



Integrated geophysical appraisal of crustal structure and tectonic evolution of the Angria Bank, western continental margin of India

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Abstract

Angria Bank, a submerged plateau with coral reefs, is located off the central-west coast of India. Biologically, the bank attracts scientific community for its coral formations. But geologically, origin and tectonic setting of this feature are not established yet due to scarcity of geological and geophysical data. Newly acquired bathymetry and magnetic data along with existing geophysical data have allowed us to determine crustal structure and tectonic evolution of the Angria Bank. The entire geological setup of the bank consists of 34 km long water plateau (average water depth ~20 m), and two prominent spurs extending to its western side. The area of water plateau and entire geological setup are 365 km² and 1460 km², respectively. The bank is characterized by two prominent magnetic low with a relative high in the middle. Integrated gravity and magnetic models revealed that flood basalt has carpeted the entire geological structure which later acted as a foundation for coral growth. The crust below the bank is continental in nature and underplated by high-density magmatic material. Moho is almost flat and lies at a depth of ~27 km. The results of 3D Euler deconvolution suggest that the study area is characterized by two types of linear trend viz. NE–SW to NNE–SSW and NW–SE. These trends are interpreted mostly as basement faults but at few places, they might be associated with sills/dykes. The geological setup of the bank is fault-bounded and comprised of two horst structure (interpreted as spurs) trending NE–SW to NNE–SSW. Integrated interpretation of the geophysical data revealed that the Angria Bank is an isolated feature, evolved during rifting between India and Seychelles-Laxmi Ridge in the Late Cretaceous.

Keywords Angria Bank · Integrated gravity and magnetic modeling · 3D Euler deconvolution · Flood basalt · Western continental margin of India

Introduction

Angria Bank, a submerged plateau, is located 130–135 km off the coastal districts of Ratnagiri and Sindhudurg of Maharashtra, India in the Arabian Sea (Fig. 1). Coral formation, rich marine biodiversity, high productivity and geological formation of the Angria Bank make it a unique feature on the western continental margin of India. It is one of the

largest submerged coral reefs of India. The submerged plateau of this bank is approximately 39 km long and 17 km wide, with an average water depth of ~20 m. The total area of this site is 1300 km², which include 350 km² area of submerged coral reefs (Sivakumar and Joshi 2015). Bathymetrically, Angria Bank, a clear water plateau, is steep-to on all sides, with 250–1500 m water depths surrounding its base. The peculiarity of Angria Bank corals is its location in the middle of the sea, unlike other corals which are either coastal in nature like the Gulf of Mannar or the Andaman and Nicobar corals which are island corals. This bank is said to have begun developing after the Holocene sea-level rise and coral communities dated 240 years (22 m water depth) indicate suitable conditions for reefs development in the shallow offshore bank (Rao et al. 2003; Sivakumar and Joshi 2015).

Angria Bank is mainly studied biologically for its coral formations, biodiversity and productivity by several

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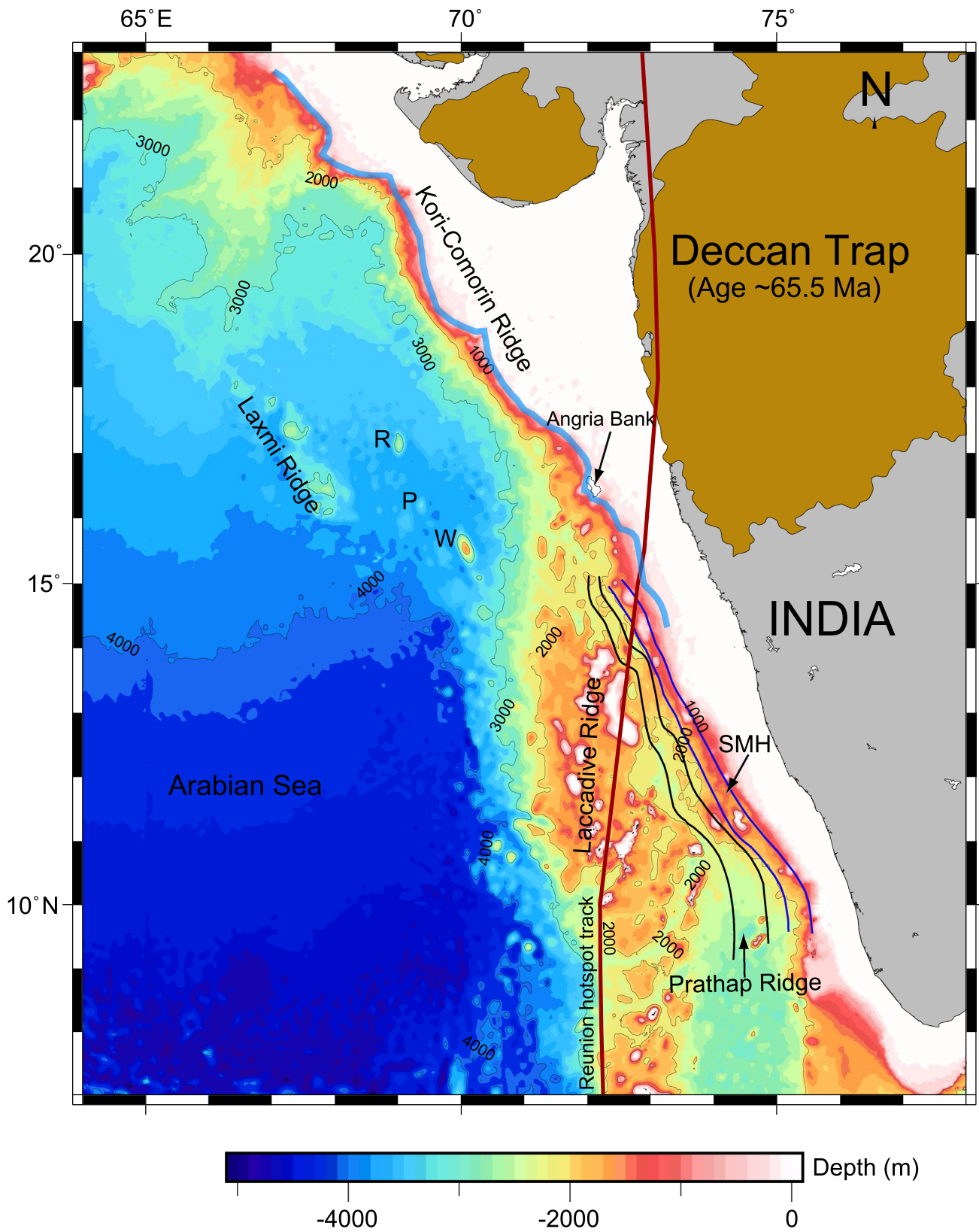


Fig. 1 Gridded bathymetric map of the western continental margin of India depicting major structural features of the region. Thick brown line represents Reunion hotspot track. SMH: Shelf Margin High; R: Raman Seamount; P: Panikkar Seamount; W: Wadia Guyot

researchers (Nair et al. 1966; Untawale et al. 1989; Ingole 2017). The coral development was supposed to form at an undulated foundation, which is not studied in detail. Some researchers (Ramaswamy and Rao 1980; Agrawal and Singh 1981) believe that undulated foundation is composed of flood basalts. Similarly, studies on crustal nature and origin of the bank have not given much attention in the literature, although differences in opinions exist regarding nature of crust and origin of the Angria Bank. Some researchers (Ramaswamy and Rao 1980; Agrawal and Singh 1981; Krishna et al. 1994) considered the Angria Bank to be a part of continuous submerged ridge which is parallel to the west coast of India. Whereas, Murti et al. (1981) considered it to be northward extension of Chagos Laccadive Ridge. Raju et al. (1990) suggested that reversely magnetized intrusive body is present below the Angria Bank. The existing knowledge does not establish unequivocally whether the Angria Bank is an isolated structure or part of other nearby geological features. Further, crustal structure of the bank is also not yet known.

The main objectives of this paper are to (i) determine crustal structure of the Angria Bank, (ii) investigate tectonic evolution of the bank, and (iii) establish its association, if any, with other nearby geological features. The study garners its importance in providing updated knowledge on crustal structure and tectonic evolution of the bank and has direct implications for marine tourism.

Regional tectonic framework

The western continental margin of India (WCMI) is a volcanic rifted margin and formed due to breakup and dispersal of India, Madagascar and Seychelles continental blocks. The margin experienced multiple phases of extensional tectonics in geological past and evolved in different phases (Norton and Sclater 1979; Naini and Talwani 1983; Bhattacharya and Yatheesh 2015). In the first phase, southwestern India got separated from eastern Madagascar during the Late Cretaceous under influence of the Marion hotspot volcanism and sea-floor spreading occurred in the Mascarene Basin (Norton and Sclater 1979; White and McKenzie 1989; Storey et al. 1995; Torsvik et al. 1998; Raval and Veeraswamy 2003). The opening of the Laxmi Basin between Seychelles-Laxmi Ridge and India was the second major tectonic phase, which resulted short sequence of two-limbed seafloor spreading type magnetic anomaly in the basin (Bhattacharya et al. 1994; Bhattacharya and Yatheesh 2015). Seychelles separated from Laxmi Ridge-India and drifted in the last phase during the Early Paleocene, while the Reunion hotspot activity was in its peak phase (Norton and Sclater 1979; Naini and Talwani

1983; Chaubey et al. 2002). The Eastern Somali Basin and conjugate Arabian Basin evolved during this phase of rifting. Reunion hotspot played a major role in shaping up of WCMI and modified crustal geometry of the region.

