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Basin and sub-basin crustal structure of a part of the western offshore, India

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ABSTRACT
The basin modeling/analyses based upon structure, isopach (sediment thickness), lithofacies, paleogeologic and the geophysical maps, of a part of the western offshore has been attempted. In this study, two gravity profiles have been utilized for modeling. Other geophysical information like seismic data, as obtained from ONGC and NIO published reports, and the corresponding sub-basin crustal models have been utilized for correlation and generation of whole crustal models. RE-11 has been taken as per the existing NIO model and the results of the forward model have been compared/validated with the satellite gravity data.

INTRODUCTION

In this paper, the basin modeling/analyses based on subsurface features over a part of the western offshore has been attempted. Different techniques of basin analyses, depending upon structure, isopach (sediment thickness), lithofacies, paleogeologic and the geophysical maps have been studied. However, as the study is mainly dependent upon geophysical database, different geophysical information for subsurface modeling has been considered. Two gravity profiles have been chosen and utilized along with other geophysical information (like seismic data and subsurface geological formations as obtained from ONGC and NIO published reports) to generate whole crustal models. In addition, the subsurface crustal information along the profile RE-11 has been taken as per the existing NIO model and the results of the forward model have been compared/validated with the satellite gravity data. The basin analyses have also been studied in detail and the techniques for basin analyses with geophysical information have been discussed.

Basin analyses

Basin analysis for studying geodynamical processes is an integrated programme of study, which involves application of sedimentologic, stratigraphic and tectonic principles. It aims at developing a full understanding of the rocks that fill the sedimentary basin for the purpose of interpreting their geological history and evaluating their economic importance (Boggs 1995). The origin of a sedimentary basin is related to the crustal movements and the plate tectonic processes. A sedimentary basin is commonly classified in terms of the following (Dickinson 1974; Clifton et al. 1988; Miall 1990):

i. type of the crust on which the basin rests
ii. position of the basin with respect to plate margins
iii. type of plate interactions occurring during sedimentation for basins lying close to a plate margin.

Mitchell and Reading (1986) used a straightforward and reasonable classification for various basins with respect to the tectonic settings. These are:

a. Interior basins, intercontinental rift and aulacogens (including thermally related rifts and collision related rifts)
b. Passive or rifted continental margins (Atlantic-type margin comprising a shelf, slope and rise)
c. Oceanic basins and rises (the deep ocean floor and smaller basins associated with mid-ocean spreading ridges and rises but excluding transform fault related settings)
d. Subduction-related settings (convergent plate boundaries characterized by a trench, arc-trench gap and volcanic arc)
e. Strike-slip/transform fault related settings
f. Collision-related settings (resulting from closure of an oceanic and marginal basin).

The present study area in the western offshore is a passive continental margin. These types of margins are also called as Atlantic-type margins and are characterized by the presence of a sedimentary prism and experience little or no seismic or volcanic activity. The rifting and drifting of Indian landmass from the Gondwanaland probablycreated the western margin of India (Biswas1982,1987). Sediment accumulates in several parts of this margin- shelf; slope and continental rise at the foot of the slope. Sediments deposited in this setting can include shallow neritic sands, muds, carbonates on the shelf; hemipelagic muds on the slope; turbidites on the continental rise. Basin analysis to the petroleum geologists means locating reservoir rocks and traps within depositional basins. To find an oil/gas deposit, geologists 1) carry out exploration in basins that have the right condition for the formation and migration of hydrocarbons, and 2) locate a suitable trap, such as a structural anticline, in which hydrocarbons might have accumulated. The application of basin assessment techniques to develop petroleum play is described by Allen and Allen (1990).

TECHNIQUES OF BASIN MODELING AND ANALYSES

Analyses of characteristics of sediments and sedimentary rocks that fill basins and interpretation of these characteristics in terms of sediments and basin history, demand a variety of sedimentological and stratigraphic techniques. These techniques require the acquisition of data through outcrop studies and subsurface methods that can include deep drilling and geophysical studies including gravity, magnetic and seismic information. These data are then commonly displayed for the study in the form of maps and stratigraphic cross sections (Boggs 1995).

Stratigraphy

The formal litho-stratigraphies of the Indian Petroliferous basin have been updated and standardized (Zutshi et al, 1993). A summarized account of the formations recognized and other rock units of the western offshore basins are presented in Table 1 (Srinivasan and Khar 1995). The formations containing hydrocarbons are highlighted.

