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Imaging Mesozoic Sediments in Deccan Volcanic Province of India: Inferences from Seismic and Gravity Studies

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ABSTRACT

Imaging sub-basalt Mesozoic sediments in the Deccan Volcanic Province (DVP) of India is a major challenge for hydrocarbon exploration. However, long-offset coincident seismic reflection (CDP) and refraction/wide-angle seismic reflection techniques may be applied for imaging sub-trappean Mesozoic sediments with proven success. The CSIR-NGRI executed several such deep seismic profiles with maximum offsets less than 100 km along with other geophysical methods like magneto-telluric, deep-resistivity-sounding and gravity surveys in the DVP covering Kutch, Saurashtra and Deccan Syneclise regions of India during the last three decades with an aim of integrated geophysical modeling. This has been sponsored and supported by the ONGC and OIDB. We used some of the selected deep seismic profile data in the DVP to image low-velocity-layer (LVL) like Mesozoic sediments, hidden below the high-velocity-layer (HVL) corresponding to basalts/traps. We applied ray-trace inversion of travel time data, robust tomographic inversion and advanced seismic imaging techniques to obtain seismic sections and velocity models. The derived velocity models delineate thick sub-basalt Mesozoic sediments in the south of Kutch, north-western part of Saurashtra and western segment of Deccan Syneclise along with extension of trap and basement configuration with details shown through fence diagrams. They are further constrained and corroborated by the corresponding density models obtained from inversion of residual Bouguer gravity anomaly data. The results provide an insight of the presence of hydrocarbon bearing sub-trappean Mesozoic sediments hidden in the DVP.

INTRODUCTION

Imaging sub-basalt Mesozoic sediments is a challenging problem ever faced by the oil industries all over the world. The most important regions covered with Mesozoic sediments hidden below the thick rugose basalts in the Kutch, Saurashtra and Deccan Syneclise form the Deccan Volcanic Province (DVP) of India (Fig. 1). The DVP is considered as one of the largest basalt covered regions of the world (White and M^{c}Kenzie, 1989) formed due to extensive outpouring of tholeiitic lavas during the Deccan volcanism (~65 Ma). The Mesozoic sediments are expected to be hydrocarbon bearing (Biswas, 1981, 1982, 1987) with a significant potential of more than fifty percent hydrocarbon reserves in India, which need tremendous impetus for exploration activities to meet the oil and gas demand of the country.

To meet the demand and supply of oil and gas, exploration of frontier sedimentary basins are necessary for finding new hydrocarbon reserves. Hence, Oil and Natural Gas Commission (ONGC) came out with a novel plan to explore the hidden Mesozoic sediments in the Deccan trap covered regions namely Saurashtra peninsula, Kutch and Deccan Syneclise regions of India. The presence of thick sub-trappean Mesozoic sediments have been imaged in the Saurashtra peninsula from the magneto-telluric (MT) study conducted by CSIR-NGRI during 1988-90 (Sarma et al., 1992), sponsored by Oil Industry Development Board (OIDB). The results obtained from this regional MT study were confirmed subsequently from the wells drilled at Dhanduka and later at Lodhika in the Saurashtra (Fig. 1b). This success has brought immense insight about the presence of vast tracts of sub-trappean Mesozoic sediments in the northwest part of Saurashtra. Taking into account the vast experience and expertise available in CSIR-NGRI with different geophysical tools and techniques, ONGC has decided to sponsor for deciphering the complex geological problem of imaging sub-trappean Mesozoic sediments and basement configuration in the entire Saurashtra peninsula. This was carried out by CSIR-NGRI with the help of integrated geophysical study, by suitable deployment and execution of a judicious combination of seismic, gravity, MT and deep-resistivity-sounding (DRS) methods. Under this project, total 950 line km along five seismic profiles, 10,000 gravity stations, 600 MT stations and 50 DRS stations were covered during 1994-97 (NGRI, 1998). The integrated geophysical study has discovered two major sedimentary basins called Jamnagar and Dwarka basins in the northwest quadrant of the Saurashtra peninsula having thickest (>3 km) column of Mesozoic sediments hidden below the Deccan trap, suitable for presence of hydrocarbons. In addition, the study has indicated presence of other complex subsurface geological targets of interest like detection of major fractures/fissure zones, basement ridges, several sub-sedimentary volcanic plugs with varied nature and Deccan trap thickness across the entire peninsula. The Jamnagar basin has an extension toward northwest into the Gulf of Kutch and Dwarka basin extends into the offshore Arabian Sea (Fig. 1b).