The Reunion hotspot related volcanism occurred on continental shield as well as on adjacent oceanic region as the Indian plate moved northwards over the hotspot. It created the Deccan continental flood basalt province on western and central India (Mahadevan 1994) as well as continental flood basalt on the Seychelles micro-continent (Devey and Stephens 1991). The Reunion hotspot also emplaced numerous magmatic intrusions within the crust of western continental margin of India. The Deccan flood basalt consists of multiple layers of solidified lava flows, most of which (~80%) erupted in less than 1 million years (Courtillot et al. 1988; Venkatesan et al. 1993) during the magnetic Chron 29r (~65.6–64.8 Ma) through the Cretaceous–Tertiary boundary.

Geological and geophysical investigations of the western continental margin of India revealed the presence of several bathymetric highs, lows, buried basement ridges and basins. The prominent ridges are Laxmi Ridge, Chagos-Laccadive Ridge, Prathap Ridge, Panikkar Ridge, mid-Shelf Basement Ridge, Shelf Margin High and Kori-Comorin Ridge (Fig. 1). Kori-Comorin Ridge connects the Kori High in the north, the Prathap Ridge in the Kerala offshore and Cape Comorin at southern tip of India. The ridge follows 200 m bathymetric contour in most part of its length up to Vengurla Arch. Further south, it crosses shelf-slope boundary and joins the Prathap Ridge along the slope in deep water (Biswas and Singh 1988, Biswas 2008). Seismically imaged Prathap Ridge, identified by Naini and Talwani (1983), is considered as a basement ridge formed by volcanic activity (Krishna et al. 1992). Krishna et al. (1994) identified a small segment of sub-surface ridge located on the continental slope and suggested this ridge to meet Prathap Ridge complex at the Angria Bank and continues further north probably as a single feature.

Recently, Kumar et al. (2015) have acquired multibeam bathymetry data over the Angria Bank and generated a Digital Elevation Model (DEM) of the area. According to the DEM, Angria Bank rises from seabed at water depth of ~1500 m and forms terraces between 700 and 200 m, between 200 and 30 and <30 m water depths with surface area of 806 km², 307 km² and 333 km², respectively. They have also shown that the bank is characterized by two prominent spurs extending towards southwest with a valley in between. The spurs are wider on the eastern side and taper towards the west. On eastern side, the Angria Bank ends with a steep slope parallel to the coast and connects to main continental shelf at ~250 m water depth.

Data

New data acquisition and compilation of magnetic data in the Angria Bank region is very important because no new data is available this area. Though, magnetic data along three tracks are available, it is very old and have coarser interval. In order to fill data gap in and around the Angria Bank region, ship-borne bathymetry and magnetic data were acquired during two recent cruises of Research Vessel (RV) Sindhu Sankalp (Cruise SSK096) in the year 2016 and RV Sindhu Sadhana (Cruise SSD032) in the year 2017. Bathymetry data were acquired using shallow water echosounder (SyQwest BATHY-1500C), deep water echosounder (SyQwest BATHY-2010 and Knudsen), EM302, Atlas Hydrosweep MD and Hydrosweep DS multibeam echosounders. Magnetic data were acquired using cesium-vapor marine magnetometer model G-882. Data along track were recorded with satellite based navigation system (Hemisphere R220 GPS Receiver and Veripose DGPS). The surveyed tracks are shown in Fig. 2. Magnetic data were processed for layback correction and spike removal. International Geomagnetic Reference Field (IGRF) of appropriate epochs has been subtracted from the total magnetic intensity data to compute residual magnetic anomalies. Multi-channel seismic reflection section along track RE11 from Krishna et al. (2006), traversing close to the Angria Bank, is utilized to get better structural information of the region.

In addition, public domain data (bathymetry, magnetic and free air gravity anomalies) have also been incorporated in the study. Ship-borne magnetic data acquired along track RC1707, OPR476G and OWEN61 in the years 1974, 1967 and 1962, respectively are taken from National Geophysical Data Centre, U.S.A. (NGDC). Bathymetry grid from General Bathymetric Chart of the Ocean (GEBCO_2014 from Weatherall et al. 2015), 30 arc-second gridded-data, is merged with ship-borne bathymetry data and used to generate bathymetry map of the study area (Fig. 2). GEBCO_2014 is the latest version of the global digital bathymetric model which includes the most recent bathymetric compilations from bathymetric chart of the oceans plus bathymetric surveys and soundings gathered along ship tracks. Free air gravity anomaly and vertical gravity gradient grids (1 min gridded data) were extracted from global marine gravity data (grav.img.24.1 and curv.img.24.1 of Sandwell et al. 2014) for analysis and interpretation. Free-air gravity anomaly and vertical gravity gradient maps are generated using these grids and presented in Fig. 3a, b.

Two drilled wells R-1-1 and RO21, drilled by Oil and Natural Gas Corporation of India, have been used for deriving lithology information of the study area (Mathur

and Nair 1993). Drilled well R-1-1 is located on the Spur 2 of the Angria Bank, whereas, RO21 is located on the continental shelf near the bank (Fig. 2). In order to investigate P-wave velocity structure of the bank, refraction station S3 (Rao 1970) located north of the bank is used. Velocity structure at this station shows two sedimentary layers of thickness 975 and 3140 m with P-wave velocity of 1.9 and 2.8 km/s, respectively. The sedimentary layer is followed by two layers of P-wave velocities 4.6 km/s (3720 m thick) and 6.6 km/s. The layer with velocity 4.6 km/s is interpreted as flood basalt by Kumar and Chaubey (2019).

Litholog of the well R-1-1 (Mathur and Nair 1993; Pandey and Dave 1998) indicate that the seabed lie at water depth of ~50 m, below which whitish chalky limestone formation is present up to 1500 m, but the lower part of the formation was not clearly interpreted in the litholog. Weathered flood basalt was encountered from 1500 m to 1520 m depth. Litholog of well RO21, located in water depth of ~100 m (Pandey and Dave 1998) revealed a 2105 m thick sedimentary strata consisting of limestones and shales, dominated by limestones in upper part and shales in lower part. Flood basalt layer was encountered at a depth of 2105 and continued up to target depth of 2330 m.

Ship-borne magnetic data along all tracks (Fig. 2) are further analyzed for crossover error as the data have been compiled from different cruises. The crossover errors at each intersection are estimated and appropriate linear models of systematic corrections for each track are determined using the x2sys package (integrated with GMT package) of Wessel (2010). Relative weight for each track is assigned by following formula (Hsu 1995):

$$W_i = \frac{N}{\sum_{j=1}^N (D_{ij})^2}$$

where, W_i : weight for the i th track, D_{ij} : j th crossover error for i th track, N : total number of crossover points in the i th track.

After determining appropriate linear models of corrections and relative weight, systematic corrections have been applied for each tracks using 'x2sys_datalist' to obtain corrected and adjusted magnetic data. The crossover corrected data is gridded with minimum curvature method and resulted magnetic grid is utilized to generate magnetic anomaly map of the study area (Fig. 4) for further analysis and interpretation.

Results

Geophysical characteristics of Angria Bank

Detailed bathymetric study reveals that the Angria Bank lies immediately after the shelf break and situated on continental