Geophysical studies

Geophysical investigations play important role in basin analyses. The gravity anomaly data gives information essentially about the lateral distribution of density. The high and low gravity anomalies could be interpreted as due to the presence of high-density material and thick sediments in the subsurface respectively. In general, sedimentary basins correspond to gravity low. The seismic techniques are used to document the regional structural trend, such as, anticlines and faults; they provide information about demarcation of different subsurface layers that may provide traps for hydrocarbons. However, the gravity undulations on the periphery of a basin also give impression about the nature of the area.

Lithospheric modeling

To study the anomalous masses inside the earth requires determination of the gravity anomaly fields. Anomalies are the difference between the observed gravity and the calculated gravity. To compute an anomaly, observed gravity is therefore first reduced to its sea level equivalent, for measurements made above the sea level.

The use of gravitational method is based on the simple principle that the gravitational effect of a rock body is a function of its density, size, shape and distance from the observer. The presence of folds, buried ridges, salt domes, faults and igneous intrusions may be deduced from gravity data. In calculating the depth, size and shape of rock bodies that cause gravity anomalies, different hypothetical models/ bodies are to be tested. The parameters of these bodies are initially assumed e.g. density, depth, shape etc. Varying these parameters, the gravitational effects of these bodies are computed. The model that best explains the observed anomalies is considered to be the correct one (Dehlinger 1978, Billings 1997). However, gravity anomalies cannot provide unique solutions to mass distributions. Assumptions or extraneous information are, therefore, made for quantitative interpretation. GMSYS modeling software has been used for this purpose (Geosoft Software, India). To constrain the model as much as possible, it is made to conform to existing bathymetry, seismic and borehole data.

The present study is an investigation for understanding the structural configuration of the basin corresponding to its gravity signature and other geophysical and geological information.

Two gravity profile sections have been utilized for subsurface modeling using satellite gravity data. As

Table 1. Different existing hydrocarbon formations (after Srinivasan and Khar 1995)

	CHRONO - STRATI GRAPHY		TECTONIC HISTORY	LITHOSTRATIGRAPHY						
	SERIES				SHELF MARGIN BLOCK	BOMBAY HIGH – DCS BLOCK	RATNAGIRI BLOCK	PANNA - BASSEIN BLOCK	TAPTI – DAMAN BLOCK	DIU BLOCK
0	HOLOCENE / PLEISTOCENE		POST RIFT STAGE	ANGARIA GROUP	CHINCHINI FORMATION					
	PLIOCENE	Up								
		Lr								
5	MIOCENE	Up								
		Md			TAPTI FMN + RATNAGIRI FMN	RATNAGIRI FMN + (BANDRA FMN / TAPTI FMN)	RATNAGIRI FMN	BANDRA FMN/ TAPTI FMN	TAPTI FMN	BANDRA FMN / TAPTI FMN
		Lr			MAHIM FMN + RATNAGIRI FMN	RATNAGIRI FMN + (MAHIM/ BOMBAY FMN)	RATNAGIRI FMN	MAHIM FMN / BOMBAY FMN	MAHIM FMN	MAHIM FMN / BOMBAY FMN
25	OLIGOCENE	Up			ALIBAGH FMN	PANVEL FMN + ALIBAGH FMN	PANVEL FMN + ALIBAGH FMN	ALIBAGH FMN	ALIBAGH FMN + DAMAN FMN	ALIBAGH FMN
		Lr			HEERA FMN / MUKTA FMN	MUKTA FMN	HEERA FMN / MUKTA FMN	HEERA FMN / MUKTA FMN	MAHUVA FMN	MUKTA FMN / MAHUVA FMN
36	EOCENE	Up								
		Md			BASSEIN FMN / BELAPUR FMN	BASSEIN FMN	BASSEIN FMN	BASSEIN FMN	DIU FMN + PIPAYAV FMN / BELAPUR FMN	DIU FMN / BELAPUR FMN
		Lr	RIFT STAGE		DEVGARG FMN / PANNA FMN	DEVGARG FMN / PANNA FMN	DEVGARG FMN / PANNA FMN	DEVGARG FMN/ PANNA FMN	PANNA FMN	JAFARABAD FMN
54	PALEOCENE	Up								
		Lr								
65	CRETACEOUS	Up	STAGE	DECCAN TRAPS						
70	ARCHAEAN			IGNEOUS / METAMORPHIC COMPLEX						

