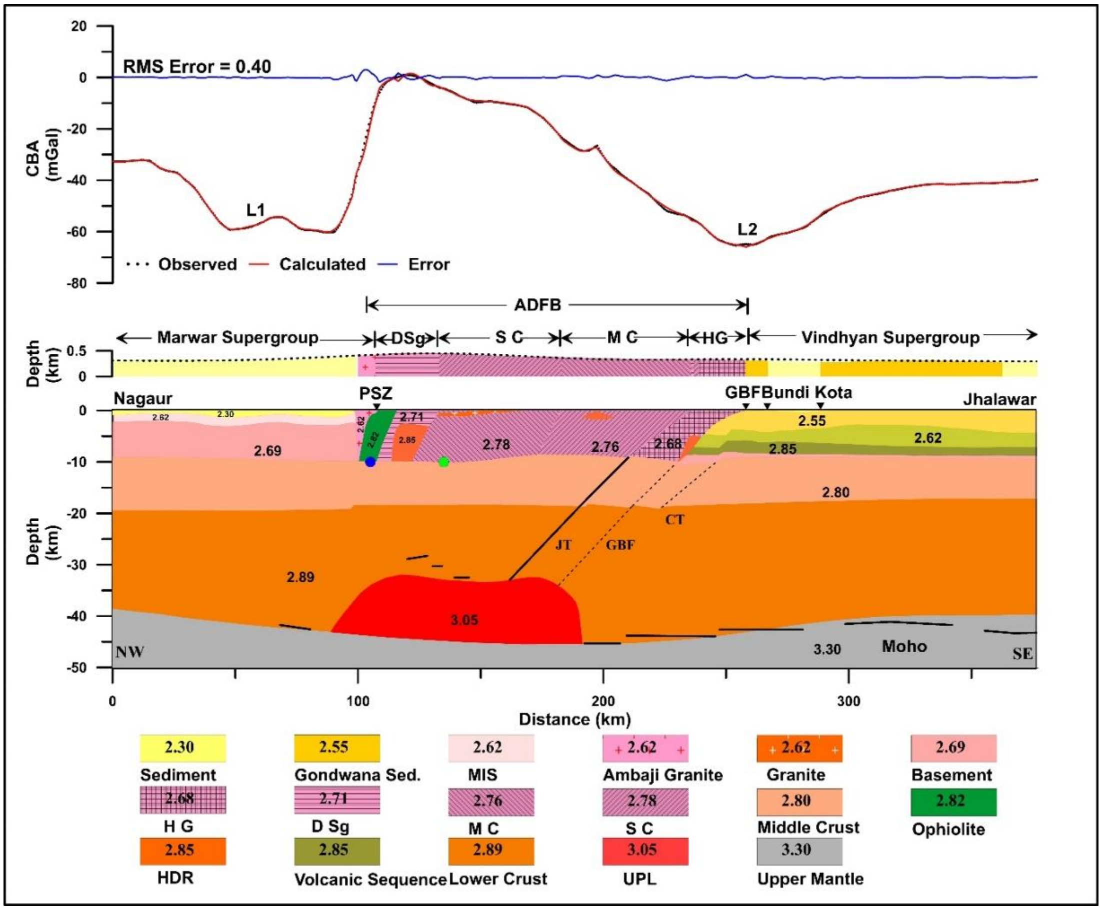

Figure 5. 2.5D crustal density (in g/cm^3) structure along the Nagur-Jhalawar seismic Profile-I, keeping our model as close as possible to the seismic constraints used. A high-density (3.05 g/cm^3) lower crustal body in ADFB is modelled at the base of the crust. The extent of the Marwar block, ADFB, and Bundelkhand craton is displayed on topography. Thick black solid lines indicate the seismically defined Moho, high-velocity layer (7.3 km/s), and Jahazpur thrust (JT). Abbreviations are the same as those given in Figure 1. Note the change in the exaggeration of the vertical scale at sea level.