With the success in the Saurashtra peninsula, ONGC and subsequently OIDB extended the sponsorship to image Mesozoic sediments and basement configuration in the on land Kutch sedimentary basin of India. Accordingly during 1996-97, seismic refraction and wide-angle reflection studies were carried out along the four profiles (Fig. 1c) having 350 line km (NGRI, 2000). Subsequently, gravity studies have been carried out with total 3300 stations covered in the central part and along the seismic profiles in the Kutch on land basin during 1998. During 1999-2000, both MT and DRS studies were carried out in the on land Kutch with 50 stations and 20 stations, respectively. The integrated interpretation results are constrained from the well log input of five wells drilled in this basin to meet the objective of these studies to determine the thickness of the sub-trappean Mesozoic sediments, basement configuration and plausible 3D depth model down to the basement (NGRI, 2000). The integrated study has explored two basement highs in the NE of Jakhau and in the vicinity of Mundra with basement depression and presence of thick sedimentary layers in the southern part of Kutch. The thickest sediments (5-6 km) are obtained close to Mandvi with presence of deep basinal east-west trending faults near Mandvi-Mundra. The

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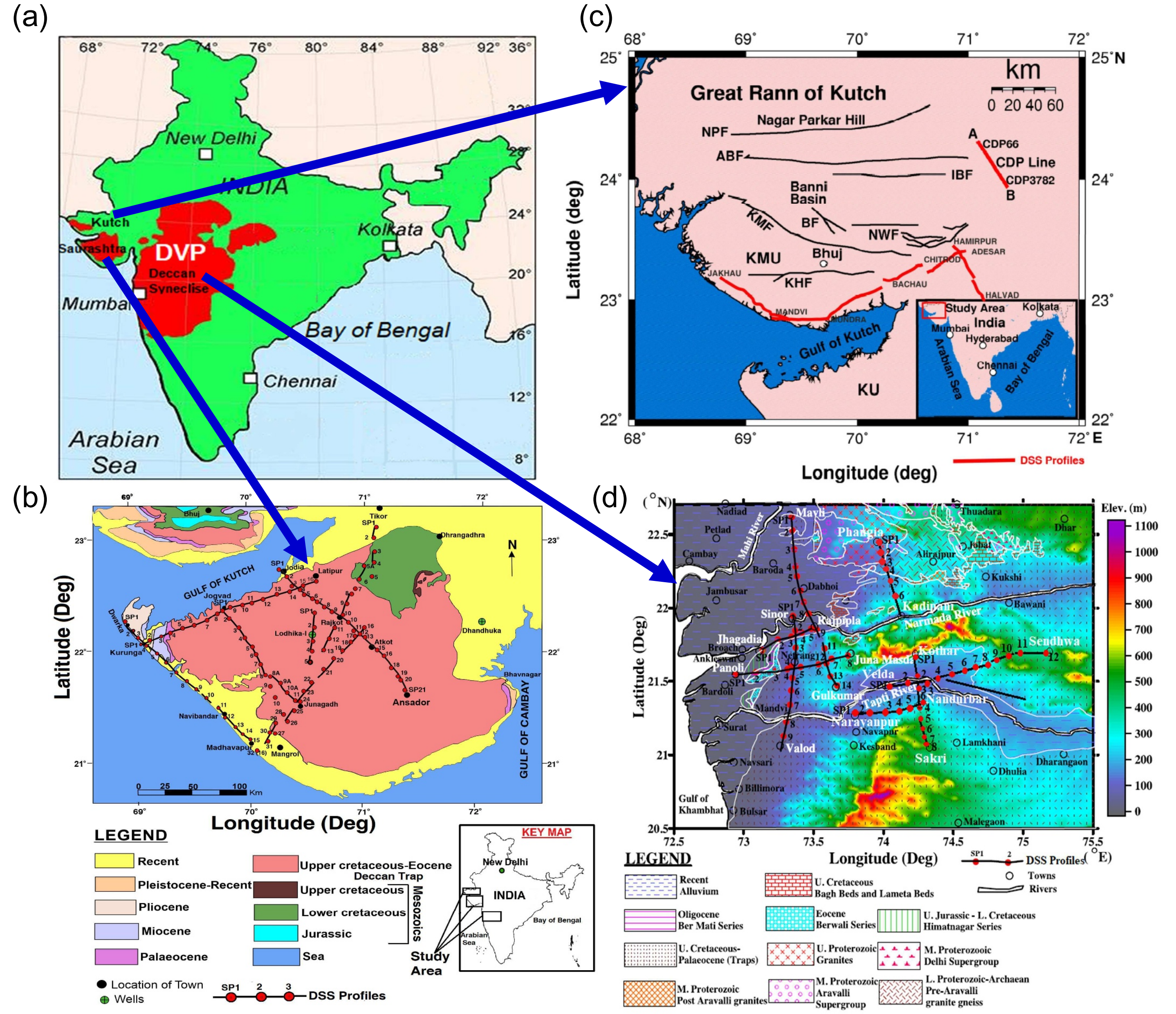