the major fault patterns are trending NW-SE, the profile sections have been taken across the faults. Different densities have been assigned to fit the observed gravity anomaly with the predicted gravity anomaly. Information about various formations, structural patterns are taken from seismic profiles and drill-hole data for profile sections. The structural information is taken from seismic data available in various literatures and published reports of NIO and ONGC. The profiles utilized for lithospheric modeling are:

a. Profile RE-11 (NIO model) taken from Krishna et al. (2006) for subsurface modeling over a part of the western offshore across the Laxmi Ridge-Basin.
b. Profile ONGC east-west geological cross section across Panna-Bassein, Bombay High DCS and Shelf margin block (Zutshi et al. 1993; SrinivasanandKhar 1995).

Figure 1 shows the free-air gravity anomaly map over a part of the western offshore covering the study area from high resolution satellite gravity data showing various geological/ subsurface features (Bhattacharyya et al. 2009).The AB profile (A: 65.30°E, 13.88°N; B: 72.72°E, 16.43°N) is for RE-11 (NIO, Goa) and the CD profile (C: 70.22°E, 18.71°N; D: 71.87°E, 19.29°N) from ONGC Reports (Srinivasan and Khar 1995) have also been marked in Fig. 1.

a) Profile RE-11: The regional gravity profile AB taken for subsurface modeling in and along the same extent with the published model of Krishna et al. (2006). To extract the dataset along AB, a number of softwarehas been used. A line vector file has been generated along the RE-11 regional gravity profile. The gravity data have been extracted by using the 'transect data using vector option' of ENVI (version 4.2) software (RSI 2005). The gravity data is stored in a text file. Similarly, the bathymetry profile has been obtained from GEBCO digital data along AB using a similar procedure. These two datasets are the main input for the subsurface modeling using GMSYS software. In subsurface modeling, first the existing model has been placed in the background of the modeling windows and the basement has been outlined. After this, different blocks have been prepared from the information obtained from the seismic sections. Finally, the blocks have been assigned various density values depending upon the density of crustal rocks, to fit the observed gravity dataset with the calculated one. Figure 2 shows

