CHAPTER 3
Chapter - 3  
DATA AND METHODOLOGY

3.1 Introduction

The main data utilized for the present study are; sea-surface gravity, magnetic and bathymetric profiles, satellite derived free-air gravity anomalies, GEBCO bathymetry contours, published regional scale tectonic element identifications and available finite rotation parameters of relative motions of the continental blocks bordering the study area. The methods of forward modeling of magnetic and gravity data, and paleogeographic reconstruction have been used as main tools for interpretation. In this chapter, the types and sources of these data and methodology adopted for interpretation have been described.

3.2 Types and sources of data

3.2.1 Sea-surface magnetic and gravity profiles

Several geoscientific studies carried out in the deep offshore regions west of India/Pakistan mainland attempted to infer about the nature of the crust underlying the Laxmi Basin and Offshore Indus Basin regions. Out of these studies, some (Bhattacharya et al., 1994b; Malod et al., 1997; Talwani and Reif, 1998) inferred the crust underlying both these basins as oceanic in nature, while some others (Miles et al., 1998; Todal and Eldholm, 1998) inferred both these basins to be underlain by thinned continental crust. A recent study carried out by Krishna et al. (2006) supports oceanic crust inference for the Offshore Indus Basin, but favours the inference of a thinned continental crust underlying the Laxmi Basin. In view of these divergent opinions, it is felt necessary to re-look into the available gravity and magnetic data of the study area and carry out reinterpretation.

The sea-surface gravity and magnetic data of the Laxmi Basin and Offshore Indus Basin regions, which are available in the public domain, were collected during various cruises of Indian and foreign research vessels. The Indian magnetic and gravity data were acquired during various cruises conducted by the National Institute of Oceanography, Goa, onboard ORV Sagar Kanya belonging to the Ministry of Earth Sciences, New Delhi. The additional magnetic and gravity data in and around the study area were extracted from the CD ROM...
database entitled "Marine Geological and Geophysical data from NGDC", which was obtained from the National Geophysical Data Centre (NGDC), Boulder, Colorado, USA. The NGDC database is a compilation of data generated by various international organizations from time to time. The residual total field magnetic anomalies were calculated by removing the International Geomagnetic Reference Field (IGRF) of the appropriate epoch from the measured magnetic total field values. Similarly, residual gravity anomalies were obtained by applying normal and Eötvös corrections to the gravity measurements. The locations of these gravity and magnetic anomaly profiles used in the present study are shown in Fig. 3.1 and the summary of cruise identifications is presented in Table 3.1.

3.2.2 Published seismic reflection and refraction information

In this study, few published (Fig. 3.2) seismic data in the Laxmi Basin (Naini and Talwani, 1982; Krishna et al., 2006) and Offshore Indus Basin (Naini and Talwani, 1982; Malod et al., 1997; Collier et al., 2004a, b) have been used to examine the morphology of the basement of these regions as well as to provide seismic constraints while carrying out the gravity and magnetic modeling. The seismic reflection section (along C1707-04) in the Laxmi Basin presented in Naini and Talwani (1982) is a continuous seismic reflection profile, acquired onboard R/V Conrad using a single channel receiver and airgun sound sources. The velocity-depth information presented by them over several refraction stations in the study area are based on sonobuoy refraction experiments. The interpreted line drawing of a seismic reflection section (along RE-02) in the Laxmi Basin, which was presented in Krishna et al. (2006), is based on the reflection data acquired onboard M/V Anweshak, using a 48-channel streamer and Bolt-type airgun array with a total capacity of 10L. Since the publication of Krishna et al. (2006) did not present the time section over the full profile, so the interpreted line drawings presented by them for the full profile have been considered to get the estimate of depth to the basement while carrying out gravity and magnetic modeling. The seismic reflection section (MD51-01a) in the Offshore Indus Basin region presented in Malod et al. (1997) is based on single channel seismic reflection data acquired onboard R/V Marion Dufresne using a water gun sound source. The latest available multichannel seismic reflection section (CD144-01) in the Offshore Indus Basin presented in Collier et al. (2004a, b) is based on the
The data along these profiles were collected by National Institute of Oceanography, India.
The data along these profiles were extracted from the database of National Geophysical Data Centre, Boulder, Colorado.
The data along this profile has been obtained from Malod et al. (1997).

Fig. 3.1 The locations of the sea-surface gravity and magnetic profiles used in the present study. Annotations along the tracks are profile identifiers, the details of which are given in Table 3.1. Thin dotted lines are selected bathymetry contours (in metres).
Table 3.1 Cruise identification and types of data used in the present study. Wherever information is available, the method for obtaining primary position during data acquisition has been mentioned under the column 'Primary navigation'.

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<th>Data Source</th>
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G: Gravity data; M: Magnetic data; S: Seismic data
INS: Integrated Navigation System; TS: Transit satellite; GPS: Global Positioning System
Published seismic reflection profiles after Naini and Talwani (1982), Malod et al. (1997), Collier et al. (2004a, b) and Krishna et al. (2006)

Locations of the published refraction stations along with the station identifications after Naini and Talwani (1982)

Locations of the published refraction stations after Collier et al. (2004a, b)

Deccan Trap

Fig. 3.2 The locations of the published seismic reflection profiles and the refraction stations in the deep offshore regions off India/Pakistan coast. Annotations along the tracks are profile identifiers, the details of which are given in Table 3.1. Thin dotted lines are bathymetry contours (in metres).
data acquired onboard R/V Charles Darwin using a 2.4 km, 96-channel streamer and a 3890 cubic inch airgun array fired every 30 seconds. The seismic refraction section CD144-02 presented by Collier et al. (2004a, b) is based on refraction data acquired using the Ocean Bottom Seismometers (OBS).