Fig.1. **(a)** The Deccan Volcanic Province (DVP) of India is shown. **(b)** Geological features of Saurashtra, **(c)** Kutch and **(d)** Deccan Syneclise regions are displayed. The seismic profiles in the respective regions are marked (modified after Behera et al., 2011; Behera and Sen, 2014).

central part of Kutch is characterized by shallow basement forming uplifted block bounded by Kutch Mainland Fault (KMF) to the north and Katrol Hill Fault (KHF) to the south (Fig. 1c).

With the success of exploration for sub-trappean Mesozoic sediments in the Saurashtra and Kutch basins using integrated geophysical methods by CSIR-NGRI, OIDB has sponsored about 40,000 sq. km area between Narmada and Tapti rivers in the Deccan Syneclise of western India (Fig. 1d) for exploration of Mesozoic sediments. Under this integrated geophysical exploration program in the Deccan Syneclise regions of western India, CSIR-NGRI has acquired 6000 gravity stations at about 2 km spacing, 600 MT stations at about 5-6 km grid spacing, 50 DRS stations and 700 km of seismic refraction/wide-angle reflection data covering eight seismic profiles during 2000-2002 field seasons. The integrated geophysical study in the Deccan Syneclise region has deciphered presence of Mesozoic sediments having a thickness varying from few hundreds of meters to about 3.0 km, with two major depocenters between Narayanpur-Sakri and Sirpur-Sendhwa, where maximum thickness of Mesozoic sediments of 2.5-3.0 km have been delineated. Another sub-basin of Mesozoic sediments is delineated between Kadipani and Barwani in the north with maximum thickness of 2.0-2.5 km. Trap thickness in this region varies from 0 to 4 km in the western part, which represents the centre of volcanic eruption south of Surat with general trap thickness varying from few hundred meters to 2.5 km in the eastern part of Sendhwa to Sirpur and 1.5-2.0 km around Nandurbar (Fig. 1d). The depth of the basement varies from 0.0 km in northern part (exposed) to maximum 5.0-5.5 km in the eastern part (Sirpur-Sendhwa) and western part (Surat-Bardoli). In the eastern part, Deccan trap is underlain by Mesozoic sediments followed by basement while in the western part the exposed alluvium and Tertiary sediments overlie the Deccan trap, which is in the form of a plug or feeder channel (NGRI, 2003).