The rocks of the Hindoli Group are described as granite-andesite in composition with a lower density of 2.68 g/cm^3, which explains the Bouguer gravity low (L2). A maximum depth of 6-7 km is modelled for the Upper Vindhyan rocks, a thickness of ~1.5 km is modelled for the Lower Vindhyan rocks, and the granitic gneiss basement is at a depth of 9.0 km (Figure 5). The cumulative thickness of the Lower Vindhyan is estimated to be ~1.7 km (Soni et al., 1987; Mandal et al., 2018).

The gravity modelling along Profile-I indicates considerable inhomogeneity in the upper crust due to lithological variation in different crustal blocks. The deeper layers of the modelled crustal density structure conform to the seismic section. Besides the Jahazpur thrust, the NW-dipping Great Boundary thrust to the west of Bundi and another subsurface Chambal fault to the east of Bundi are modelled up to the basement depth. The modelled crustal thickness in the Marwar block varies from ~39 km at Nagaur to ~42 km close to the ADFB zone. In the highly elevated ADFB area, the crust has a thickness of approximately 45 km, including a ~13 km thick high-density layer at its base. The crustal thickness beneath the Vindhyan Basin is ~42 km, and the lower crust has a uniform density, suggesting that its composition is homogeneous.

Jaisalmer-Indore (Profile-II)

The second gravity profile, chosen parallel to the first one, passes through the Malani Igneous Suite of the Marwar block, and the Deccan Traps covered the Vindhyan Basin of the Bundelkhand craton (Figure 1). The second most seismically active region after Delhi is covered in this profile. A layered crustal structure, similar to Nagaur-Jhalawar seismic Profile-I, is assumed across the ADFB. Additional information, such as seismic (Kumar et al., 2000), seismological (Sharma et al., 2018), MT (Nagajaneyuly and Santosh, 2012), and gravity (Mishra and Ravikumar, 2014; Prakash et al., 2020), is used to constrain the modelling in the two flanking cratonic regions. In addition to laboratory measurements to obtain density values of exposed Malani volcanic rocks, a few measured density values in the literature (Table 1) are assigned to the local geological units accordingly. An initial geometry of the crustal structure is inserted into the GMSYS (Geosoft, 2015) modelling program, and the calculated response is compared with the Bouguer anomaly observed along this profile. Portions of the initial geometry and average densities assigned to new geological bodies were then varied in order to achieve a match of the model gravity response with the observed Bouguer anomaly. A few geologically and tectonically reasonable concealed bodies of small wavelengths were added again to minimise the RMS error. The results of 2.5D density modelling of the Bouguer anomaly to determine the deep crustal structure across the three tectonic domains are shown in Figure 6. The RMS error between the observed and calculated model response is < 0.7 mGal, implying that the *a priori* model, based on the model derived along the neighbouring Profile-I, provides reasonable constraints for gravity modelling. Several significant features have been recognised from both the inferred gravity models (Figures 4 and 5).

DISCUSSION

Shallow crustal structure

The seismic section down to the granite-gneiss basement depth at the eastern end of the profile consists of four layers: a ~500 m thick Deccan Traps and another ~400 m thick Mesozoic sediments with an average velocity of 3.7 km/s (Kaila et al., 1985). It is followed by approximately 1.5 km of Vindhyan sediment and 5 km of Bijawar metasediments. Initially, the gravity low (L4) was interpreted to be caused by the subtrappean Vindhyan sediments overlying the Archaean basement (Nayak et al., 1986). This possibility was later ruled out based on the observed velocity of the subtrappean layer and the exposed Vindhyan sediments (Kumar et al., 2000). For the given layer thickness, an optimal density value of 2.36 g/cm^3 was suggested to match the observed gravity anomaly (Singh and Meissner, 1995). Given that the measured density of even Upper Vindhyan sediments is 2.55 g/cm^3, the inverted density (2.36 g/cm^3) possibly indicates a 500 m thick low-density sedimentary layer of Lameta or Bagh beds (Das et al., 2007) exposed in nearby regions (Figure 1). Though no seismic control is available to help constrain modelling of the adjoining gravity low (L3), the presence of the same low-density sedimentary layer can be a possible explanation. The two relative gravity highs in the eastern segment of the profile necessitate the presence of a high-density mafic body. The two gravity highs are attributed to the subtrappean Bijawar Group, which comprises meta-sediments with basic/ultra-basic intrusives (Mishra and Ravikumar, 2014). A thin (200-400 m) layer of upper and lower Vindhyan sediment is modelled throughout this region (Kumar et al., 2000).