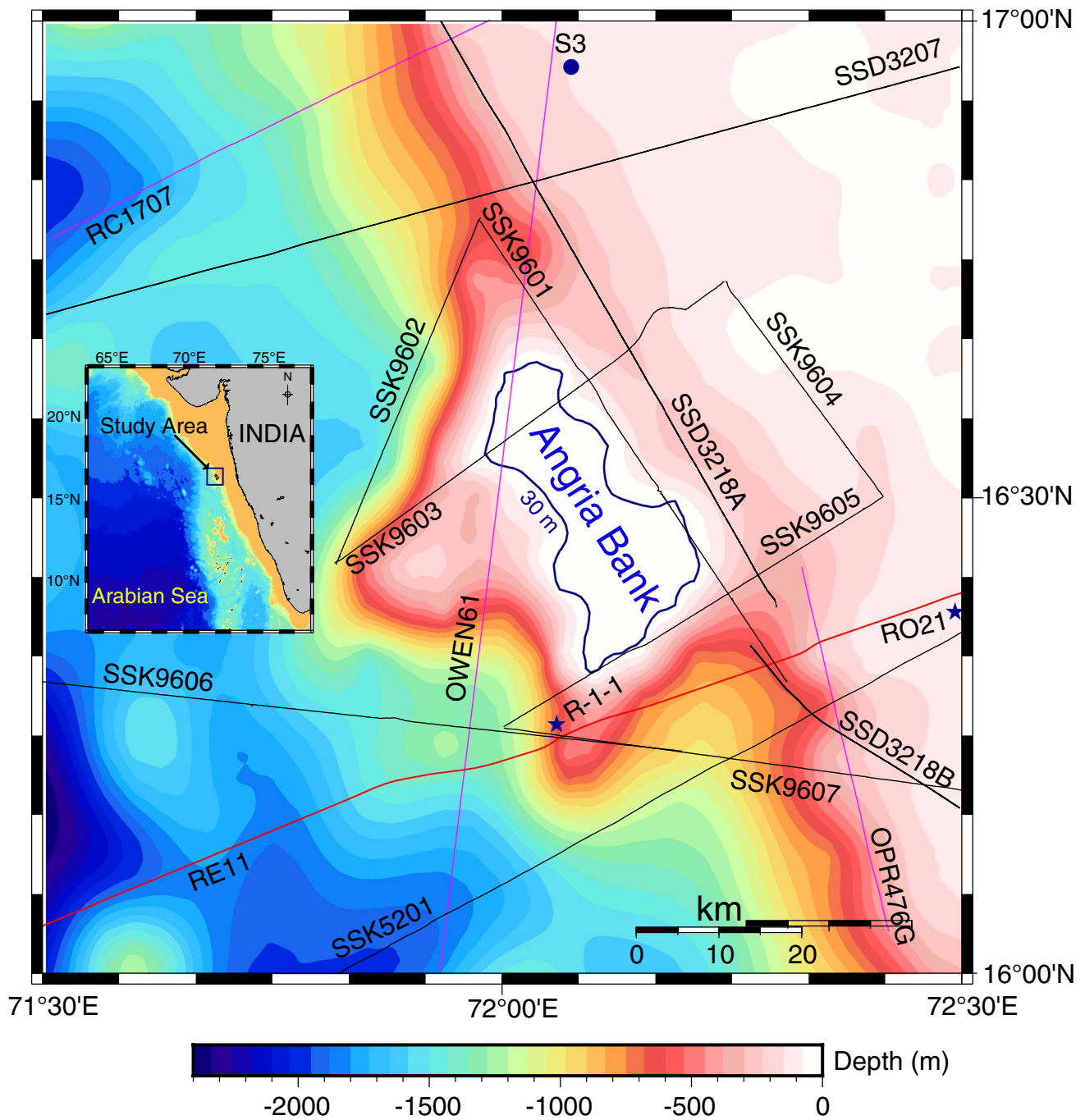


Fig. 2 Bathymetric map (GEBCO-2014) of the study area. Location of the study area is shown in Insat map. Angria Bank is shown with blue color solid line. Magnetic survey lines used in the present study are shown with black solid line (NIO database) and magenta solid

line (NGDC database). Multi-channel seismic track line is shown with red color. Sesimic shot points are shown with red and black dots. Drilled-well locations and refraction station are shown with solid blue star and solid blue circle, respectively

slope region of the west coast of India. Bathymetry map (Fig. 2) reveals that geological setup of the bank consists of a water plateau and two prominent spurs extending to its southwestern side. Water depth over the flat portion of the bank is ~20 m and varies from 20 to 1000 m over the entire geological setup of the Angria Bank. The flat-topped

water plateau is elongated in NNW–SSE direction and is ~34 km long. Width of the plateau varies along its length. It is 11 km in the northern, 6 km at the central and 19 km in the southern part of the plateau with an average width of ~14 km. Area of flat portion of the bank (considering 30 m depth contour represent its boundary) is ~365 km².

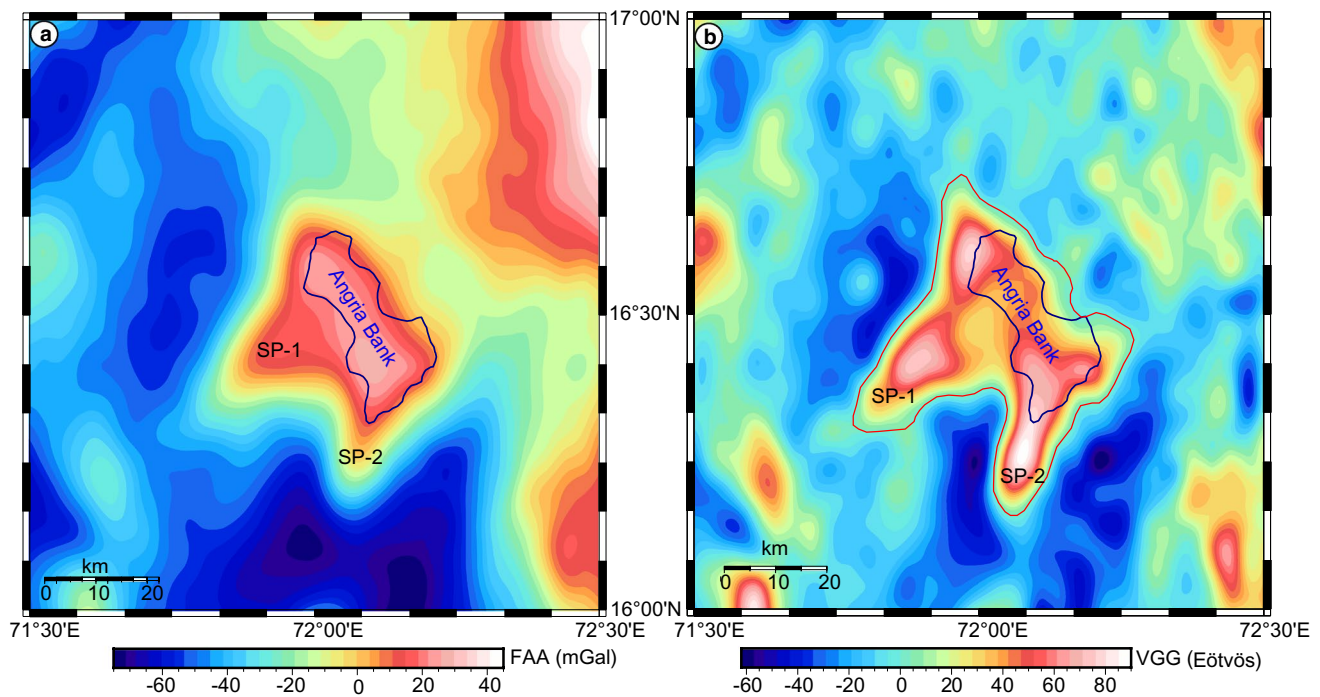


Fig. 3 **a** Satellite-derived free air gravity anomaly map (Sandwell et al. 2014) and **b** Vertical gravity gradient map of the study area. Angria Bank is shown with blue solid line

Free-air anomaly (FAA) over the bank ranges from 0 to 28 mGal while for entire geological setup of the bank, it varies from -51 to 28 mGal and is consistent with the bathymetry. Flat portion of the bank shows maximum positive FAA (~ 28 mGal) and base of the spurs on western side of the plateau shows minimum FAA (~ -51 mGal). FAA (Fig. 3a) depicts NNW–SSE trending flat plateau as well as both of its spurs (named here as SP-1 and SP-2). Though, both the spur features SP-1 and SP-2 are also seen in bathymetry and FAA maps, in the case of Vertical Gravity Gradient (VGG) map both the spurs are distinctly depicted with a clear trend of N30°E and N17°E. Therefore, boundary of the entire geological setup of the Angria Bank is demarcated based on the vertical gravity gradient which is shown with red curve in Fig. 3b. Area of entire geological setup of the bank is ~ 1460 km². Though NNW–SSE trending flat-topped plateau is clearly defined in the bathymetry as well as FAA maps, it is not distinct in VGG map. It appears that northeastern portion of both the spurs jointly formed the NNW–SSE flat-topped bank.

Magnetic anomaly map (Fig. 4) shows two prominent magnetic lows trending NNE–SSW direction which are associated with both the spurs. Maximum amplitude of the magnetic anomaly lows reaches up to 183 nT and 248 nT over the spurs SP-1 and SP-2 respectively. It is interesting to note that magnetic anomaly map does not exhibit any prominent magnetic trend along NNW–SSE trending flat-topped plateau.

Both ends of flat portion of the bank i.e. NNW end and SSE end are associated with prominent magnetic lows, whereas central part is associated with relative magnetic high. There are several other prominent magnetic anomalies (both lows and highs) around the bank which may be associated with some other geological features.

For a better understanding of crust below the Angria Bank, a multi-channel seismic section along track RE11 is presented in Fig. 5. The seismic track is 65 km long and traversed between 40 and 2000 m water depth. It covers a part of the continental shelf, shelf break, slope, basement high and eastern part of the Prathap Ridge Complex. The age of major reflectors has been assigned from Chaubey et al. (2002). The basement high, located between shot points 1330 and 1660, represents spur SP-2 which has relief of about 1.5 s TWT. The width of the basement high in this section is ~ 17 km. Prathap Ridge Complex comprised of intrusive bodies which lie just west of the spur SP-2. The reflection pattern of Prathap Ridge Complex is parabolic in nature which is characteristics of igneous intrusions.