The extensive geophysical and geological studies by employing different processing, modeling/inversion and interpretation techniques are undertaken in due course of time by CSIR-NGRI and many other oil and gas exploration companies in these regions of DVP to provide a detail image of the sub-trappean Mesozoic sediments hidden below the Deccan traps of India. It is pertinent to note that besides imaging the entire crustal column, seismic refraction/wide-angle seismic reflection and long-offset coincident seismic reflection (CDP) data acquisition techniques adopted by the CSIR-NGRI showed immense potential and success in imaging low-velocity-layer (LVL) sediments hidden below the high-velocity-layer (HVL) basaltic traps (Kaila et al., 1981; Tewari et al., 1995; Dixit et al., 2000; Reddy et al., 2001; Behera et al., 2002, 2004, 2011; Mall et al., 2002, 2008; Sain et al., 2002; Prasad et al., 2010; Murty et al., 2010, 2011, 2014; Behera, 2011; Behera and Sarkar, 2011; Behera and Sen, 2014; Talukdar and Behera, 2018). The presence of LVL below the HVL was detected from the long-offset seismic refraction and wide-angle seismic reflection data with the help of travel time skip phenomena (Greenhalgh, 1977; Whiteley and Greenhalgh, 1979; Jarchow et al., 1994; Lutter et al., 1994). Modeling/inversion of refraction and wide-angle seismic reflection data could also helped to a great extent for imaging and delineate sub-basalt/sub-trappean Mesozoic sediments and the basement configuration in the DVP by using the proven methodology as established from a study in the Columbia Plateau of USA (Jarchow et al., 1994; Lutter et al., 1994). The efficacy of modeling seismic refraction data for imaging of sub-trappean Gondwana sediments hidden below the Deccan trap has also been established for the central India (Mall et al., 2002). Also, sub-basalt reflection phases are more easily identified at wide- than at near-angles, because reflection amplitudes generally increase with offset (Fruehn et al., 2001). The wide-angle reflection arrivals are also less contaminated by multiples/noises from the overburden as a consequence of the increasing difference in travel time and moveout between the different phases. Hence, refraction and wide-angle seismic reflection data are considered as most suitable for imaging LVL sub-trappean Mesozoic sediments hidden below the HVL basalts/traps. On the other hand, conventional seismic reflection data acquisition techniques adopted by the oil industries failed to image the Mesozoic sediments hidden below the thick column of highly heterogeneous and rugose basalts due to poor penetration, absorption, and attenuation of seismic energy leading to poor data quality.

To obtain a highly pragmatic subsurface image of the sediments and other geological structures like volcanic plugs, horst and grabens, faults, synclines and anticlines etc., the high-precision Bouguer gravity maps also played an important role for hydrocarbon exploration (NGRI, 1998, 2000, 2003; Singh, 2007; Singh and Arora, 2008; Nagaswar Rao et al., 2013). Since our interest is mainly hydrocarbon exploration with delineation of shallow sub-surface geological structures, hence the regional gravity anomaly component due to deep seated density heterogeneities are removed from the observed Bouguer gravity anomalies. The resulting residual Bouguer gravity anomaly map of the DVP is shown in Figure. 2. The map provides an insight about the presence of thick sediments hidden below the Deccan trap, which are of significant interest for hydrocarbon exploration in these regions of Kutch, Saurashtra and Deccan Syneclise of India. The density models from inversion of residual Bouguer gravity anomaly data and the corresponding velocity models obtained from seismic studies decipher the shallow subsurface geological targets of interest in the study region.

The main objective of the study is to image low-velocity sub- or intra-trappean Mesozoic sediments hidden below thick columns of high-velocity basalts in the DVP using selected long-offset CDP and refraction/wide-angle seismic reflection profiles (Fig. 1). We employed robust ray-trace inversion, tomography and seismic imaging techniques along these selected seismic profiles as well as analysis of Bouguer gravity anomaly map (Fig. 2) for integration of corresponding velocity and density models. This provides an assessment of the presence and extension of hydrocarbon bearing Mesozoic sediments hidden below the Deccan trap.