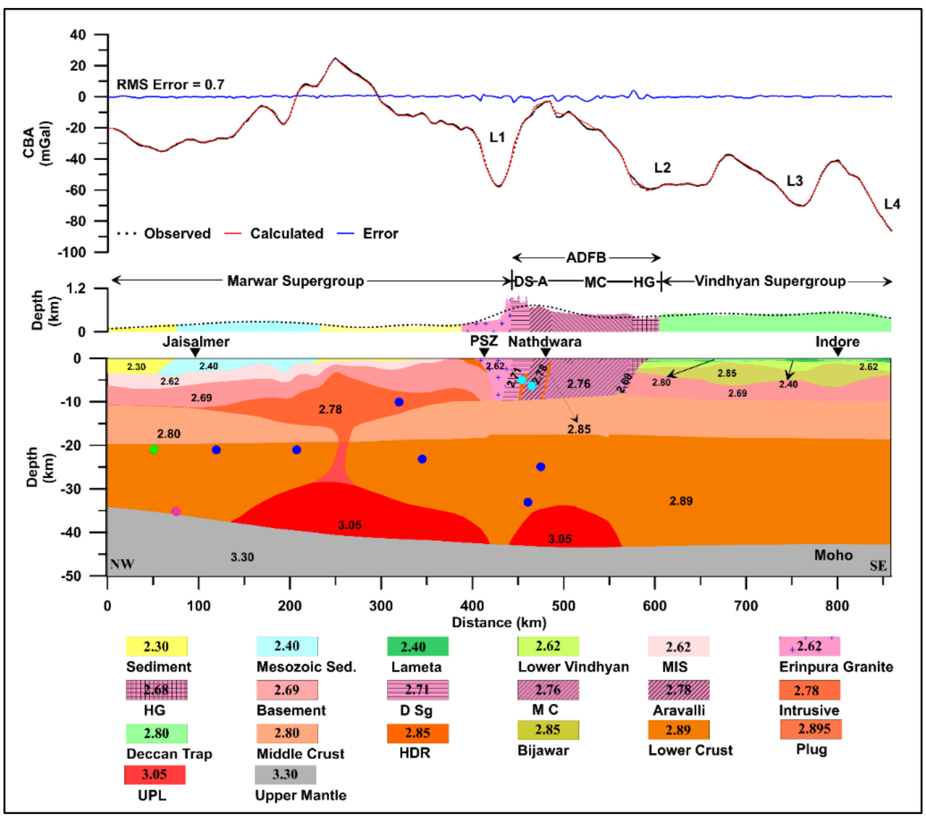

FIGURE 6. 2.5D crustal density (in g/cm^3) structure modelled along the Jaisalmer-Indore Profile-II. Two high-density bodies at the base of the crust beneath the Marwar block and ADFB, respectively, are modelled. The extent of the Marwar block, ADFB, and the Bundelkhand craton is displayed on topography. For abbreviations, see Figure 1. Note the change in the exaggeration of the vertical scale at sea level.

The near-surface crust under the ADFB has been modelled as several metasedimentary blocks extending to depths of about 9.4-10.8 km (Figures 4 and 5). A number of basic rocks in these metasedimentary sub-blocks may also be inferred, which increases the mean density to a maximum of ~2.78 g/cm^3. Our model further demonstrates that the sub-blocks of ADFB and its sub-vertical western boundary with the Marwar block dip steeply towards the west. The magmatic sills/dykes that intruded into the metasedimentary formations of various sub-blocks extend to a depth of 2 to 9 km (Figures 4 and 5).