3D Euler deconvolution and depth estimation

3D Euler deconvolution method is utilized in the present study for identifying faults and lineaments from the gridded magnetic data. The Euler deconvolution is a widely used

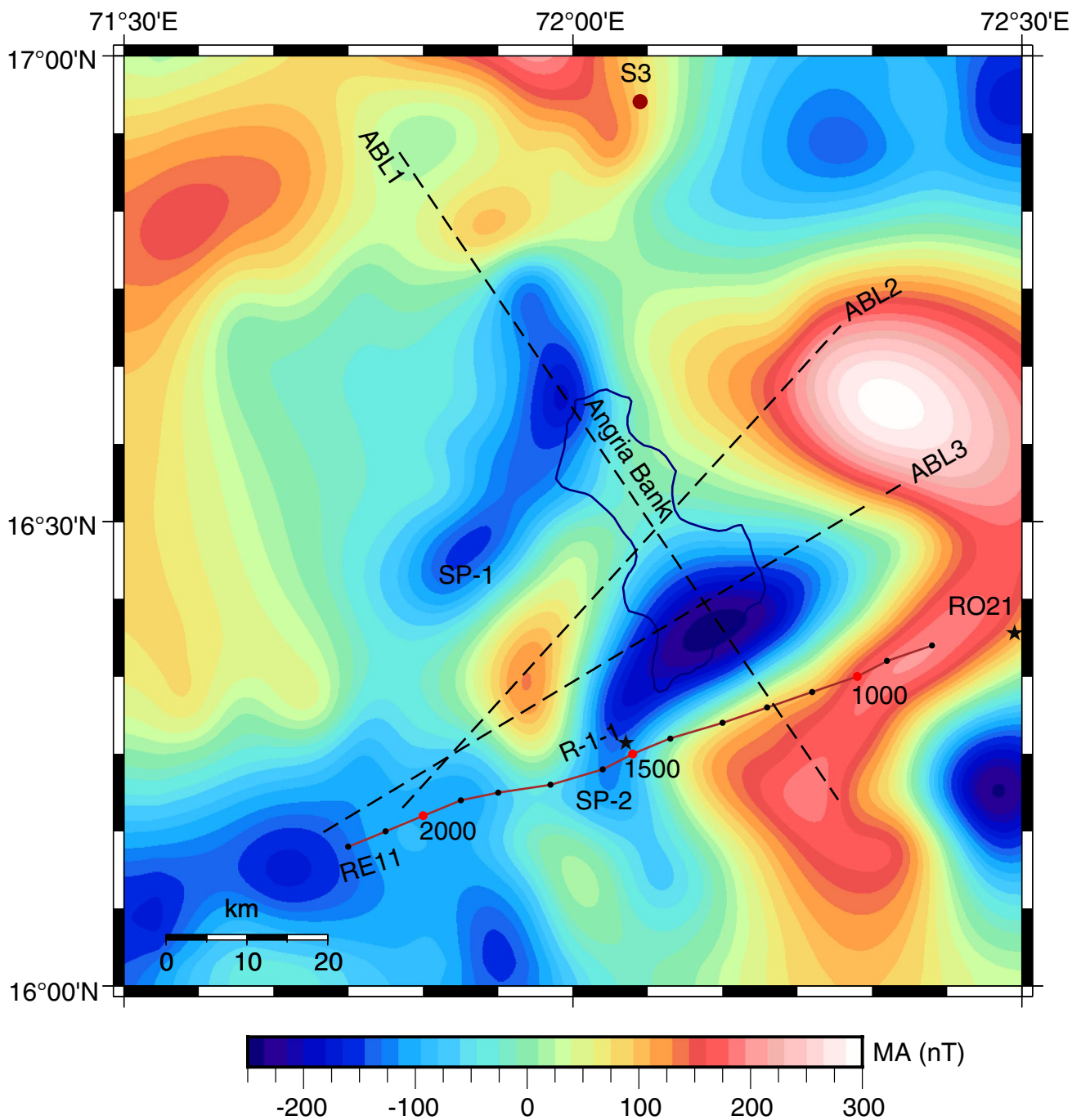


Fig. 4 Magnetic anomaly map of the study area. Angria Bank is shown with solid blue line. 2D crustal models along dashed black lines are generated and presented in Fig. 7a–c. Seismic track line

RE11 is shown with red color. Drilled-well and refraction stations are shown with solid green star and circle, respectively

technique and is based on solving Euler’s homogeneity equation

$$(x - x_0) \frac{\partial F}{\partial x} + (y - y_0) \frac{\partial F}{\partial y} + (z - z_0) \frac{\partial F}{\partial z} = -NF$$

where F is total magnetic field anomaly observed at (x, y, z) due to magnetic source located at (x₀, y₀, z₀) and N is

the Structural Index (SI). The advantage of this method is that the magnetic data need not be reduced to pole, so that remanence is not an interfering factor (Reid et al. 1990). Since, structural index is dependent on source geometry, and observed anomaly might have different sources, therefore, the above equation should be solved for a number of indices.

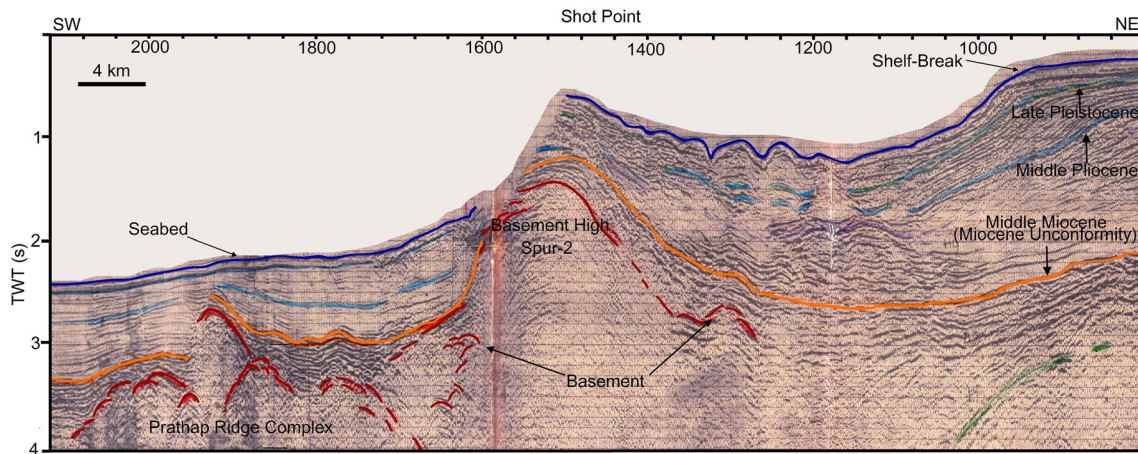


Fig. 5 Multi-channel seismic section along a segment of track RE11 showing prominent basement high associated with spur (SP-2) of the Angria Bank. Major reflectors are marked with different colors. Igne-

ous basement is marked with brown color. Location of the track RE11 is shown in Figs. 1 and 4. TWT: two way travel-time

The indices, which give good clusters of Euler solutions, should be chosen for interpretation.

In this study, the Euler deconvolution is applied on gridded magnetic data with a window size of 5 km × 5 km. The Euler solutions are obtained for different SI ranging from 0 to 3 and it is found that for higher SI (> 2), solutions are widely dispersed which suggest absence of cylindrical or spherical body in the study area. Faults or contacts are best displayed at SI = 0, therefore, the Euler solutions are obtained for SI = 0 for identifying major faults or lineaments in the study area. The Euler solutions corresponding to SI = 0 displayed good cluster as shown on vertical gravity gradient map (Fig. 6a). Prominent cluster solutions are interpreted as possible basement faults or lineaments which are shown in Fig. 6b. Most of the clustered solutions demonstrate two types of trends in the study area viz. NE–SW to NNE–SSW and NW–SE (Fig. 6a, b).

Integrated modeling of gravity and magnetic data

Integrated gravity and magnetic modeling is carried out using GM-SYS software along 3 transects ABL1 (along the bank), ABL2 and ABL3 (across the bank) to derive crustal model of the Angria Bank (Fig. 4). The transects are chosen in such a manner that they intersect the most prominent magnetic and gravity anomalies. Densities of different crustal layers were obtained from refraction derived P-wave velocity using Brocher formula (Brocher 2005). Based on refraction survey of Rao (1970), velocity structure in various crustal layers below continental shelf adjacent to study area reveals P-wave velocity range of 2.7–2.8 km/s, 4.2–4.6 km/s and 6.3–6.6 km/s. The layers with P-wave velocities 2.7–2.8 and 6.3–6.6 km/s is considered as sedimentary and upper crustal layer, respectively. The layer of velocity range 4.2–4.6 km/s

is interpreted as flood basalt by Kumar and Chaubey (2019). Since P-wave velocity structure of lower crust is not available on the continental shelf; therefore, refraction derived velocity on adjacent western Indian shield are considered to derive density of lower crust. P-wave velocity structure of Deccan volcanic province of western Indian shield reveals 5.8–6.5 km/s in upper continental crust, 6.6–6.9 km/s in lower continental crust and 8.0–8.4 km/s in upper mantle (Kaila and Krishna 1992). High velocity (7.1–7.4 km/s) underplated layer above upper mantle is also reported at some places. Presence of lava flow (Deccan flood basalts equivalent), which lie below sedimentary strata of the Angria Bank, is also reported on the basis of drilled well data (Ramaswamy and Rao 1980; Agrawal and Singh 1981; Mathur and Nair 1993) at a depth of ~ 1500 m (Mathur and Nair 1993).

In order to generate crustal model, densities of seawater and sediments are taken as 1.03 g/cm³ and 2.2 g/cm³, respectively. Representative densities of flood basalt, upper continental crust, lower continental crust and upper mantle are taken as 2.46, 2.81, 2.89 and 3.3 g/cm³, respectively. Published crustal models and velocity structure of nearby offshore area suggest that a high-density layer is also present just above the upper mantle and density of this underplated layer is taken as 3.03 g/cm³. Constraints from published drilled well, refraction and reflection seismic data (Mathur and Nair 1993; Rao 1970; Krishna et al. 2006) have also been taken into consideration while creating the model.