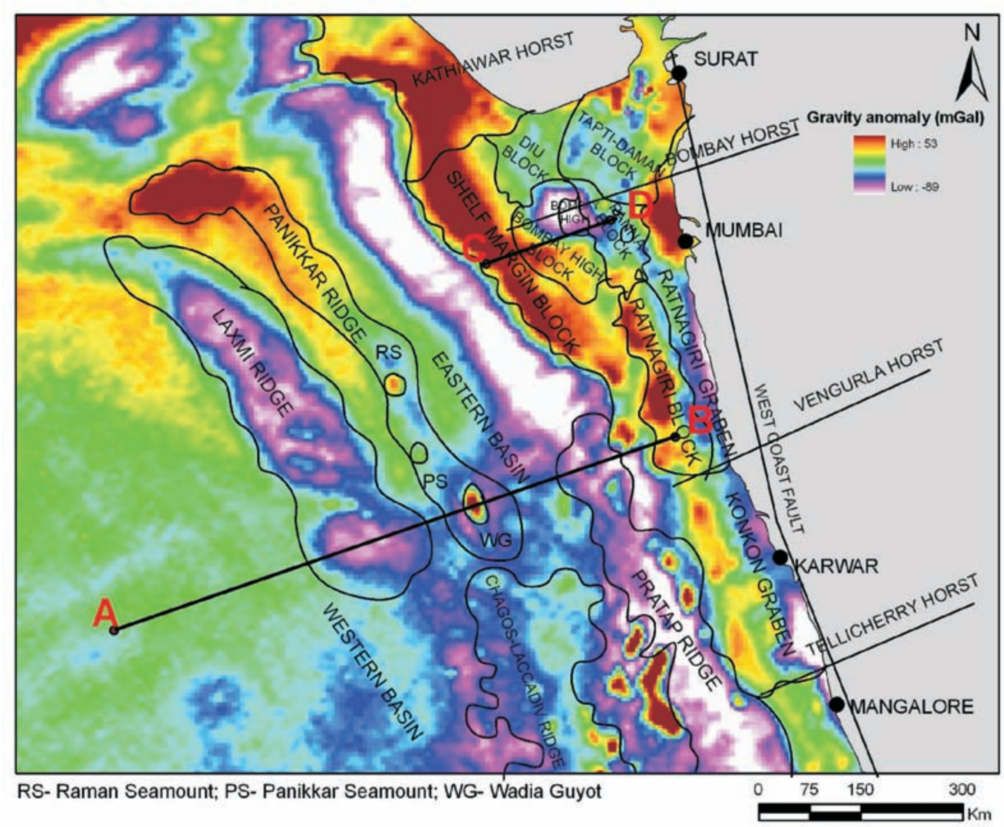

Figure 1. Free-air gravity anomaly map over a part of the western offshore covering the study area from high resolution satellite gravity data showing various geological/subsurface features (after Bhattacharyya et al. 2009). Profiles AB and CD are also shown.

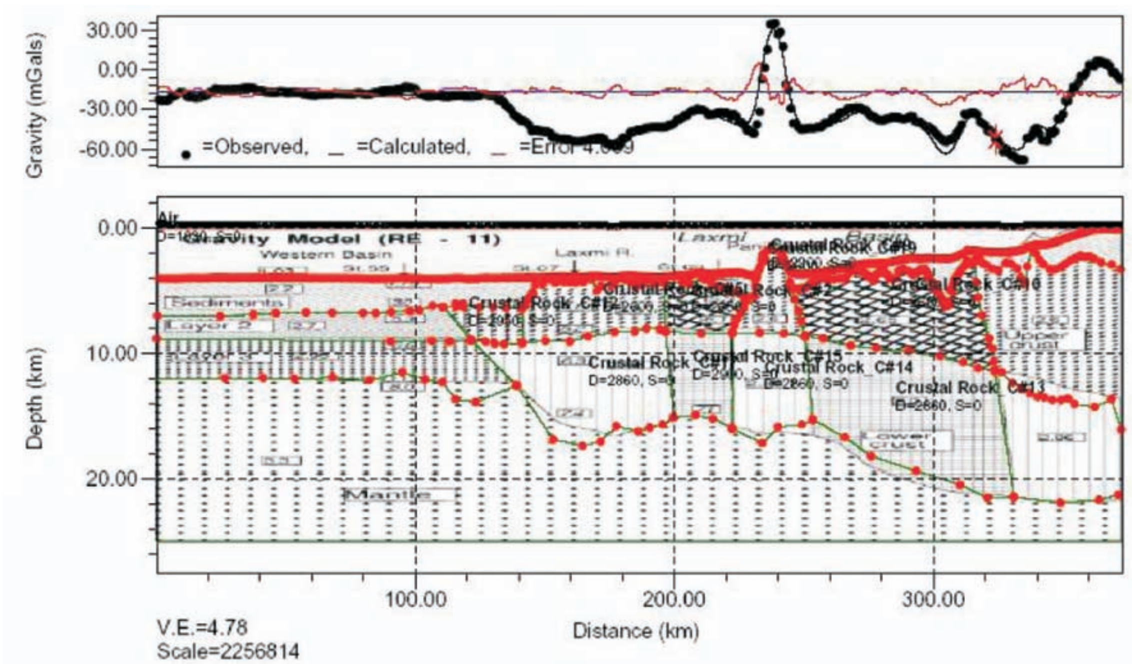

Figure 2. Results of forward model compared with existing satellite gravity data. Modeled crustal structure across the profile RE-11 (AB in Fig. 1) is as per existing NIO model

gravity profile model across RE-11 (AB in Fig. 1) with the modeled crustal structure from east to west across the Continental Shelf, Laxmi Basin, Panikkar Ridge, Laxmi Ridge, and the eastern Arabian Sea, from free-air gravity. The Laxmi Basin basically consists of stretched continental crust, while the crust adjacent to the Panikkar Ridge in the basin is intermixed with the Deccan volcanic rocks (Krishna et al. 2006). The modeled gravity profile is able to reflect the subsurface structures. It implies that the upper crust varies in thickness of about 12-20 km, with increasing crustal thickness towards continents. The Laxmi Ridge shows a deeper basement of about 16 km. The subsurface crustal information along the profile AB has been taken as per the existing NIO model and the results of the forward model have been compared/validated with the satellite gravity data (Fig. 2). Since, the existing satellite gravity data is of higher spatial resolution (~3.5 km), it helps to generate more information about the subsurface than the published report of Krishna et al. (2006). The bases of the Laxmi Ridge and the Laxmi Basin show difference in depth of about 2-4 km (Fig. 2).