The low gravity anomaly (L1) over the Marwar block indicates the presence of a sizeable felsic body underneath the Sendra-Ambaji (Mesoproterozoic)/ Erinpura-Phulad (Neoproterozoic) granite to the west of ADFB (Figure 6). Our gravity modeling suggests that these felsic bodies have a typical density of 2.62 g/cm^3, which may indicate a granite-dacite composition. The modelled granite body is a rootless, tabular body extending to a depth of ∼10 km, and its margins dip steeply inward. Malani Rhyolites, exposed in the Marwar block, are best represented as a thin layer (of density 2.62 g/cm^3) with a maximum thickness of ∼3.0 km overlying the high-density (2.69 g/cm^3) basement rocks of the Delhi Fold Belt. A particularly interesting feature of the model in this area is a 6-8 km thick high-density (2.78 g/cm^3) lens-shaped body that significantly contributes to the high Bouguer gravity anomaly (Figure 6). This body of probable intermediate to mafic composition emplaced in the upper crust may be a product of early magmatic activity associated with the Malani Igneous Suite (Prakash et al., 2020, and references therein).

Deep crustal structure and Moho geometry

Along the Nagaur-Jhalawar Profile-I, a 10-12 km thick high-velocity (V_p = 7.30 km/s) layer at the base of the crust has been documented underneath the ADFB by seismic studies (Tewari et al., 1997; Mandal et al., 2014). The P_{MS} interface observed at a depth of 29 km beneath the Ajmer broadband station is also reported to be the top of the atypical crustal layer (Ravi Kumar et al., 2001). Gravity modelling along this seismic profile also indicates a thick crust (~45 km) and a high-density (3.05 g/cm^3) dome-shaped body above the Moho zone (Figure 5). A high-velocity (7.3 km/s)/density (3.05 g/cm^3) layer in the lower crust with a seismically transparent upper mantle may be characteristic of magmatic underplating above the Moho (Thybo and Artemieva, 2013). However, without sufficient seismic refraction profiles, it is challenging to determine the lateral extension of the high-velocity body under the ADFB or ascertain its spatial distribution in the adjoining Marwar block. Our gravity modelling of Profile 2 establishes that the high-density (3.05 g/cm^3) mafic body in the lower crust persists from the central up to the southern part of the ADFB (Figure 6). A similar body was also modelled in the gravity profile with increasing Moho depth towards the northern extension of the ADFB (Dwivedi et al., 2019). The crustal configuration derived by inverting regionalised group velocity dispersion data (Sharma et al., 2018) in the Saurashtra region indicates an almost flat Moho lying at about 37-39 km depth in the south of the ADFB. The thick crust (~45 km) with abnormally high Vp (7.30 km/s) in the central part of ADFB was hypothesised as crustal thickening through magmatic underplating and fractionation of basaltic mantle magma (Mandal et al., 2014).

The crust in the adjoining tectonic domains, the Marwar block and the Bundelkhand craton, is characterised by typical Moho geometry with no signatures of modification along Profile-I. Despite the Deccan basalt at the surface, the crust beneath the Bundelkhand craton remains unmodified along Profile 2. However, a significant amount of crustal modification through ascending parent Malani Igneous Suite magma (of density 3.05 g/cm^3) is observed to accumulate in the lower crust, forming a deep crustal mush zone, some of which then ascended to a shallow depth in the Marwar block to feed the Malani Igneous Suite extrusion. The derived crustal density structures indicate high-density magmatic infiltration from the mantle into the lower crust at two discrete locales with distinct tectonic settings for the crustal modifications, namely beneath the orogenic belt of ADFB and the intraplate region of the Marwar block, where the Malani Igneous Suite is emplaced in the upper crust.