Magnetic properties of flood basalt are taken from published literature from western offshore region of India (Rao 1990; Subrahmanyam et al. 1994; Krishna et al. 2006; Rao et al. 2010). Paleomagnetic measurement of tholeiitic flows of Deccan flood basalt indicated normal–reverse–normal (N2–R1–N1) polarity sequence which corresponds to

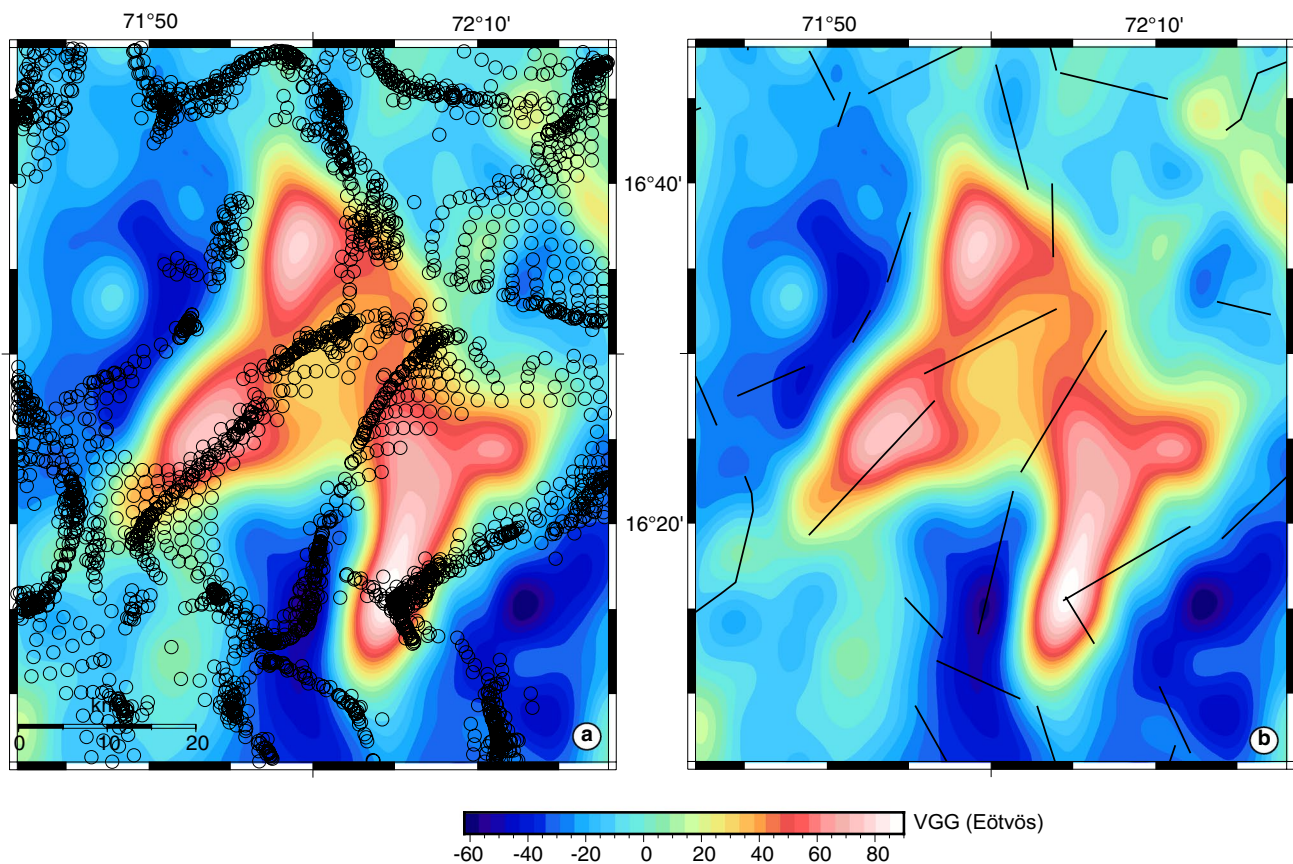


Fig. 6 **a** 3D Euler solutions for Structural Index (SI)=0. **b** Interpreted trends from cluster of solutions are plotted on vertical gravity gradient map

magnetic Chrons 30n, 29r and 29n, respectively of the standard magneto-stratigraphy scale (Vandamme et al. 1991). Maximum volume of flood basalt (80%) erupted within < 1 My during Chron 29r (Courtillet et al. 1988). It is possible that flood basalt might have accreted beneath the bank during more than one magnetic reversals, but we prefer to present simple model based on published fact that more than 80% flood basalt erupted during magnetic Chron 29r. Therefore, we consider entire flood basalt belongs to one polarity (Chron 29r) in the present study. In order to compute magnetic anomaly, magnetic parameters for reversely magnetized bodies (flood basalt and intrusive bodies) such as susceptibility 0.0017 CGS unit, remanent magnetization 0.002–0.003 emu/cm³, inclination + 50° and declination + 130° are considered. For normally magnetized bodies (intrusive bodies), inclination and declination are taken as –50° and –40°, respectively while values of other parameters are kept the same.

Initially, crustal model is generated considering that the magnetic anomalies are due to flood basalt only. In order to model observed high magnetic anomaly, a thicker layer (> 4 km) of flood basalt was needed to introduce. However,

maximum reported thickness of flood basalt on adjacent onshore region is ~3.4 km and at nearby refraction station S3 is ~3.9 km, did not allow us to use thick layer of flood basalt (> 4.0 km). Therefore, intrusive bodies were introduced at appropriate locations in order to model observed magnetic anomaly. Density of intrusive body was taken as 2.9 g/cm³ to compute gravity anomaly.

To obtain consistency between observed and computed gravity and magnetic anomalies, physical parameters are kept constant and layer dimensions are changed in an iterative manner. The best fit between observed and computed gravity and magnetic anomalies was obtained by minimizing Root Mean Square (RMS) error and interactively modifying configuration of the crustal layers. The best fit crustal models are shown in Fig. 7a–c.

Crustal model along transect ABL1

Integrated gravity and magnetic modeling was carried out along NNW–SSE trending transect ABL1. Consistency between the observed data and computed gravity and magnetic responses of the crustal model is shown in Fig. 7a.

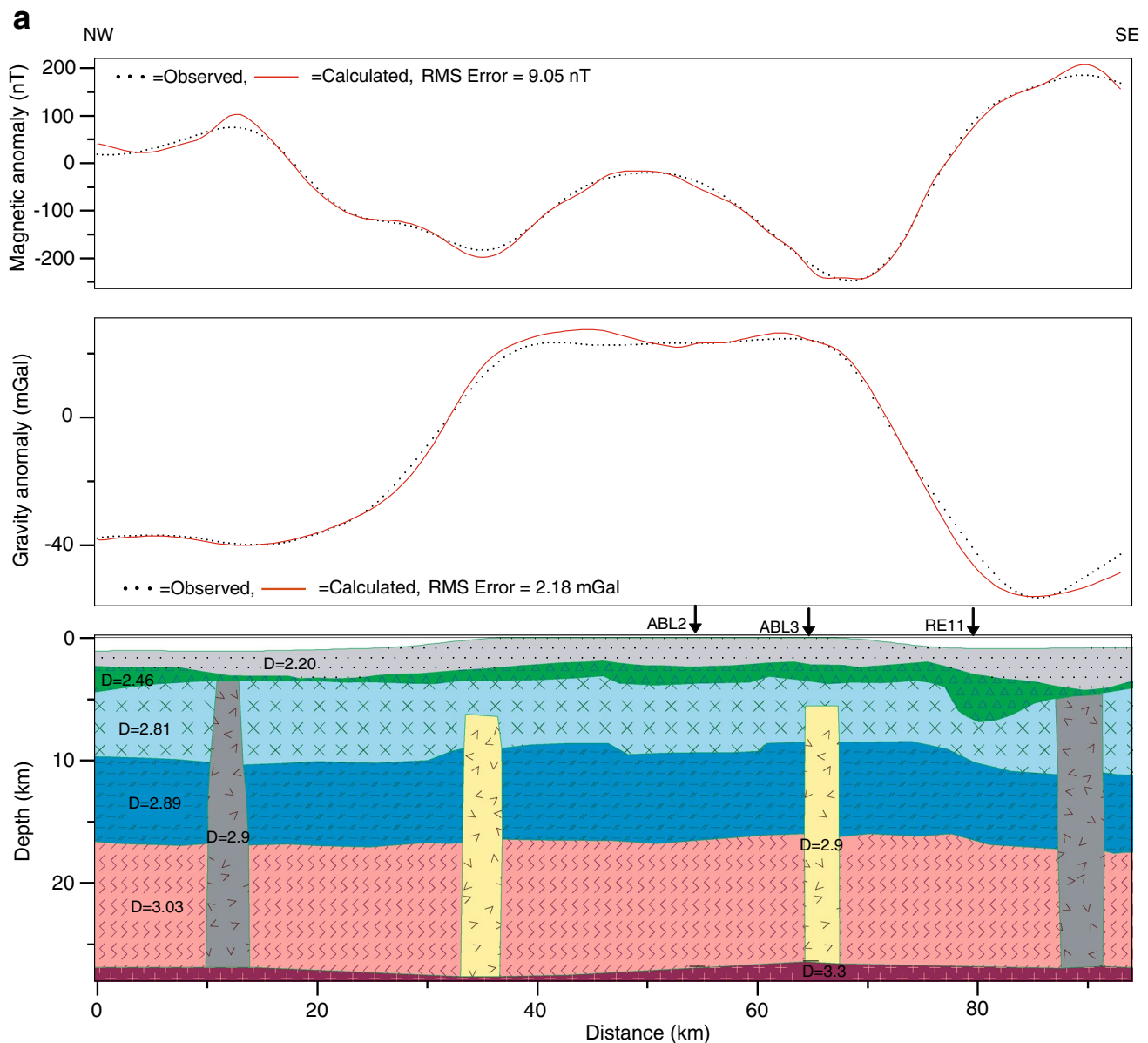


Fig. 7 Integrated gravity and magnetic 2D crustal model along transects **a** ABL1, **b** ABL2 and **c** ABL3. Location of the transects are shown in Fig. 4. Magnetic parameters of flood basalt and intrusive bodies for magnetic anomaly computations are taken as susceptibility 0.0017 CGS unit and remanent magnetization 0.002–0.003 emu/cm³.