b) ONGC profile: The Bombay offshore basin is situated on the western continental terraces of the Indian landmass. The eastern portion is bounded by the exposure of the Deccan Trap, while the western portion is marked by a basement high arch, corresponding to Kori – Prathap Ridge (Harbison and Bassinger 1973; Naini and Talwani 1983; Bhattacharya and Chaubey 2001). Drilling in the Bombay High field, India has revealed large volume of oil and gas, within the basement rocks composed of basaltic and granitic gneiss. The Bombay High, largest oil field in India, is situated around 161 km west-northwest of the Mumbai coast. Most of the oil and gas is contained in Miocene limestone reservoirs and a smaller proportion in the basal clastic sandstone reservoirs, which overlie the fractured metamorphic rocks. The main limestone reservoir is encountered at a depth of approximately 1300m but the basement hydrocarbons occur at 1900 m, on the crest of the structure (Akbar 1993).

The gravity profile has been drawn along profile CD, following a similar procedure as described above. The detailed seismic information is available

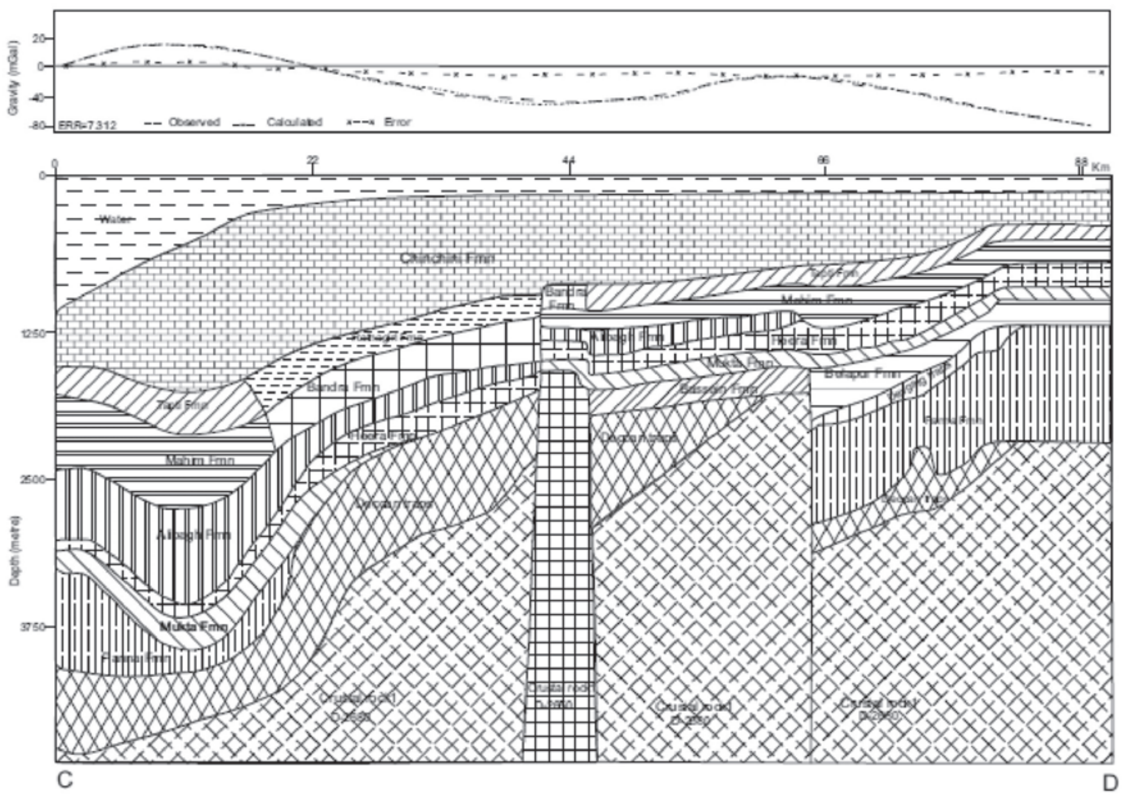

Figure 3. Subsurface model along CD profile up to a depth of 5 km

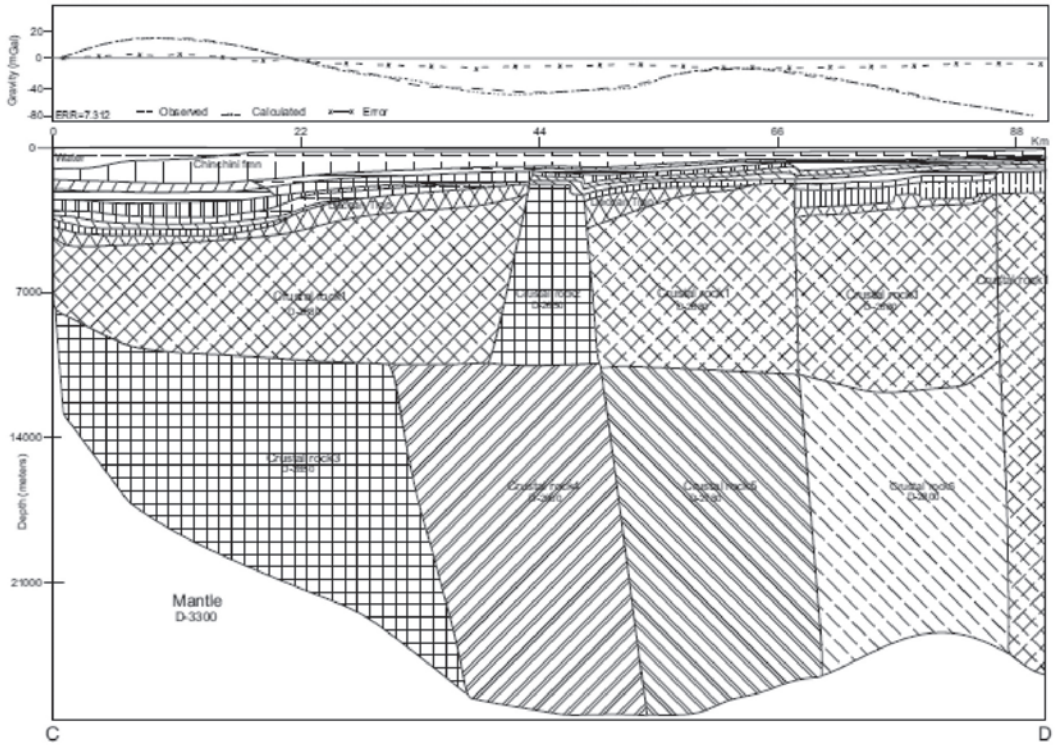

Figure 4. Crustal structure along CD profile based on integrated geophysical data.

with ONGC upto 5 km depth along the profile (Fig. 3). Hence the subsurface could be modeled upto 5 km depth. Various formations have been put chrono-stratigraphically with corresponding seismic information. The Root Mean Square Error (RMSE) is approximately 7 mGal. The modeled crustal structure shows that the area is structurally complicated. The structure of various formations, sediment thickness and successive intrusive bodies of Deccan volcanics make the area prospective for