GEOLOGY AND TECTONIC SETTINGS

The DVP of India consisting of Kutch, Saurashtra and Deccan Syneclise region bears complex geology and tectonic settings with wide-spread tholeiitic lava flows (basalts), the Deccan traps (Fig. 1). The Kutch sedimentary basin is an E-W oriented Mesozoic rift basin bounded by the Nagar Parkar Fault (NPF) in the north and Kathiawar Uplift (KU) toward south (Fig. 1) forming a pericratonic continental margin basin (Fig. 1). The Kutch basin has deposition of sediments from middle Jurassic to Holocene. The major sedimentation in the basin took place during the Mesozoic in early rift phase followed by Tertiary sediments (Biswas, 1987). The Mesozoic (middle Jurassic to early Cretaceous) sediments are widely exposed in the central uplifted highland areas known as Kutch Mainland Uplift (KMU) of the Kutch basin (Fig. 1), whereas Tertiary sediments are present in the low-lands bordering coastal plains in the Rann of Kutch. Deccan traps of late Cretaceous separate the Mesozoic and Tertiary sedimentary stratigraphy of Kutch in the north and south. The Deccan traps are largely restricted in southern part of the Kutch mainland, gradually thinning toward north and absent in the outcropping areas farther north toward NPF (Fig. 1). The important structural features of the Kutch basin are a group of E-W trending uplifts like KMU surrounded by depressions like Great Rann of Kutch and Banni basin in the north and Gulf of Kutch in the south. The major uplifts are bounded by faults forming the Kutch rift basin. The KMU is controlled by major E-W structural faults like Kutch Mainland Fault (KMF) and North Wagad Fault (NWF) in the north whereas Katrol Hill Fault (KHF) is located in the central part (Fig. 1). These faults cut through the Mesozoic sediments in this region and play an important role in the geomorphic evolution of the Kutch sedimentary basin (Biswas, 1987). Similarly Island Belt Fault (IBF) and Allah Bund Fault (ABF) to the north are E-W trending. The KMF, on the other hand, extends about 100 km in NW-SE orientation in the western part of the Kutch basin changing to E-W in the central part. The Kutch basin is considered as a Mesozoic sedimentary basin with thick accumulation of late Triassic to lower Cretaceous sediments of ~3.0 km (Biswas, 1987). Sediments were deposited within sheltered gulf in a sub-littoral to deltaic environments in two major cycles: middle Jurassic transgressive and late Jurassic-early Cretaceous regressive cycles (Biswas, 1981). During the transgressive cycle, mainly carbonates and shales were deposited, while deltaic clastics constitute the regressive deposit. Sediments were laid down on a Precambrian granitic basement exposed only in the NPF bordering the northern flank of the graben (Fig. 1).

The Saurashtra basin located in the north-western margin of the Indian shield forms a horst block between three intersecting rifts namely Kutch, Cambay and Narmada (Biswas, 1987). The major portion of this basin is occupied with Deccan basalts with lower Cretaceous sediments exposed in the north-eastern part (Fig. 1). A broad domal topographic rise in the central part of it is represented by the Mesozoic outcrop. The eastern fringe of Saurashtra is a low-land interspersed with marshy lakes. The coastal plains fringing the trappean highland comprise a Cenozoic cover consisting of Tertiary and Quaternary sediments. The general stratigraphy of the Saurashtra basin consists of Precambrian basement overlain by Mesozoic sediments followed by Deccan trap basalts with a top cover of thin Neogene and Quaternary sediments. The Deccan trap lava flows in the Saurashtra region (Fig. 1) are of tholeiitic type with several intrusions of acidic, alkaline and mafic/ultramafic plugs, the major ones being Girnar, Osham, Barda, Alech in the western part and Vallabhipur, Palitana and Rajula in the south-eastern part (Merh, 1995).

The Deccan Syneclise region is mainly confined by the Narmada and Tapti river basins in the western part of central India. The Archaean-Neoproterozoic granite gneiss and Palaeo-Mesoproterozoic Dehli/ Aravalli supergroup rocks are exposed to the north, the Meso-Neoproterozoic Vindhyan sediments to the east and the Cambay sedimentary basin to the west. Most of the subsurface geological features are obscured because of the exposed Deccan basalts (Fig. 1), and became a major challenge for the hydrocarbon exploration. This region is also topographically highly variable with the presence of hillocks and valleys confined by three major rivers (Narmada, Tapti