3.2.3 Satellite derived free-air gravity anomalies

In this study, the satellite derived free-air gravity anomalies (Fig. 3.3) have been mainly used to construct free-air gravity profiles in between sea-surface gravity transects in some areas of the Laxmi Basin and Offshore Indus Basin regions. The contour maps of satellite derived free-air gravity anomalies have been used to infer and/or refine the extents of some of the tectonic elements, which are not readily available. The satellite derived free-air gravity anomalies have been extracted from the binary gridded file of gravity anomalies (version 11.2) for the world (Sandwell and Smith, 1997, 2003), available from the ftp site ftp://topex.ucsd.edu/pub/global_grav_2min/, which is maintained by the Scripps Institution of Oceanography, USA. This gridded gravity anomaly is for 2 minutes spatial resolution and the stored anomaly values are in gravity units ($10^{-6}$ m/sec$^2$). These values have been multiplied with 0.1 to convert them into mgal while generating shaded-relief image and profiles of anomalies. A comparison with shipboard gravity data shows that the accuracy of the satellite derived gravity anomaly is about 4-7 mgal for random ship tracks (Sandwell and Smith, 1997).

3.2.4 Mapped seafloor spreading magnetic lineations

The mapped seafloor spreading type magnetic lineations (Fig. 3.4) used in this study are those presented by Bhattacharya et al. (1994b) in the Laxmi Basin, Malod et al. (1997) in the Offshore Indus Basin and those from Mascarene Basin area presented by Schlich (1982), Dyment (1991, 1996) and Bernard and Munschy (2000).

The magnetic lineations in the Laxmi Basin have been interpreted by Bhattacharya et al. (1994b) as a two-limbed seafloor spreading sequence corresponding to anomalies 33n (66.5 Ma) to 28n (63.0 Ma). In a similar way, the magnetic lineations in the Offshore Indus Basin have been interpreted by Malod et al. (1997) as a two-limbed seafloor spreading sequence corresponding to anomalies 29r-29n (65.58 – 63.98 Ma). India is believed (Norton and Sclater, 1979; Besse and Courtillot, 1988) to have been juxtaposed with Madagascar and
Fig. 3.3 Colour shaded-relief image of the satellite derived free-air gravity anomalies (Sandwell and Smith 1997, 2003) of the deep offshore regions off west coast of India.
Fig. 3.4 Generalized map of the Western Indian Ocean showing locations of the mapped seafloor spreading magnetic lineations. The lineations used in the present study are given as thin red lines with numbers. The other magnetic lineations are shown as thin grey lines. Magnetic lineation identifications used in the present study have been compiled from Malod et al. (1997), Bhattacharya et al. (1994b) and Bernard and Munschy (2000). The other magnetic lineations of the Arabian Sea and remaining part of the Western Indian Ocean are from Chaubey et al., 2002a; Royer et al., 2002; and NGDC database. The thick dashed lines orthogonal to magnetic lineations represent fracture zones.
magnetic lineations in the Mascarene Basin is considered to record the episode of seafloor spreading which was related with the separation of India and Madagascar. It is observed that the oldest magnetic lineations mapped (Fig. 3.4) in the Mascarene Basin area are anomaly 34n (83.0 Ma), which are located along the east coast of Madagascar and its conjugate in the southwestern part of Seychelles-Mascarene Plateau. In the southern part of Mascarene Basin, conjugate magnetic isochron sequence 34ny (83.0 Ma) – 27ny (60.920 Ma), which are offset by NE-SW trending right lateral fracture zones, are present. No continuous sequences of conjugate magnetic isochrons were mapped in the northern part of the Mascarene Basin, although anomalies 32n-30n, 34n-30n, 34n-32n are reported (Dyment, 1996) to exist at few locales. The magnetic anomalies in the Mascarene Basin show an increasing age of fossil ridge axis from south (anomaly 27n) to the north (anomaly 30n) possibly suggesting a southward progressive extinction of the Mascarene Basin spreading centre.

3.2.5 GEBCO bathymetry contours

In this work, bathymetry contours (Fig. 1.3) have been used to define the boundaries of some of the offshore tectonic elements, such as the terrace like feature off Trivandrum, Laccadive Plateau, Seychelles Bank and northern Madagascar Ridge. These bathymetric contours were extracted from the CD ROM database entitled “The Centenary Edition of the GEBCO Digital Atlas (GDA)”, which was prepared by the General Bathymetric Charts of the Oceans (GEBCO) functioning under the auspices of the Intergovernmental Oceanographic Commission (IOC) and the International Hydrographic Organization (IHO). The bathymetry contours in this database are in ASCII format and are available as isobaths of 200 m, 500 m, and at 500 m contour intervals thereafter.

The bathymetric contours published in the GEBCO Digital Atlas are based on the bathymetry data acquired, as discrete soundings and continuous recording along ship tracks, by hydrographic and oceanographic ships during surveys and on passage between survey areas and ports. This Centenary Edition of the GEBCO digital Atlas, published in 2003 (Intergovernmental Oceanographic Commission et al., 2003), contains the most recent and completely updated bathymetry contours for the Indian Ocean region. For the present study required bathymetry contours, of 200 m, 1000 m and all other contours of greater depth
values at 1000 m interval, have been extracted and stored as separate ASCII data files.

3.2.6 Available finite rotation parameters

Finite rotation parameters are a set of values used to describe the relative motion of two lithospheric plates over a sphere in a fixed reference frame. It consists of an Euler pole, about which two plates move over a sphere, and an Euler angle, which is the amount of angle to be rotated about the Euler pole. Angle is positive when the motion of the moving plate is counter clockwise with respect to the fixed plate when viewed from outside the Earth (Duncan, 1981). In plate tectonic reconstructions, using a set of finite rotation parameters one brings pairs of conjugate isochrons of same age from two plates into coincidence. Therefore, the finite rotations for the entire period of relative motion between two plates are usually presented as a table consisting sets of finite rotation parameters along with their corresponding isochron ages and anomaly numbers (anomaly identifications) for corresponding magnetic lineations (isochrons) if available. The present study involves understanding and improvement of the relative motion of India, Laxmi Ridge, Seychelles and Madagascar since the time of their early drifting. However, it was observed that different sets of finite rotation parameters defining the relative motions of these continental blocks were suggested in various publications. All these different sets of finite rotation parameters were therefore compiled (Table 3.2) for evaluation and selecting the most suitable set, which can be used for developing reconstruction models for this study. Further, as it was observed that in earlier studies different authors have used different geomagnetic timescales while giving the finite rotation parameters, therefore, while compiling these rotation parameters, the ages corresponding to each isochrons have been re-assigned using the common geomagnetic polarity timescale of Cande and Kent (1995). Following Cox and Hart (1986), the symbol $\text{FixR}OT_{MOB}$ is used to mean the finite rotation of plate MOB (the mobile plate) with respect to plate FIX (the fixed plate). For example, finite rotation of India with respect to Madagascar in fixed Madagascar reference frame can be represented as $\text{MAD}ROT_{\text{IND}}$. This convention of symbols has been followed in this study while presenting the tables of finite rotation parameters.
Table 3.2 Finite rotation parameters describing relative motions between various plates used in the present study. The given rotation angles are those required to reconstruct the plate positions backwards in time. Angle is positive when the motion of the moving plate is counter clockwise with respect to the fixed plate when viewed from outside the earth. Ages are after Cande and Kent (1995).