Tectonic implications of the model geometry

Accretion of the three tectonic domains and magmatic infiltration within the continental crust point towards Precambrian crustal modification and destruction, both at domain margins and intraplate regions of north-western India (Figure 7). The crustal growth of the Bundelkhand-ADFB-Marwar protocontinent began in the Archaean by rifting followed by accretion, orogenesis, and intermittent magmatism (Fareeduddin and Banerjee, 2020). The growth of ADFB is hypothesized as an outcome of either episodic oceanic crust-continent interactions or their evolution within the craton under ensialic regimes (Sinha-Roy, 1988; Sinha-Roy et al., 1995; Sharma, 2009; Bhowmik and Dasgupta, 2012; Pandey, 2020). The amalgamation of the Bundelkhand-ADFB-Marwar protocontinent started with the collision of the three blocks first along the Great Boundary Fault and subsequently along the Phulad Shear zone during the Proterozoic (Sinha-Roy et al., 1995). At the outset, the collage of the ADFB was accreted to the Bundelkhand craton along the Great Boundary Fault, up-thrusting the Mangalwar complex over the Hindoli-Jahazpur block (Sinha-Roy and Malhotra, 1989; Tewari and Kumar, 2003; Dey et al., 2019). The crustal-scale Jahazpur Thrust along the Great Boundary Fault defines the boundary of the westward subduction of the Bundelkhand craton (Mandal et al., 2018). Similarly, the NE-SW trending Phulad Shear Zone defines the terrane boundary between the Delhi Fold Belt and the Marwar block (Chatterjee et al., 2017, 2020; de Wall et al., 2022). The SE-dipping sub-crustal reflections observed in the Trans-Aravalli regions are interpreted as a relic subduction zone (Figure 4) and indicate the continental collision between the Marwar-ADFB domains (Mandal et al., 2014). The time of accretion of the Marwar block with the ADFB-Bundelkhand protocontinent was suggested as ~1.0 Ga (Kaur et al., 2021) to >0.8 Ga (Chatterjee et al., 2017, 2020).

The sharp gravity gradients on either side of the ADFB (Figure 2) corroborate the faulted contacts with adjoining domains within the craton, which have distinct crustal structures (Mishra et al., 2000). Our model (Figures 5 and 6) supports the accretion of the Bundelkhand-ADFB-Marwar blocks as a subduction-collision complex during the early Neoproterozoic (Bhowmik and Dasgupta, 2012). The Neoproterozoic crustal shortening of the ADFB between the adjoining blocks would have resulted in the crustal thickening with an elevated topography and a deeper Moho along its strike. A reflection-free lower crust, together with a strong reflector at ~30 km on top of the high-velocity layer containing a lensoid high-density (3.05 g/cm^3) magmatic layer just above the Moho (Figures 5 and 6) under the thicker crust of the ADFB represents the imprint of sequential bivergent collision and subsequent modification by rising of hot mantle material to fill the gap as magmatic underplating in the Archaean crust during Late Neoproterozoic. A similar dynamic crustal modification occurs through high-density basaltic magmatic underplating above the Moho across the orogenic belts (Thybo and Artemieva, 2013; Mandal et al., 2014; Dwivedi et al., 2019).

In active asthenosphere melt, a significant part of the rising mantle material solidifies as an underplate at the crust base, whereas large volumes of fractionated primary magma of rhyolitic composition reach the surface through the anatectic crust (Ayalew et al. 2019; Ernst et al., 2019). The delineated high-density bodies in the Marwar block indicate that the cumulates of the primary magma associated with Malani Igneous Suite are present at two levels: namely, a high-density (3.05 g/cm^3) ultrabasic body at the Moho (34 to 40 km depth) and another of granitic density (2.78 g/cm^3) at a depth of ~9 km.