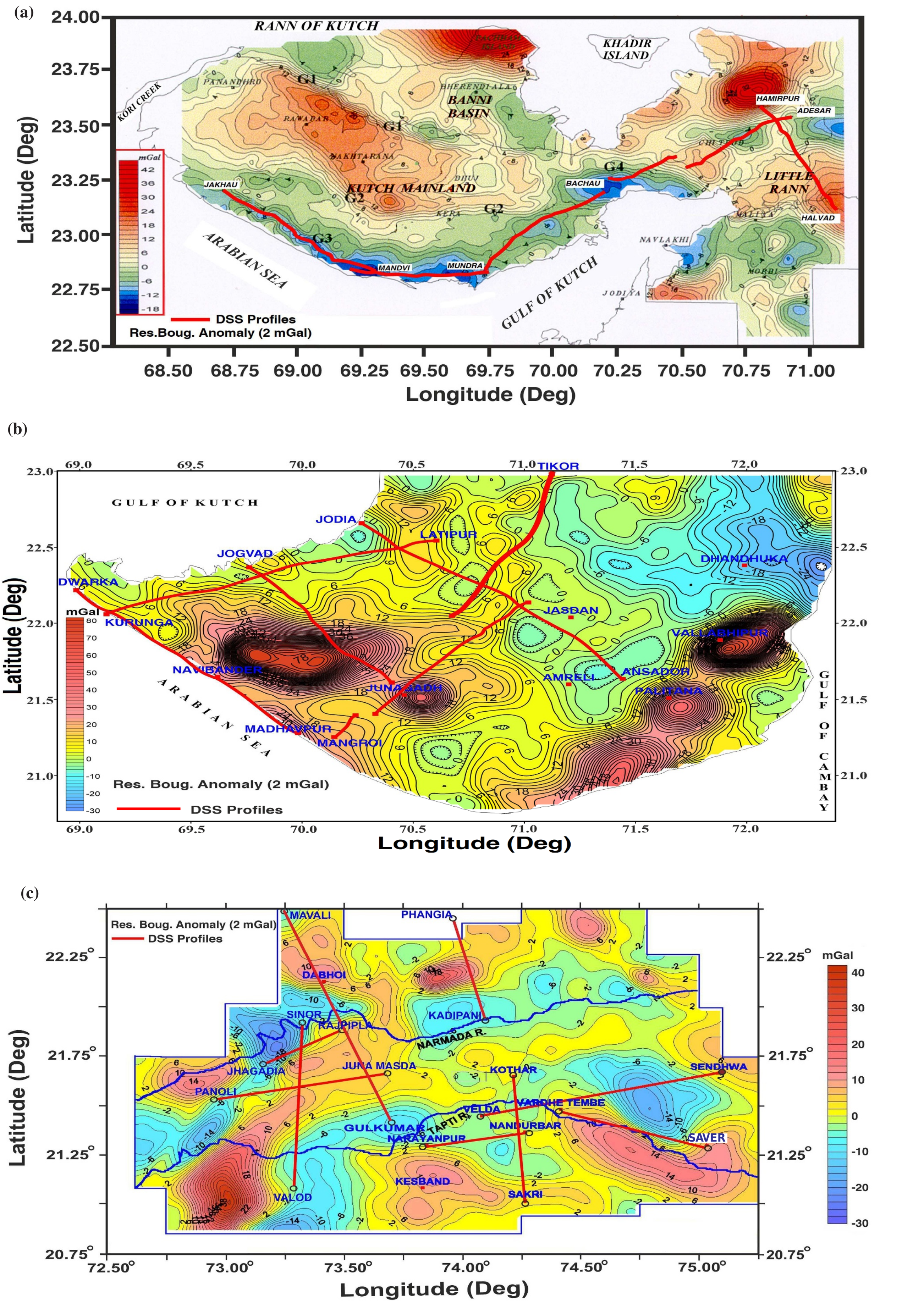

Fig.2. The residual Bouguer gravity anomaly maps of **(a)** Kutch, **(b)** Saurashtra and **(c)** Deccan Syneclise regions of India are shown with corresponding DSS profiles (red lines) executed superimposed on these maps. (Modified after NGRI, 1998, 2000, 2003).