(a) Between Laxmi Ridge (LAX) and Seychelles (SEY) in fixed Seychelles reference frame (SEY ROT LAX), after Royer et al. (2002).

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(b) Between India (IND) and Africa (AFR) in fixed Africa reference frame (AFR ROT IND), after Norton and Sclater (1979).

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(c) Between India (IND) and Africa (AFR) in fixed Africa reference frame (AFR ROT IND), after Besse and Courtillot (1988)

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(d) Between hotspot (HS) and India (IND) in fixed hotspot reference frame (HS ROTIND), after Morgan (1981)

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(e) Between hotspot (HS) and Africa (AFR) in fixed hotspot reference frame (HS ROTAFR), after Morgan (1981)

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(f) Between hotspot (HS) and India (IND) in fixed hotspot reference frame $({\text{HS}}_{\text{ROT}}{\text{IND}})$, after Müller et al. (1993)

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(g) Between hotspot (HS) and Africa (AFR) in fixed hotspot reference frame $({\text{HS}}_{\text{ROT}}{\text{AFR}})$, after Müller et al. (1993)

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3.2.7 Other onshore and offshore tectonic elements

(a) Onshore tectonic elements

The onshore tectonic elements (Fig. 3.5 and Fig. 3.6) considered in this study are: (i) the Precambrian lineaments which have been used in earlier studies to constrain the juxtaposition of India-Seychelles-Madagascar, (ii) the Narmada-Son lineament representing a failed continental rift (Narmada Rift) system of India which orthogonally cuts the west coast of India, and (iii) the locations of volcanics on the conjugate shores, which are between 90 Ma and 65 Ma in age and are considered to be related to those rifting which initiated separation of the continental blocks under consideration of this study. The Precambrian lineaments of India and Madagascar, which have been considered for the above purpose in various earlier studies, are Achankovil Shear Zone (ASZ), Moyar Shear Zone (MSZ) and Palghat-Cauvery Shear Zone (PCSZ) of India (Fig. 3.5) and the Ranotsara Shear Zone (RSZ) and Axial Shear Zone (AXSZ) of Madagascar. The geographical extents of these Precambrian lineaments have been digitized from figures presented in Meissner et al. (2002), Windley et al. (1994) and Biswas (1982).

The location of India-Madagascar rifting related volcanics, which were considered in various earlier studies are:

A) on Indian side;
   (i) St. Mary Islands (SMI) located off Mangalore (Valsangkar et al., 1981; Torsvik et al., 2000; Pande et al., 2001),
   (ii) North Kerala Dykes (Radhakrishna et al., 1999)
   (iii) Cretaceous dykes of Karnataka (Anil Kumar et al., 2001).

B) on Madagascar side;
   (i) Cretaceous dyke rocks of Madagascar (Storey et al., 1995)
   (ii) Analalava Gabbro Pluton located in northeastern part of Madagascar (Torsvik et al., 2000).

In a similar way, the locations of volcanics of age ~65.0 Ma, which have been reported in conjugate sides of India (Rathore et al., 1997; Hofmann et al., 2000; Widdowson et al., 2000) and Seychelles (Dickin et al., 1987) have also been
Fig. 3.5 Onshore and offshore tectonic elements in the west coast of India and the adjoining deep offshore regions. Locations of onshore shear zones simplified after Meissner et al. (2002). The axial basement high in the Laxmi Basin is modified after Srinivas (2004) and that in Offshore Indus Basin is after Malod et al. (1997). TOT: Terrace off Trivandrum; BH: Bombay High; R: Raman Seamount; P: Panikkar Seamount; W: Wadia Guyot; PTR: Palitana Ridge; PKR: Panikkar Ridge; ASZ: Achankovil Shear Zone; PCSZ: Palghat-Cauvery Shear Zone; MSZ: Moyar Shear Zone; NR: Narmada Rift; SMI: St. Mary Islands. Other details are as in Fig. 2.2.
Fig. 3.6 Onshore and offshore tectonic elements in Madagascar, Seychelles and the adjoining deep offshore regions. Locations of onshore shear zones after Windley et al. (1994). NMR: Northern Madagascar Ridge; RSZ: Ranotsara Shear Zone; AXSZ: Axial Shear Zone; SB: Seychelles Bank; SM: Saya de Malha Bank; MI: Mauritius Island; RI: Reunion Island. Other details are as in Fig. 2.3.
compiled. The locations of these volcanics have been obtained by digitization from figures of the respective publications.

(b) Offshore tectonic elements

The major offshore tectonic elements (Fig. 3.5 and Fig. 3.6) of the study area and the adjoining regions are a terrace like feature located off Trivandrum, the Laxmi Ridge, the axial basement high zone (Panikkar Ridge) of the Laxmi Basin, the axial basement high zone (Palitana Ridge) of the Offshore Indus Basin, the Raman-Panikkar-Wadia seamount chain of the Laxmi Basin, the inferred offshore extension of Narmada Rift, the Bombay High, the paleo-shelf edge off west coast of India, the Laccadive-Chagos Ridge, the Seychelles Bank, the Mascarene Plateau and the northern Madagascar Ridge. Some of these features were digitized from figures of respective publications, such as; offshore extension of Narmada Rift from Bhattacharya and Subrahmanyan (1986), Bombay High from Biswas (1982), Panikkar Ridge from Srinivas (2004), Palitana Ridge from Malod et al. (1997), Raman-Panikkar-Wadia seamount chain from Bhattacharya et al. (1994a) and paleo—shelf edge from Rao and Srivastava (1981). The boundaries, which define the extent of other tectonic elements, have been inferred based on either GEBCO bathymetry contours or the satellite derived free-air gravity anomaly contours.