The resulting crustal model reveals that flood basalt overlies the granitic basement and a high density underplated layer (~9 km thick) above the upper mantle is present all along the profile. Flood basalt is observed at a depth of ~2000 m over the flat top plateau. Thickness of flood basalt along the profile is variable, with a minimum of 100 m at NNW flank and a maximum of 3100 m at SSE flank of the plateau. A relative magnetic high located at centre of the plateau is associated with thick layer of flood basalt. Two intrusive bodies, reaching to granitic basement are present, which are

For reversely magnetized bodies (grey-shaded), inclination is +50° and declination is +130°. For normally magnetized bodies (yellow-shaded), inclination is –50° and declination is –40°. D: density in g/cm³

reversely magnetized and associated with magnetic high located near both ends of the profile, whereas two normally magnetized intrusive bodies which are not reaching to the granitic basement are present below the bank and are associated with prominent magnetic low. These intrusive bodies are ~3 to 4 km wide. Upper crustal layer is ~6 km thick and undulated, whereas lower crust has an average thickness of ~8 km, and is underlain by underplated layer. The crustal layers are more or less horizontal and crust-mantle boundary lies at ~27 km below sea-surface.

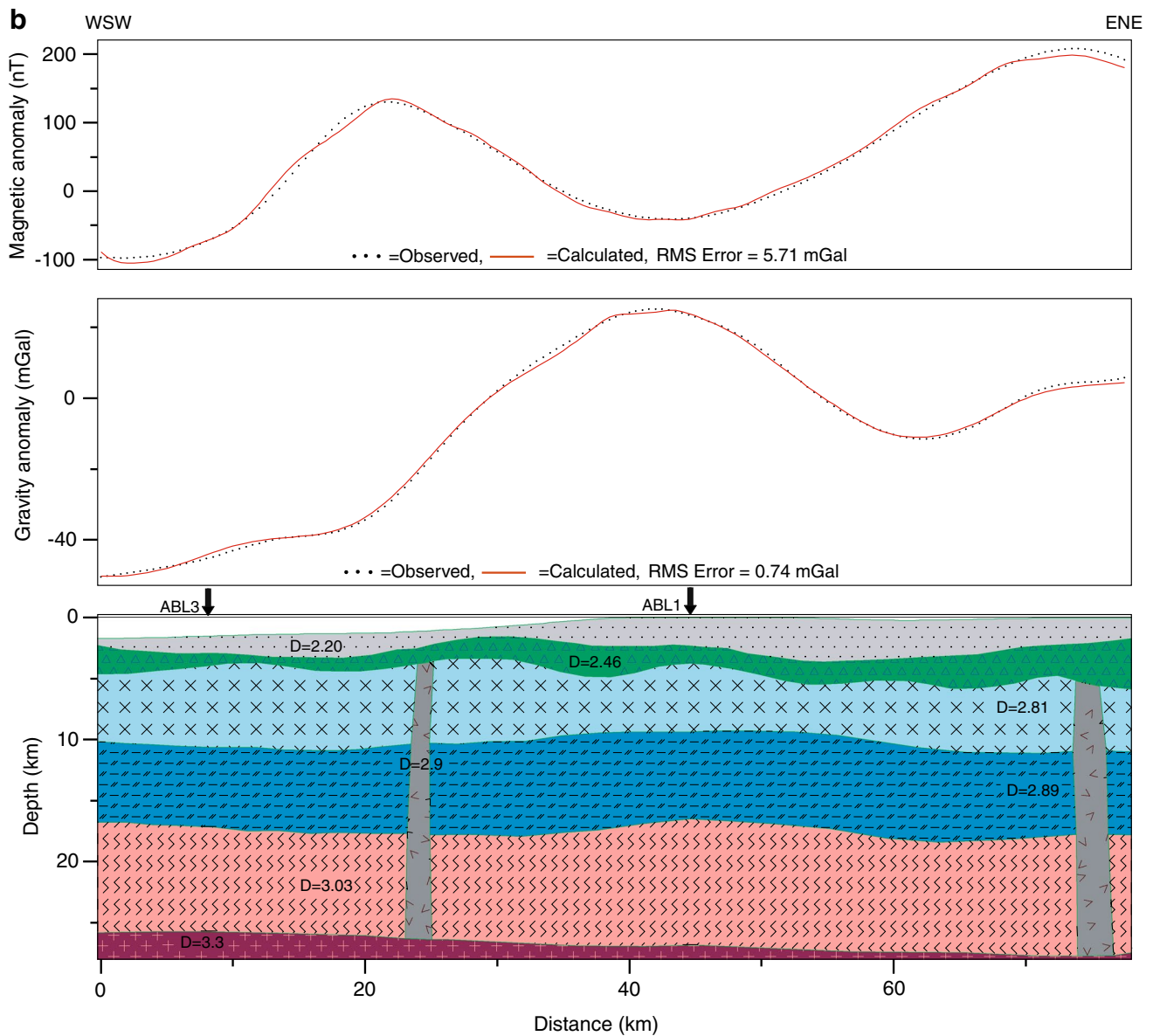


Fig. 7 (continued)

Crustal models along transect ABL2

Crustal model along transect ABL2 (Fig. 7b) reveals presence of flood basalt all along the profile over an undulating granitic basement. Flood basalt occurs at a depth of ~2100 m below the flat top plateau and its depth of occurrence varies between ~1500 and ~3600 m along the profile. Thickness of flood basalt below the flat top plateau varies from 1500 to 2700 m, whereas maximum thickness is found to be 3800 m on eastern side of the plateau. Reversely magnetized two intrusive bodies are also present which correspond to prominent magnetic highs. The best fit model also reveals a high density underplated layer (~9 km thick) and Moho at depth of ~18 km and ~27 km, respectively.

Crustal model along transect ABL3

Since profiles ABL2 and ABL3 are very close to each other and traversing in almost same direction, therefore, crustal models along these two profiles are quite similar. The best fit crustal model (Fig. 7c) revealed that flood basalt occurs at a depth of ~2000 m beneath the flat top plateau. High density underplated layer (~8 km thick) is also present below the lower crust. Depth of occurrence of flood basalt ranges from ~2000 to 3500 m below the plateau and from ~2000 to 4200 m all along the profile. Thickness of flood basalt, below the plateau, varies from ~1100 to 2600 m. Reversely magnetized intrusive body, ~4 km wide, is present on southwestern side of the flat top