hydrocarbons. Figure 4 shows the complete modeled subsurface structures upto the lower crust. Deep crustal root of the Bombay High basin lies approximately at a depth of 25 km. The basement faults are also associated with the main Bombay High basin area showing anticlinal structure (structural high) (Zutshi et al. 1993). However, in the eastern and western regions, the basement shows upliftment than in the main basin area.

CONCLUSIONS

The present study shows the structural configuration of the basin corresponding to its gravity signature and other geophysical and geological information. The subsurface crustal information along the profile AB has been compared/validated with the satellite gravity data. The crustal model of AB gravity profile shows high resemblance with that of NIO model by Krishna et al. (2006). The RMSE between observed and calculated gravity is about 4.8 mGal.

In the other section, the CD profile could be modeled for the subsurface upto the lower crust using the satellite gravity data. RMSE between observed and calculated gravity data is found to be about 7 mGal. The Bombay High basin as a whole is characterized by a broad gravity low within its central portion. However, the basin structure could be studied/ investigated through the subsurface model. It has been found that the Bombay High basin shows a deep crustal root of about 25 km. while in the eastern and western portion, the basement becomes uplifted. The basement topography/crustal root in the Bombay High basin is relatively smooth. It has also been found that the Bombay High region is of high sediment thickness and having economic implication, due to its sediments and complex structures. Due to the prevailing security restrictions at this end, Latitude/Longitude markings have been omitted in few figures.

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