3.3 Methodology adopted

Several techniques have been used in this study to analyze the geophysical data from the complex deep offshore areas adjoining the west coast of India/ Pakistan. In these deep offshore regions, attempt has been made to understand nature of the crust underlying the Offshore Indus and Laxmi basins, based on the forward modeling technique of gravity (Taiwani et al., 1959) and magnetic (Taiwani and Heirtzler, 1964) data. As these regions are inferred to be underlain by oceanic crust formed as a result of two-limbed seafloor spreading, therefore further attempt has been made for the identification of those magnetic anomalies with reference to geomagnetic polarity reversal time scale and delineation of the boundaries of the magnetized blocks (isochrons). The boundaries of the magnetized blocks have been demarcated by following the conventional method of inter-profile correlation and comparison with synthetic anomaly profiles computed for model of juxtaposed normally and reversely
magnetized blocks of oceanic crust. After delineation of conjugate magnetic isochrons, the finite rotation parameters are estimated to describe the relative motion between India/Pakistan and Laxmi Ridge. Followed by these exercises, the paleogeographic reconstruction technique has been used to evaluate the existing plate tectonic evolutionary models for Western Indian Ocean and to provide improved models pertaining to the early drift and pre-drift juxtaposition of India, Seychelles and Madagascar continental blocks. In this section, tools and methods used in the present study have been briefly discussed.

3.3.1 Computation of gravity anomalies over 2-D bodies

Most of the submarine features can be approximated as two-dimensional bodies (Jones, 1999). The method proposed by Talwani et al. (1959) has been widely accepted for computation of gravitational attraction of a two-dimensional mass of constant density. In the present work, the gravity modeling has been carried out using the commercially available interactive GM-SYS software, a product of Northwest Geophysical Associates, Inc, where the gravity response for the given body is computed based on the method of Talwani et al. (1959). In this section, firstly a brief description of this method is given and then the steps for gravity modeling followed in this study are described.

a) Method of Talwani et al. (1959) for computation of gravitational attraction of a two-dimensional mass

The two-dimensional mass is a polygon (Fig. 3.7) lying in the x-z plane and extending to infinity in the y-direction. The vertical component of gravitational attraction, $\Delta g$, at the origin P(0,0) is

$$\Delta g = 2G\rho \int zd\theta$$

where $\int zd\theta$ is a line integral given by Hubbert (1948) quoted by Jones (1999).

$$\int zd\theta = \int_A zd\theta + \int_B zd\theta + \int_C zd\theta + \int_D zd\theta + \int_{BC} zd\theta + \int_{CF} zd\theta$$

For a point Q on the side BC,

$$PS = a_i \text{ and } z = (x-a_i) \tan \gamma_i$$

Thus,
Fig. 3.7 Geometry of a two-dimensional polygon ABCDEF, lying in the x-z plane and extending to infinity in the y-direction (Redrawn from Jones, 1999) as used to compute gravitational attraction of two-dimensional bodies of arbitrary shape by the method of Talwani et al. (1959).
\[ z = \frac{a_i \tan \gamma_i \tan \theta}{\tan \gamma_i \cdot \tan \theta} \quad \text{and} \]
\[ \int_{bC} zd\theta = a_i \sin \gamma_i \cos \gamma_i \left[ \left( \theta_i - \theta_{i+1} \right) + \tan \gamma_i \ln \left( \frac{\cos \theta_i (\tan \theta_i - \tan \gamma_i)}{\cos \theta_{i+1} (\tan \theta_{i+1} - \tan \gamma_i)} \right) \right] \]

By making the substitution,
\[ a_i = x_i + 1 - Z_i + 1 \left( \frac{x_i + 1 - x_i}{z_i + 1 - z_i} \right) \]
The depth at Q is
\[ z = \frac{x_i + 1 (z_i + 1 - z_i) - Z_i + 1 (x_i + 1 - x_i)}{(z_i + 1 - z_i) \cot \theta - (x_i + 1 - x_i)} \]
The gravitational attraction around the whole polygon is therefore,
\[ \Delta g = 2 G \rho \sum_{i=1}^{5} \left\{ \frac{x_i z_i + 1 - z_i x_i + 1}{(x_i + 1 - x_i)^2 + (z_i + 1 - z_i)^2} \right\} \left\{ x_{i+1} - x_i \right\} (\theta_i - \theta_{i+1}) + (z_{i+1} - z_i) \ln \left( \frac{r_{i+1}}{r_i} \right) \]

where,
\[ r_i = \sqrt{x_i^2 + z_i^2} \]

The expression for $\Delta g$ is then readily transformed into computer code.

(b) Steps for gravity modeling followed in this study

The objective for gravity modeling in this study is to obtain a plausible crustal structure section, which is compatible with the observed gravity anomaly and known geological constraints. The broad steps followed for this purpose is given below:

(i) A crustal section is constructed by integrating all available bathymetric, seismic reflection and refraction results.

(ii) The main crustal units in this model are identified and the average interval velocities of these crustal units are calculated, wherever available or assigned from other geological considerations.
(iii) The layer densities for these crustal units are estimated according to the velocity-density relationship of Ludwig et al. (1970).

(iv) Considering each of these crustal units as separate body, defined by a co-ordinated bounding polygon surface and a density, the gravity anomaly for the crustal section is computed as a sum of anomalies for all separate bodies comprising the crustal section.

(v) The initial crustal model is refined by trial and error, to obtain a plausible model which gives good fit between the observed and computed gravity anomalies and satisfies other constraints.