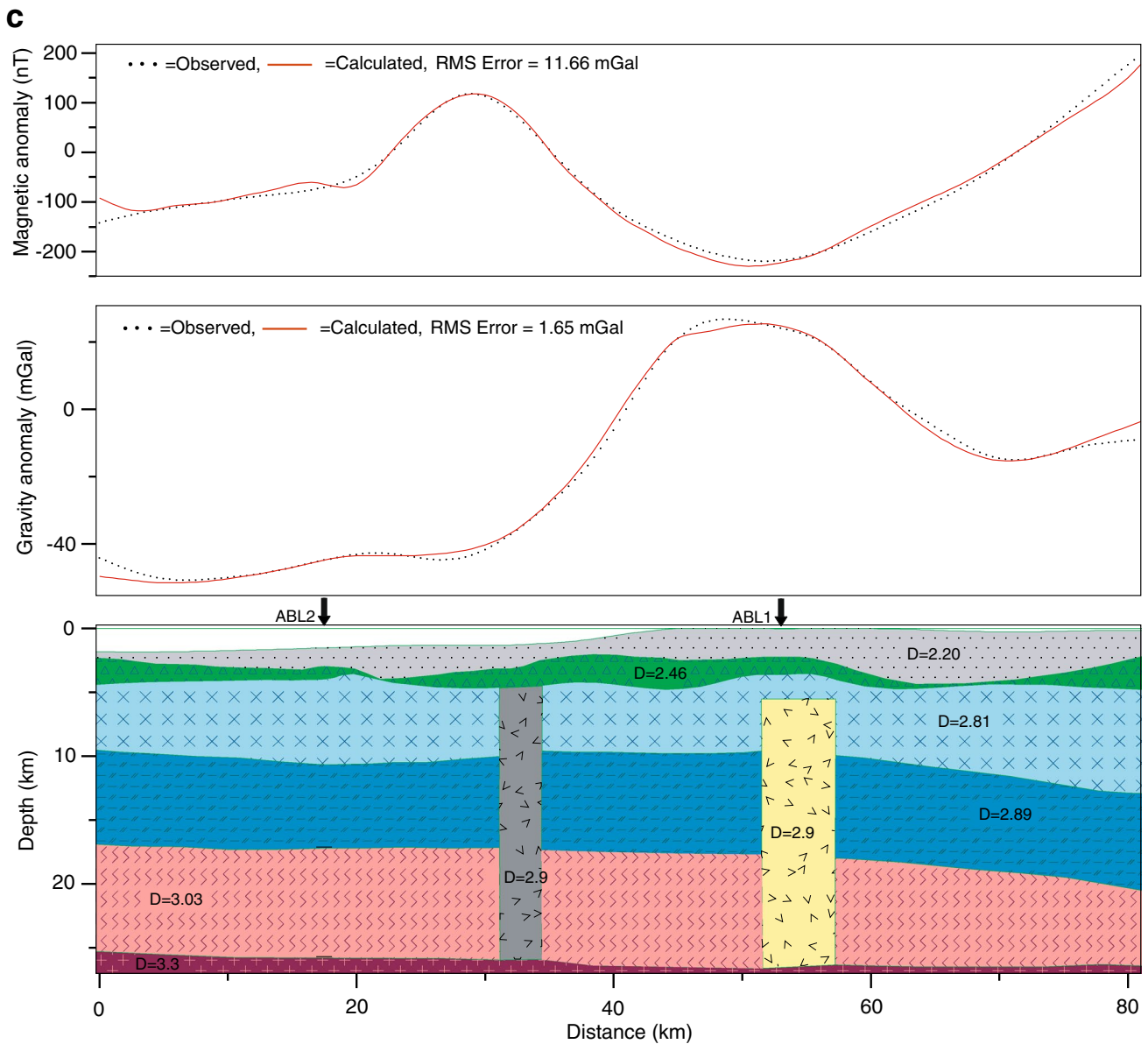


Fig. 7 (continued)

plateau and corresponds to magnetic high anomaly. A normally magnetized intrusive body is also present beneath the bank which terminated within upper continental crust. Maximum thickness of flood basalt is ~3200 m which is observed at southwestern flank of the plateau.

In summary, the Angria Bank is NNW–SSE trending positive bathymetric feature associated with two prominent spurs trending NE–SW and NNE–SSW directions. These spurs are interpreted as horsts with a graben between them. The northeastern part of the graben is filled with sediments. Interpretation of all the models suggests that flood basalt is present in the entire region and mark basement of the region. Flood basalt occurs at a depth of

~2000 m below the Angria Bank and its thickness varies from ~1000 to ~2700 m.

Discussion

Crustal architecture of the Angria Bank

Interpretation of simultaneous modeling of gravity and magnetic data suggest that main crustal units of geological setup of the Angria Bank are sediments, flood basalt, upper continental crust, lower continental crust and high density underplated layer. Flood basalt is reversely

magnetized and outpoured by the Reunion hotspot during the early Paleocene. The observed magnetic low of ~ 248 nT over the spurs is not generated by *reversely* magnetized basaltic flow / intrusive bodies. Rather, it resulted due to *normally* magnetized intrusive body into the horsts structure (spurs). It is worth to mention here that Raju et al. (1990) suggested the high amplitude negative magnetic anomaly (magnetic low) over the Angria Bank is due to reversely magnetized intrusive body at shallow depth. This indicates that they assumed that magnetic low was due to reversely magnetized magmatic body which was intruded when the study area was in the northern hemisphere. Existing knowledge and published literature of the region support intrusions of magmatic bodies when the study region was in the southern hemisphere and not in the northern hemisphere. Therefore, the observed magnetic low resulted due to such intrusive bodies. Further, it may be noted that crustal models generated in this study reveal normally and reversely magnetized intrusive bodies associated with magnetic low and high anomalies respectively. Magmatic bodies (normally magnetized) might have intruded the crust below Angria Bank either immediate before or after the main pulse (29r) of the Deccan volcanism. Therefore, we suggest that the magnetic low observed over the spurs are manifestation of magnetic response due to normally magnetized intrusion along weak zones into horsts structure of the spur.

The results of the integrated model suggest undulating nature of the basaltic basement which indicates sub-aerial exposure and weathering in the geological past. The interpretation is further supported by sub-aerial offshore volcanism related to Deccan flood basalt inferred in earlier studies (Nair et al. 1992; Rao et al. 2002). We also interpret intrusive bodies of 2 to 4 km wide below the bank as well as at its boundaries, which are associated with deep-seated faults. The existence of faults near boundary of the bank are also reported by Agrawal and Singh (1981), based on multi-channel seismic data. They suspected that the faults may extend up to granitic basement. The model studies also reveal ~ 7 km and ~ 8 km thick upper and lower crust in the region, respectively. The whole bank shows an underplated layer of ~ 9 km thick high-density material. Moho is almost horizontal and observed at depth of ~ 27 km in the study area, indicating no response of load of the bank on the Moho. Fault-bounded nature of the bank and undulating basaltic basement overlying on the granitic layer in the region have been interpreted in terms of horst and graben structure of the bank. These results led to suggest that the Angria Bank is continental in nature, carpeted by flood basalt and intruded by magmatic intrusive bodies at places.

Is Angria Bank a part of existing lineament?

There are several elongated structural features distributed over WCMI such as Prathap Ridge Complex, Shelf Margin High, Kori-Comorin Ridge, Mid-Shelf Basement High, and Subsurface Ridge which were identified earlier (Ramaswamy and Rao 1980; Biswas and Singh 1988; Agrawal and Singh 1981; Raju et al. 1990; Subrahmanyam et al. 1991, 1994, 1995; Krishna et al. 1992, 1994; Chaubey et al. 2002; Rao et al. 2010). Shelf Margin High is also known as Mid Shelf Basement Ridge and Upper Slope Ridge (Mukhopadhyay et al. 2008).

Prathap Ridge Complex is a volcanic construct emplaced on the northward-moving Indian Plate by Reunion hotspot (Krishna et al. 1992; Rao et al. 2010). It is seen as a continuous feature on a regional scale parallel to the coast (Fig. 8). Its extension is marked up to 15°N based on seismic reflection data (Ajay 2011), but Angria Bank is not falling in its trend. Seismic section along RE11 reveals that the basement high feature (shot points 1330 to 1660) is associated with the Spur 2 of the bank. Intrusions have been observed west of this basement high between shot points 1700 and 3000, which are interpreted as a part of the Prathap Ridge Complex. Crustal models derived from the present study also support presence of intrusive body west of the bank. If the basement high feature associated

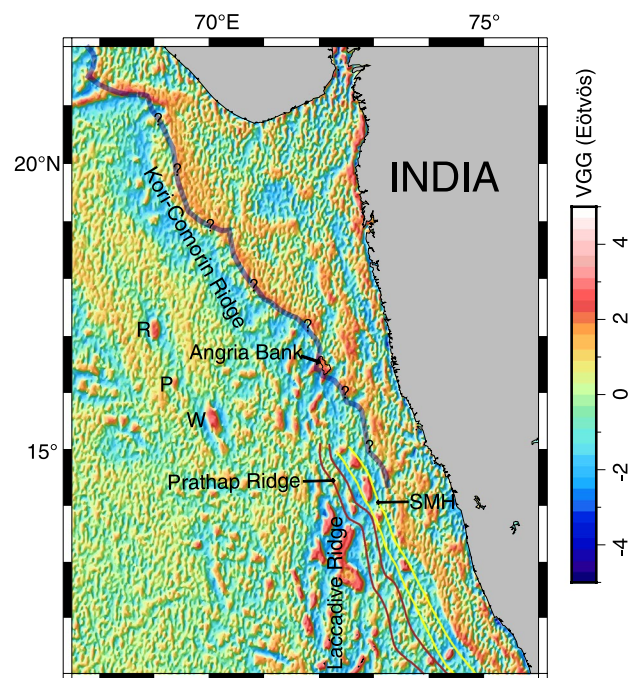


Fig. 8 Histogram equalized vertical gravity gradient map of the WCMI. Kori-Comorin Ridge (Biswas et al. 2008), Prathap Ridge and Shelf Margin High (Ajay 2011) are shown with blue, brown and yellow solid lines, respectively. SMH: Shelf Margin High, R: Raman Seamount, P: Panikkar Seamount, W: Wadia Guyot

with the Spur 2 of the Angria Bank is intrusive, akin to the Prathap Ridge, it should depict similar seismic reflection pattern which is not seen in the present case (Fig. 5). Reflection pattern and crustal model study revealed that igneous crust beneath the Angria Bank is not volcanic but continental in nature, therefore, it is interpreted that the bank is not a part of the Prathap Ridge complex.

Shelf Margin High, comprised of several flat-topped structural highs along the continental slope, is located adjacent to the eastern boundary of Prathap Ridge Complex on southwestern continental margin of India (Chaubey et al. 2002; Rao et al. 2010; Ajay 2011). It is considered as continental slivers and fault-bounded horst structure formed during rifting (Rao et al. 2010). Like Prathap Ridge, Shelf Margin High is also a continuous feature on a regional scale parallel to the coast and extends up to 15°N (Ajay 2011). Further north, Angria Bank also shows a flat-topped plateau and is present on the slope region of the WCMI as depicted in seismic sections along RE11 (Fig. 5), WC-13 (Pandey and Pandey 2015) and in the digital elevation model (Kumar et al. 2015). Though, Angria Bank and Shelf Margin High are structurally similar, the trend of spurs (horst structure) of the bank does not lie in the trend of Shelf Margin High (Fig. 8). Therefore, we believe that the Angria Bank is not part of the Shelf Margin High.