The high-density lower crustal ultramafic layer delineated in the present case is observed to occur in two distinct tectonic settings (Figure 7). To visualise the differential degree of deformation and exhumation across the components of the NW Indian craton, we plotted an average geotherm observed at the surface based on the metamorphic grade of rocks observed in the litho-tectonic unit (Figure 7). It is clear that the Archean BGC formations constitute the base of the orogenic belt. Sedimentation in the extensional regime, followed by collision and deformation during ~1.8 Ga, is observed in the Aravali belt. The granulite-amphibolite grade rocks from the lower-mid crust were exhumed until 1.4-1.3 Ga. The adjacent Vindhyan basin received sedimentation in the shallow foreland basin over the underthrusting Bundelkhand Gneissic Complex since 1.4 Ga (Raza et al., 2009), which remained undeformed since, and the basin did not experience metamorphism, possibly representing ~200°C diagenetic temperature. The locus of deformation and exhumation remained confined to the Aravali belt, with over 20 km across the Great Boundary Fault, which has remained a steeply dipping terrane boundary since then. Towards the western margin of the Aravali orogenic belt, the rocks of the Delhi Fold Belt were deposited during the early rifting phase of the Rodinia orogeny, followed by deformation and exhumation of the medium-grade metamorphic rocks from a depth of ~550°C geotherm, suggesting intense deformation. The Neoproterozoic Phulad/Erinpura granite intrusion along the Phulad Shear Zone (PSZ), west of ADFB, represents the beginning of the Rodinia dispersal, which climaxed with the emplacement of the variegated rocks of Malani Igneous Suite during ~0.75 Ga. The recent seismicity in the southern ADFB and adjoining areas represents the reactivation of an older tectonic boundary under the influence of the present plate tectonic regime, and it remains confined to shallow structures. We speculate that the lower-middle crust has stratified due to the prolonged thermal equilibration since the Neoproterozoic period, obliterating the density contrast across the orogenic root zone, though the boundary between the ADFB and Bundelkhand along the Great Boundary Fault and Jahazpur Thrust is distinctly reflected in seismic signature (Tewari et al., 1997; Mandal et al., 2014).

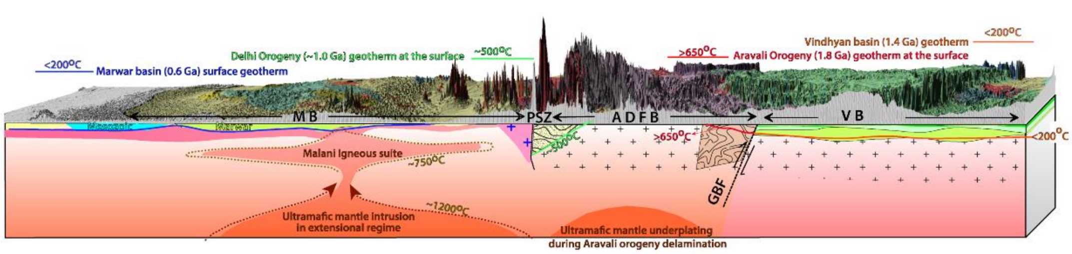

FIGURE 7. A schematic diagram for the evolution of the derived crustal density model of the Marwar-ADFB-Bundelkhand protocontinent. Abbreviations are the same as those given in **Figure 1**.

CONCLUSIONS

The Precambrian crustal growth of north-western India has involved a series of terrane accretions and modifications through mantle magmatism. The 2.5D gravity model, aided by geological and other geophysical constraints, represents the density structure of the litho-tectonic units and provides a realistic crustal structure for discussing the geodynamic evolution. The derived crustal density structure reinforces the bivergent collision hypothesis for ADFB evolution. Some major conclusions, derived from our data analysis and regional data review, are given below:

(i) The elevated ADFB has a thicker crust of ~45 km depth with a defused Moho boundary marked by the presence of a high-density magmatic mantle underplating above the Moho.

(ii) The crustal modification of the Marwar block during Late Neoproterozoic Rodinia dispersal was associated with mantle magmatic extrusion and progressive lower crustal melting, resulting in felsic rhyolitic magmatism of the Malani Igneous Suite.

(iii) The Bundelkhand craton and Vindhyan Basin, to the east of ADFB, largely remained stable with no crustal modification throughout the ADFB and Marwar block deformation.

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Authors credit statement

Om Prakash: Gravity data collection, processing, modelling and making of figures; A.P. Singh: Conceptualisation, overall supervision and paper finalisation; Niraj Kumar: Gravity data collection, validation and paper draft; K.N.D. Prasad: Gravity data collection and curation, and Anand K. Pandey: Geological and geodynamic input, draft improvisation

Data Availability

Gravity data used in this study is proprietary of CSIR-National Geophysical Research Institute, Hyderabad, and governed by its data sharing policy

Compliance with ethical standards

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper, and they adhere to copyright norms

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