3.3.2 Computation of magnetic anomalies over 2-D bodies

The magnetic anomalies observed in the study area are linear in nature and have good correlation from profile to profile. The sources of magnetic anomalies can be approximated by two-dimensional polygons extending to infinity in the direction of the magnetic anomaly (Jones, 1999). The most common method of computing the magnetic field over such bodies is to use the algorithms developed by Talwani and Heirtzler (1964). In this section, firstly a brief description of this method is given and then the steps for magnetic modeling followed in this study are described.

(a) Method of Talwani and Heirtzler (1964) for computation of magnetic anomalies caused by two-dimensional structures of arbitrary shape

According to the approach of Talwani and Heirtzler (1964), the total field magnetic anomaly at a point (0,0) due to a polygon stretching to infinity in the y-direction of the co-ordinate system (Fig 3.8a-d) can be calculated by first considering a volume element \( \Delta x \Delta y \Delta z \) of an infinitely long magnetized rod (Fig. 3.8a) with a cross section ABCD. Let \( J \) be the intensity of magnetization, where \( J_x, J_y, \) and \( J_z \) are the components of this in the x, y, and z directions.

The magnetic moment \( \mathbf{m} \), on the element volume \( \Delta x \Delta y \Delta z \) is given by

\[
\mathbf{m} = J \Delta x \Delta y \Delta z
\]

and its magnetic potential at the origin is
Fig. 3.8 Diagrams related to derivation of formulae for computation of the total field magnetic anomaly over two-dimensional polygon of infinite extent as used in the method of Talwani and Heirtzler (1964). Geometry of infinite rod (a) and lamina (b) Geometry of the polygon discussed in the text is shown in (c). The relation between the components of magnetization is illustrated in (d). (after Talwani and Heirtzler, 1964).
The magnetic potential of the infinite rod of cross section ABCD is then given by

\[
\Omega = \Delta x \Delta z \int_{-\alpha}^{\alpha} \frac{J_x x + J_y y + J_z z}{(x^2 + y^2 + z^2)^{3/2}} \, dy = 2 \Delta x \Delta z \frac{J_x x + J_z z}{x^2 + z^2}
\]

The vertical magnetic field strength \( V \) is then

\[
V = -\frac{\partial \Omega}{\partial z} = 2 \Delta x \Delta z \frac{2xz J_x - J_z (x^2 - z^2)}{(x^2 + z^2)^2}
\]  

(3.1)

The horizontal magnetic field \( H \) in the \( x \) direction is given by

\[
H = -\frac{\partial \Omega}{\partial x} = 2 \Delta x \Delta z \frac{J_x (x^2 - z^2) + 2xz J_z}{(x^2 + z^2)^2}
\]  

(3.2)

The values of \( V \) and \( H \) for the lamina shown shaded in Fig. 3.8b are obtained by integrating the equations 3.1 and 3.2 with respect to \( x \), between the limits \( x \) and \( \alpha \). Thus,

\[
V = 2 \Delta z \frac{J_x x - J_z x}{x^2 + z^2}
\]  

(3.3)

\[
H = 2 \Delta z \frac{J_x x - J_z z}{x^2 + z^2}
\]  

(3.4)

To derive the field due to the prism KLMN, equations 3.3 and 3.4 are integrated with respect to \( z \) along KN between the depth limits \( Z_1 \) and \( Z_2 \)

\[
V = 2 \int_{Z_1}^{Z_2} \frac{J_x z - J_z x}{x^2 + z^2} \, dx
\]

For any point on KN, \( x = (x_1 + z_1 \cot \phi) - z \cot \phi \)

\[
V = 2 \sin \phi \left\{ J_x \left[ (\theta_2 - \theta_1) \cos \phi + \sin \phi \log \frac{r_2}{r_1} \right] - J_z \left[ (\theta_2 - \theta_1) \sin \phi - \cos \phi \log \frac{r_2}{r_1} \right] \right\}
\]

\[
H = 2 \sin \phi \left\{ J_x \left[ (\theta_2 - \theta_1) \sin \phi - \cos \phi \log \frac{r_2}{r_1} \right] + J_z \left[ (\theta_2 - \theta_1) \cos \phi + \sin \phi \log \frac{r_2}{r_1} \right] \right\}
\]
The above equations can be rewritten as

\[ V = 2(J_x Q - J_z P) \]
\[ H = 2(J_x P + J_z Q) \]

where

\[ P = \frac{z_{21}^2}{z_{21}^2 + x_{12}^2} (\theta_1 - \theta_2) + \frac{z_{21} x_{12}}{z_{21}^2 + x_{12}^2} \log \frac{r_2}{r_1} \]
\[ Q = \frac{z_{21} x_{12}}{z_{21}^2 + x_{12}^2} (\theta_1 - \theta_2) + \frac{z_{21}^2}{z_{21}^2 + x_{12}^2} \log \frac{r_2}{r_1} \]

using the notation

\[ x_{12} = x_1 - x_2 \]
\[ z_{21} = z_2 - z_1 \]
\[ r_1 = (x_1^2 + z_1^2)^{1/2} \]
\[ r_2 = (x_2^2 + z_2^2)^{1/2} \]

The values for \( P \) and \( Q \) are calculated from the co-ordinates in Fig. 3.8c. The relations between \( J \), \( J_x \) and \( J_z \) can be seen by referring to Fig. 3.8d, where \( J \) is defined with respect to the co-ordinate system and geographic north. The inclination of \( J \) is denoted as \( A \) (measured positive downwards) and the angle between the horizontal projection of \( J \) and geographic north is \( B \). The angle in the x-y plane between the positive x-axis and geographic north is \( C \), both \( B \) and \( C \) being measured in a clockwise direction from geographic north. The components of the magnetization \( J_x \) and \( J_z \) are then given by

\[ J_x = J \cos A \cos (C - B) \]
\[ J_z = J \sin A \]

If the polygon is magnetized by induction in the earth's field, then \( J=\kappa F \), \( A \) is the field Inclination (I) and \( B \) is the declination (D).