We also evaluated affinity of the Angria Bank with the Kori-Comorin Ridge which is a basement high feature on the slope. The Kori-Comorin Ridge is NW–SE trending linear fault-bounded structural high and comprised of Kori High, Prathap Ridge and Cape Comorin (Biswas and Singh 1988). It may be noted that Kori High in the north and Cape Comorin in the south are continental in nature, whereas, Prathap Ridge Complex is volcanic construct. Therefore, Kori-Comorin Ridge do not appear to be a continuous feature constituting Kori High, Prathap Ridge and Cape Comorin. Further, when digitized boundary of the Kori-Comorin Ridge (Biswas et al. 2008) is plotted (Fig. 8), Angria Bank falls within the boundaries of the ridge but seismically mapped Prathap Ridge (Ajay 2011) falls quite away from it. Orientation of bounding faults of Angria Bank and Kori High is different, therefore, it is concluded that the bank is not part of the Kori-Comorin Ridge. Further, we believe that nature and extension of Kori-Comorin Ridge need to be redefined based on detailed geological and geophysical investigations.

The subsurface ridge characterized by gravity high and magnetic low/high identified by Krishna et al. (1994) is of volcanic origin. They speculated that the subsurface ridge joins the Prathap Ridge near the Angria Bank. The results of present study suggest that the crust beneath the Angria Bank is of continental nature, therefore, subsurface ridge cannot be its part.

Based on the present study it is difficult to propose any linkages between Angria Bank and other adjacent features viz. Shelf Margin High, Prathap Ridge, Kori-Comorin Ridge, subsurface ridge. Therefore, it is concluded that the Angria Bank is an isolated feature comprised of two horsts and a graben structure.

Origin of the Angria Bank

The WCMI evolved due to rifting and drifting of India, Madagascar and Seychelles continental blocks. A series of local horst and graben resulted due to rifting (Biswas and Singh 1988) along dominant Precambrian structural trends (NNW–SSE Dharwar trend, NE–SW Aravalli trend and ENE–WSW Satpura trend). Emplacement of Deccan flood basalt, contemporaneous with the rifting between India and Seychelles-Laxmi Ridge tremendously modified crustal structure of the WCMI.

WCMI can be divided into two parts viz. North western continental margin of India (NWCMI) and south western continental margin of India (SWCMI) on the basis of their origin and depositional history. Angria Bank lies on the continental slope at transition zone of the above two margins. Tectonic trends present over continental crust of the bank are parallel to the Aravalli trend i.e. NE–SW direction (Fig. 6b). These trends controlled structural style of faulting of continental crust of the Angria Bank during rifting between India and Seychelles-Laxmi Ridge. Faulting along pre-existing trend resulted horst–graben structure beneath the bank. A schematic diagram, showing main stages of evolution of the Angria Bank, is presented in Fig. 9. Horst and graben structure developed in the early phase of rifting during the Late Cretaceous, and later floored by flood basalt due to the Reunion hotspot activity at ~65 Ma. Initially, flood basalt was emplaced in subaerial environment and later subsided. Coral reef was built-up in marine environment on the subsiding basaltic foundation. Basu et al. (1982) and Rao et al. (2002) also suggested that basaltic flow related to Deccan trap constitutes floor of the sediments in the Bombay Offshore Basin and Konkan Basin. Foraminiferal information of drilled well R-1-1 and RO21 (Pandey and Dave 1998) also suggest that marine environment initiated after Deccan volcanism. Since Deccan volcanism developed several dyke injections in the crust of the Indian shield (Chandrasekhar et al. 2002), it is surmised that observed intrusions below the plateau have developed during Deccan volcanic activity.

The bank experienced subsidence since the Late Cretaceous during its evolution. Post-Deccan volcanism subsidence of the bank is reported by Whiting et al. (1994) based on drilled well results. Based on results of the drilled well R-1-1, Mathur and Nair (1993) suggested that the carbonate buildups started developing in Late Paleocene or Early Eocene on the Angria Bank. The results suggest that the

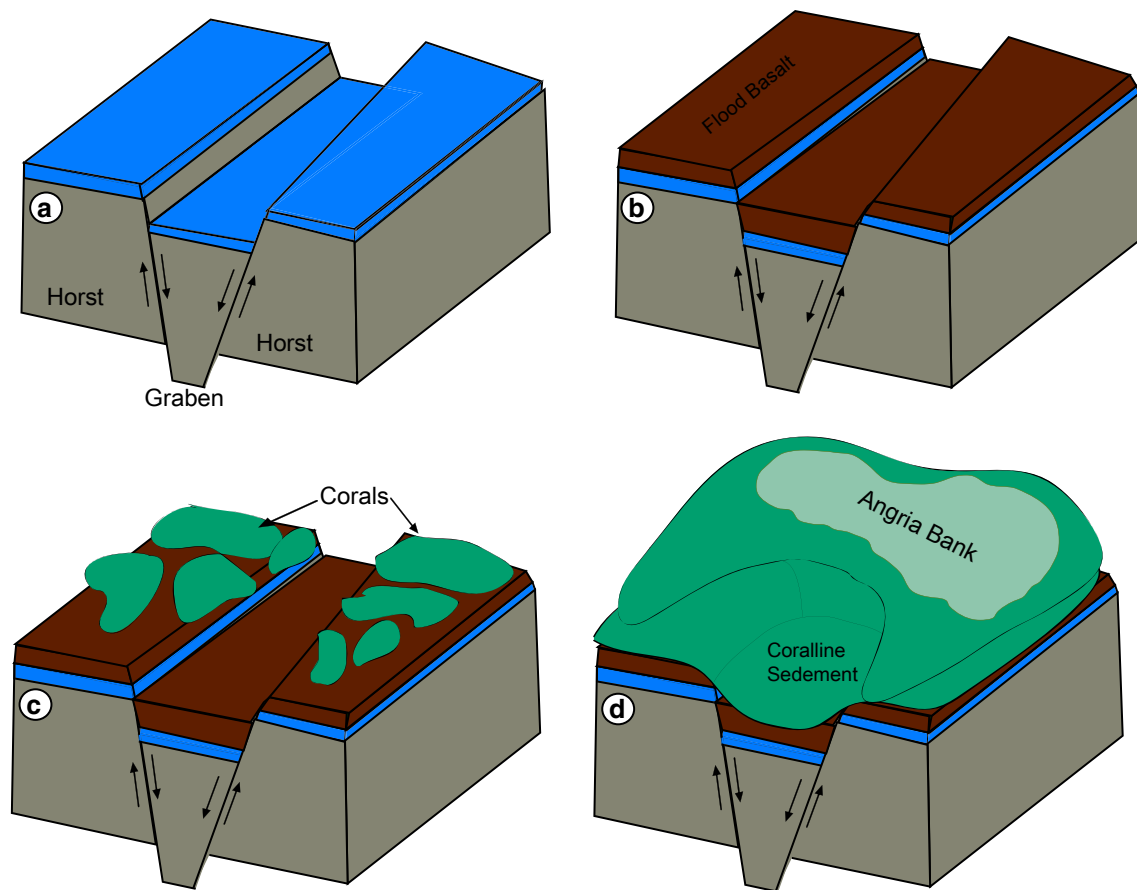


Fig. 9 Schematic diagram showing four main stages of evolution of the Angria Bank. **a** Development of horst and graben structures in the continental crust of the bank during the Late Cretaceous, **b** carpeting

of flood basalt over the horsts and graben at ~65 Ma, **c** formation of coral reef over subsiding basalt platform, and **d** present scenario of the Angria Bank. Horst corresponds to spurs (SP1 and SP2)

subsiding basaltic platform of the bank was in euphotic zone in the Late Paleocene/Early Eocene which supported coral growth. Nair et al. (1992) also reported the initiation of formation of carbonate bank in Paleocene on structurally elevated parts. Further, the coral reef derived coralline sediments filled the graben, which finally gave rise to flat top plateau. Coralline sediments from the uplifted part got eroded in marine environment and settled down at base of the bank through gullies/channels. Erosional features in the form of valleys are also observed in DEM (Kumar et al 2015), which displays a radial drainage pattern. These V-shaped fluvial channels on an average are 100–200 m deep and 1–3 km wide and have well developed tributaries (Kumar et al. 2015).

It may be speculated that tectonic features south of the Angria Bank developed during the India Madagascar separation while features north of the Angria Bank are result of the rifting between India and Seychelles-Laxmi Ridge. Angria Bank lies in the transition zone of these two kinds of features and is an isolated horst–graben structure.

Conclusions

Integrated interpretation of bathymetry, magnetic, gravity and seismic reflection data carried out in the present study has provided new understanding on crustal structure and origin of the Angria Bank. Major findings of the study are summarized as follows:

- (i) Angria Bank is an isolated feature comprised of horst and graben structure representing two spurs trending NE–SW to NNE–SSW. Area of water plateau and entire geological setup of the bank are 365 km² and 1460 km² respectively. The bank is associated with two prominent magnetic lows of about 183 nT and 243 nT, and free-air gravity high of ~28 mGal.
- (ii) Model studies revealed that flood basalt is present beneath the entire bank which acted as a foundation for coral growth. Depth to the top of the basalt varies from 2000 to 3800 m, and thickness ranges from 1000 to 2700 m beneath the bank.

- (iii) Igneous crust beneath the Angria Bank is continental in nature with minor intrusions. Thickness of crust below the bank is estimated to be ~27 km. The crust is underplated by ~9 km thick high-density material.
- (iv) The bank was formed during rifting between India and Seychelles-Laxmi Ridge in the Late Cretaceous. Presence of NE–SW trending horsts (spurs) and faults suggest that the bank was governed by Aravalli trend during its evolution.

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