To obtain the field over the bounded polygonal section KNPQR the anomalies due to prisms such as KLMN that extend to infinity in the +x direction are calculated. Systematic addition of field values on moving around the polygon will give the total anomaly at (0,0) if due regard is made to the sign of the contributions of each prism as indicated by an increase or decrease in \( \theta \). For the anomalies small with respect to the total filed \( F \), the total intensity anomaly, \( T \) is
the sum of the projections of $H$ and $V$ along the direction of $F.$, i.e.,

$$T = V \sin I + H \cos I \cos(C - D)$$

Talwani and Heirtzler (1964) have provided a FORTRAN program, which can be used to calculate the synthetic magnetic anomaly of a two-dimensional body based on their method. Macnab (1966) developed an algorithm as an adaptation to Talwani and Heirtzler (1964) program to compute the magnetic anomaly caused by multiple bodies along a profile in a direction perpendicular to the strike direction of 2-D bodies. For the present work, an available (Bhattacharya, personal communication) software developed based on Macnab (1966) have been used to compute magnetic anomalies of models.

(b) Steps for magnetic modeling followed in this study

The study area contains magnetic lineations of alternate positive and negative magnetic anomalies. To interpret these magnetic anomalies, an initial model of juxtaposed magnetized blocks is considered as magnetic source. The magnetic polarity of these blocks is considered alternately normal and reverse. Given the boundaries of the blocks, their intensity of magnetization, the orientation of the regional field, the magnetic anomaly of the model can be calculated following the Talwani and Heirtzler (1964) method. During modeling, the boundaries of the blocks have been adjusted until an acceptable fit is obtained to the observed profile.

3.3.3 Paleogeographic reconstruction

The paleogeographic reconstruction, which is the process of restoring lithospheric plates back to the relative positions they occupied in the geological past, have been widely used to understand the evolution of ocean basins and the adjoining continents. Several researchers (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Besse and Courtillot, 1988; Scotese et al., 1988; Royer et al., 1992; Royer et al., 2002) applied this technique to understand the evolution of the Indian Ocean region. Since paleogeographic reconstruction technique has been extensively used in the present study, therefore based on Cox and Hart (1986), some concepts and conventions related to usage of this technique, have been briefly described in this section.
(a) Great circles and small circles on a sphere

On a plane, straight lines were generally used to describe plate boundaries and directions of plate movement. Geometrically, the closest analog of a line on a sphere is a circle. It turns out that most of the elements of plate tectonics described by lines on the plane are described by circles on the globe. Plate tectonic geometry on a sphere turns out to be mainly a matter of relationships between circles. The centre of the circle drawn on a sphere is called the 'pole' of that circle. The angular length ($\delta$) is the angle of an arc drawn on the surface of the sphere from the centre to some point on the circle. The equator is a circle centred at the North Pole or South Pole with an angular radius of $\delta = 90^\circ$. The circles can also be made on a sphere by cutting the sphere with a plane. If the plane passes through the centre of the sphere, the intersection of the plane with the surface of the sphere will be a 'great circle' ($\delta = 90^\circ$). Otherwise the intersection will be a 'small circle' ($\delta < 90^\circ$). So, all longitudinal meridians are great circles, but not all latitudes. The only great circle in the latitude is the equator. All other latitude meridians are small circles. The great circle passing through longitude of zero degree is referred as the 'Index Meridian'.

(b) Frames of reference

Rotation of a point over a sphere can be executed only with reference to a fixed reference frame. For example, an ordinary reference globe consists of two parts. The first part is a sphere on which is printed a set of the latitude and longitude circles and the outlines of continents. The second one is a rigid metal or wooden framework that stands on the floor and supports the globe at the points by two pivot points, the globe being free to rotate within the rigid framework. This rigid frame is considered as the fixed reference frame. This can be considered as a physical three-dimensional object like fixed framework around the geographic globe and as a fixed set of points and curves on a piece of paper. The fixed reference frame consists of three perpendicular great circles drawn on a sphere (Fig. 3.9). The circles intersect at six points. Imagine six vectors originating at the centre of the sphere and ending at the six points of intersection of the circles. These compose a set of mutually perpendicular axes or unit vectors that can be referred as $\pm 1, \pm 2, \pm 3$. The great circles that contain vectors 3 and 1 are
Fig. 3.9 Physical three-dimensional object like fixed framework around the geographic globe (a) Fixed reference frame consisting of three perpendicular great circles. The globe within the frame can rotate about either axis 2 or axis 3. (b) Globe representing the earth placed inside fixed reference frame, shown in an equal area projection (modified after Cox and Hart, 1986).
denoted by the symbol <3,1>. The three axes and the three reference circles
<1,2>, <2,3> and <3,1> compose the principal elements of the fixed reference
frame (Cox and Hart, 1986).

(c) Euler rotation parameters

Euler rotation parameters play an important role in the geometry of plate
tectonics. They are named for the 18th century mathematician Leonhard Euler
pronounced ‘oiler’. Euler’s theorem is that any motion of a rigid piece of a
sphere over the surface of the sphere can be described as a rotation about some
axis through the centre of the sphere. The intersections of the axis with the
surface are called Euler poles and the angle of rotation is called Euler angle.
Euler latitude is analogous to a geographic line of latitude relative to the Earth’s
geographic North Pole. Euler pole is the pivot point about which two plates rotate
relative to each other (Fig. 3.10a). It is like the hinge of a pair of scissors, and a
transform fault is like the arc swept only by the point of one of the blades. The
Euler pole is the only point that does not move relative to either plate. The motion
of the plates over a sphere can be explained using the ‘Euler rotation
parameters’. These parameters are the key quantitative elements in plate
tectonics. Since all transforms are segments of circles on a sphere, all plate
motions on a sphere can be described efficiently and compactly using Euler
rotation parameters. The transforms are segments of circles centred on the Euler
pole (Fig. 3.10a, b).

(d) Determination of Euler pole using the trend of transform

To calculate the location of an Euler pole, three types of data are used.
The first is the observed trend of transforms, as determined from their topography
and geology. The second is the direction in which a block on one side of a fault
slides past the block on the other side during an earthquake along a fault
boundary, as determined by analyzing earthquake waves. The azimuth of this
“slip vector” gives the direction of relative plate motion and thus is analogous to
the trend of a transform. The third type of data is the velocity of spreading across
ridges, as determined from the spacing of magnetic isochrons. In this study, the
method of determining Euler pole from transform trends has been used. The
other two methods could not be used because no data regarding slip vector is
Fig. 3.10 Schematic diagrams representing the concept of Euler pole and Euler angle and their determination from the transform trends. (a) Plate A is fixed and Plate C is moving with respect to Plate A. The pole of rotation is the Euler pole (E) and the amount of angle rotated is the Euler angle ($\Theta$).

(b) Locating an Euler pole E from the trends T of Transforms. Lines nearly intersecting at E are great circles perpendicular to transform.
available and the magnetic lineations are of too short extent to reliably compute variations of spreading velocity along the ridge axis. From analysis of transform trends, the Euler poles can be determined by two approaches, the graphical method and numerical method. The graphical method for the determination of Euler pole yields approximate values only. But, the mathematical method can yield more precise values of Euler pole.

(i) Graphical method for estimation of Euler pole from transform trends

In determining the location of an Euler pole using the trend of transforms (Fig 3.10a, b), the basic data to be analyzed consists of the local azimuth angle \( T \) of the transform at each locality \( B \). Since the Euler pole lies on a great circle perpendicular to the transform, a great circle passing through the point \( B \) can be drawn by considering a pole of great circle at local azimuth \( D = T \pm 90 \). In the same way, the great circles passing through each transform points can be drawn. The co-ordinate, which defines the intersection of these great circles, is the location of Euler pole.

(ii) Numerical method for estimation of Euler poles from transform trends

Ideally, all of the great circles from the different observed points of fracture zones should intersect at the exact position of the Euler pole, \( E \). But, nature is too complicated to provide an ideal Euler pole, so that the points of intersection are scattered along a general trend of great circles. Among these, the best fit Euler pole is determined by the least square approach. A methodology to perform the least square method to the derived trial Euler pole was provided by Le Pichon (1968), based on the computed theoretical azimuth of each observation compared with the actual observation. The procedure for this approach is as follows:

1. Select the trial Euler pole
2. At a given point of observation, calculate the theoretical azimuth.
3. Subtract the theoretical transform trend \( T_{ex} \) from the observed trend \( T_{obs} \) and square the difference \( (e^2) \). This squared error is commonly used in plate tectonics, as a measure of misfit between an observation and the predicted value.
(4) As a combined measure of misfit at all points of observation, use the sum 
\[ \sum \varepsilon^2 \] of the squared errors at all the points.

(5) Select other trial poles and repeat the process until getting a satisfied Euler 
pole, for which \[ \sum \varepsilon^2 \] is a minimum. This is the best-fit pole in the sense of 
least squares.

During the course of this study, a FORTRAN program has been developed 
to estimate the Euler pole, following the numerical method of determining Euler 
poles from transform trends. This software is developed mainly based on the 
method of Le Pichon (1968) and Cox and Hart (1986). In this program, an Euler 
pole determined based on graphical method is provided as trial Euler pole along 
with the end co-ordinates of number of fracture zones and their observed 
azimuths. The program provides the refined Euler pole.

(d) Rotation of a point over a sphere

As explained in the previous sections, any point on the Earth’s surface can 
be rotated with respect to a rotation axis. The motion of a point over the surface 
of a sphere can be described with the help of Euler rotation parameters. The 
rotated co-ordinates of a point with respect to the known Euler pole and Euler 
age can be determined using two methods – graphical method and numerical 
method.

(i) Graphical method of rotation of a point over a sphere:

Let,

(i) \( K(\lambda_k, \phi_k) \) be a point to be rotated on Plate A (eg. Indian plate in Fig. 
3.11a)

(ii) \( E(\lambda_E, \phi_E) \) be the Euler pole about which point \( K \) is to be rotated

(iii) \( \Omega \) be the angle of rotation that reconstructs Plate A with reference to 
Plate B (eg. African plate in Fig. 3.11a).

(iv) \( K'(\lambda_k, \phi_k) \) be the rotated point over plate A,

where,

\( \lambda \) is the latitude of the corresponding point and
\( \phi \) is the longitude of the corresponding point.

Using an equal area projection, any finite rotation can be accomplished using five successive rotations about the axis 2 and axis 3 (Fig. 3.11a-f). The first two rotations align the Euler pole E with axis 3, the third rotation is the desired rotation, and the last two rotations return E (and the globe) to its original position. The rotated point over plate A is given as \( K'(\lambda_k, \phi_k) \). This rotation can be accomplished graphically in the following way:

(i) Two maps of globe in a stereographic or equal area projection are prepared, one on a white paper and another on a tracing paper. The plot of globe on tracing paper is referred as rotating globe co-ordinate system and the plot on white paper is referred as projection co-ordinate system. The points E and K are plotted on tracing paper (Fig. 3.11a). To start with, both the tracing paper and white paper are superposed in such a way that both the projection and rotating globe co-ordinate system coincide.

(ii) The globe on tracing paper is rotated with reference to axis 3 of the projection co-ordinate system by an angle of \(-\phi_E\), this rotation will take Euler pole to the Index Meridian (Fig. 3.11b).

(iii) The globe on tracing paper is rotated with reference to axis 2 of the projection co-ordinate system, by an angle of \(-(90-\lambda_E)\), which will bring the Euler pole to the Projection pole +3 (Fig. 3.11c).

(iv) The globe on tracing paper is rotated with reference to axis 3 of the projection co-ordinate system, by an angle \( \Omega \), which is the Euler angle. This will bring the point K to K' (Fig. 3.11d).

(v) The globe on tracing paper is rotated with reference to axis 2 of the projection co-ordinate system (Fig. 3.11e), by an angle \( (90-\lambda_E) \). This rotation will bring the Euler pole along Index meridian back to its original latitude.

(vi) The globe on tracing paper is rotated with reference to axis 3 of the projection co-ordinate system (Fig. 3.11f), by an angle \( \phi_E \). This rotation will bring the Euler pole back to its original longitude in the same reference frame as in (a).
Fig. 3.11 Figures describing steps of rotation of a point around an Euler pole using an equal area projection map of the globe (modified after Cox and Hart, 1986). K: the point to be rotated; E: Euler pole; K': the rotated position of K at various stages. Details of stages are described in the text.
(vii) The co-ordinates of K' is the rotated position of point K, which can be read from the globe.

(ii) *Numerical method of rotation of a point over a sphere*

Since too many points are involved in the plate kinematics, it is impossible to calculate the motion of each point one by one using graphical technique. Hence, rotations of plates are performed with the help of computers. The method, which is most suitable to the computers, is based on the matrix transformation of the three Cartesian components of position vectors. If point A is a point with Cartesian coordinates \((A_x, A_y, A_z)\), prior to the rotation, then the components \((B_x, B_y, B_z)\) after rotation to B can be obtained using the matrix multiplication.

\[
B = RA,\text{ where } R \text{ represents a } 3 \times 3 \text{ matrix}
\]

\[
\begin{bmatrix}
B_x \\
B_y \\
B_z \\
\end{bmatrix} = 
\begin{bmatrix}
R_{11} & R_{12} & R_{13} \\
R_{21} & R_{22} & R_{23} \\
R_{31} & R_{32} & R_{33} \\
\end{bmatrix}
\begin{bmatrix}
A_x \\
A_y \\
A_z \\
\end{bmatrix}
\]

Applying the usual rule of matrix multiplication,

\[
B_x = R_{11}A_x + R_{12}A_y + R_{13}A_z \\
B_y = R_{21}A_x + R_{22}A_y + R_{23}A_z \\
B_z = R_{31}A_x + R_{32}A_y + R_{33}A_z \\
\]

The elements of the rotation vectors are

\[
R_{11} = E_x E_x (1 - \cos \Omega) + \cos \Omega \quad R_{12} = E_x E_y (1 - \cos \Omega) + \cos \Omega \quad R_{13} = E_x E_z (1 - \cos \Omega) + \cos \Omega \\
R_{21} = E_y E_x (1 - \cos \Omega) + \cos \Omega \quad R_{22} = E_y E_y (1 - \cos \Omega) + \cos \Omega \quad R_{23} = E_y E_z (1 - \cos \Omega) + \cos \Omega \\
R_{31} = E_z E_x (1 - \cos \Omega) + \cos \Omega \quad R_{32} = E_z E_y (1 - \cos \Omega) + \cos \Omega \quad R_{33} = E_z E_z (1 - \cos \Omega) + \cos \Omega \\
\]

The multiplication of the rotation matrix \(R\) with the position matrix \(A\) gives the rotated position matrix, \(B\) in Cartesian co-ordinates, which can be converted into spherical polar co-ordinates.

**3.3.4 Adopted magnetic chron nomenclature and allied conventions**

In this study, the geomagnetic polarity time scale and the magnetic chron nomenclature proposed by Cande and Kent (1995) have been adopted (Table
Further, mainly based on Cox and Hart (1986) following conventions have been used in connection with denoting a particular geomagnetic polarity interval or the seafloor spreading magnetic anomaly created during that polarity interval;

(i) In geomagnetic polarity time scale, the term 'chron' have been used to denote the broad time interval within which the geomagnetic polarity remained constant. Each chron is designated by identification (numbers suffixed with alphanumeric characters), where the present normal chron is identified as chron 1 and preceding (older) normal chrons are designated successively with increasing numbers such as chron 2, chron 3 etc. This convention of identification of chrons by only numbers is followed for the Cretaceous-Tertiary-Quaternary Superchron (Note: here the term ‘Superchron, denotes a large time interval during which the polarity bias is constant or nearly so). For still older Cretaceous-Jurassic Superchron, the letter ‘M’ is prefixed to the number label of the chron. Sometimes the suffix of ‘n’ or ‘r’ is further added to the chron identification to denote the episodes of normal or reverse polarity respectively. Wherever such a suffix is not added it is considered to represent a normal chron. For example, chron 27n (or, chron 27) represent the time interval for a normal episode and chron 27r represent the time interval for the reverse episode of magnetic polarity interval preceding (older in age) the normal chron 27n.

(ii) The boundaries of a chron are identified by adding the further suffix of ‘y’ to denote the younger end and the suffix ‘o’ to denote the older end of the chron.

(iii) The seafloor spreading magnetic anomaly caused by a magnetized block formed during a particular chron is designated by relating to the corresponding chron. For example, the magnetic anomaly caused by magnetized block formed during chron 28n is denoted as ‘anomaly 28n’ (or, in abbreviated form as ‘A28n’). As a consequence of this form of anomaly designation, the temporal references, such as; ‘time of anomaly 28n’, ‘time of A28n’, ‘anomaly 28n time’ or ‘A28n time’ thus corresponds to chron 28n.

(iv) The boundaries of magnetized blocks thus are synonymous with chron boundaries. Therefore, the lineations drawn by joining the boundaries corresponding to the same chron on adjacent magnetic profile can be
considered to represent an isochron.

3.3.5 *Preparation of maps and profiles*

In the present study, large number of descriptive as well as interpretative maps and profiles has been presented. These maps have been prepared in Mercator projection of different scales using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1995). Profiles and contours of different data as well as the colour shaded relief image and contours of satellite derived free-air gravity anomalies have also been prepared using the same GMT software. Many tectonic elements have been digitized from various published figures and maps using the ARC/Info GIS package. Few data profiles / sections have been digitized from published figures using WINDIG software. The digitized data were stored as GMT compatible data files and integrated to various maps and sections using GMT package.
Table 3.3 Selected magnetic anomaly numbers and their bounding ages, extracted from the Geomagnetic Polarity Timescale of Cande and Kent (1995). Magnetic anomaly number followed by the suffix 'n' represents normal polarity interval.

<table>
<thead>
<tr>
<th>Anomaly number</th>
<th>Younger boundary (Ma)</th>
<th>Older boundary (Ma)</th>
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<tbody>
<tr>
<td>16n</td>
<td>35.343</td>
<td>36.341</td>
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<td>20n</td>
<td>42.536</td>
<td>43.789</td>
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<td>21n</td>
<td>46.264</td>
<td>47.906</td>
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<td>22n</td>
<td>49.037</td>
<td>49.714</td>
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<td>52.364</td>
<td>52.663</td>
</tr>
<tr>
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<td>52.757</td>
<td>52.801</td>
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