and Mahi) flowing toward west and meeting the Arabian Sea (Fig. 1). The Deccan basalts or traps were also encountered at varying depths below the Tertiary sediments ranging in age from the Palaeocene to Recent as confirmed by drilling in the Cambay basin (Roy, 1991; Tewari et al., 1995; Dixit et al., 2010). Upper Jurassic to middle Cretaceous Bagh and Lameta beds representing the Mesozoic sediments underlain by the Deccan traps are exposed to the east of the Cambay basin near Rajpipla (Fig. 1). The presence of sporadic outcrops of the Jurassic and Cretaceous sediments on the margins of the Cambay basin leads to the possibility of a thicker marine sequence within the basin below the Deccan traps. The centre of volcanic eruption mainly confined near the west-coast of India with major, rapid and short duration eruptive phases in the Western Ghats, which might have lasted for 1.0-0.5 Ma (Courtillot et al., 1988; Duncan and Pyle, 1988) with a report of very short-lived intense volcanism at Cretaceous-Tertiary (K-T) boundary (Allegre et al., 1999). The hydrocarbon bearing Mesozoic sediments hidden below the Deccan trap, which corresponds to Bagh and Lameta beds/formations are exposed near east of Sinor in the Cambay basin (Fig. 1). The presence of sporadic outcrops of Jurassic and Cretaceous sediments on the margins of the Cambay basin leads to the possibility of a thicker sequence of marine sediments deposited within the basin below the Deccan trap. The whole province might have covered more than 1.5×10^6 km^2 of basalt with inclusion of correlative lava flows in the offshore, Arabian Sea (Courtillot et al., 1986). Several evidences indicate that most of the basaltic lavas were erupted rapidly. Recent ^{40}Ar–^{39}Ar incremental heating ages show that the Deccan volcanism has occurred within 65-69 Ma and the ~2 km thick Western Ghats section was erupted in less than 2 Ma (Duncan and Pyle, 1988). Taking into consideration all the evidences for duration of volcanism, most of the Deccan basalts accumulated within 0.5 Ma. Hence, the average eruption rate could have been approximately 1 km^3/year with several episodes of eruptions separated by period of non-depositions (unconformities) with total duration of the volcanism span within 3 Ma (Kono, 1973).

SEISMIC IMAGING OF DECCAN VOLCANIC PROVINCE

The ubiquitous and widespread cover of Deccan traps in the Kutch, Saurashtra and Deccan Syneclise region of India creates significant hindrances for imaging of Mesozoic sediments hidden below the basalts. The conventional seismic reflection method fails to image the low-velocity sediments below the basalts due to poor penetration, scattering, absorption, generation of multiples, attenuation and mode-conversions generally caused at the highly rugose top basalt leading to significant loss of seismic energy in the near-offset range. However, the refraction/wide-angle seismic reflection and long-offset coincident seismic reflection (CDP) methods mainly used in crustal studies play pivotal role and became an excellent substitute of the conventional seismic reflection methods for sub-basalt imaging. This has been successful in India and other basalt covered regions of the world due to good penetration of seismic energy in the wide-angle range and significant build-up of seismic wave amplitudes beyond the critical distance due to total internal reflection. The first-arriving seismic energies (direct and refracted waves) beyond the critical distance are not contaminated with multiples or other strong amplitude phases developed due to scattering. The travel time skips in the seismic data at certain offsets indicate the presence of LVL lie below the HVL (e.g., Greenhalgh, 1977; Whiteley and Greenhalgh, 1979). The large aperture also enables refracted arrivals from different subsurface layers, which are usually muted out in conventional seismic data processing, but retained in the wide-angle seismic data. They carry considerable information on the velocity structure, particularly of the basalt and the basement, which are crucial for travel time tomography. Wide-angle seismic data have been used to obtain a well constrained tomography image in different parts of India (Behera, 2011; Behera and Sarkar, 2011; Behera and Sen, 2014). To numerically simulate the presence of travel time skips in the seismic data, both synthetic and real data examples for different models are demonstrated in Figure. 3. The results of ray-trace inversion show (i) presence of LVL (4.0 km/s) corresponding to Mesozoic sediments hidden below the HVL (5.0 km/s) of basalts, (ii) conventional increase of velocity lie below LVL (4.0 km/s) of Mesozoic sediments. The basement with velocity 6.0 km/s is the bottom most layer for all the three models (Fig. 3). This study provides a clear insight of the presence of travel time skips in the synthetic and observed data (Fig. 3). Corresponding synthetic seismograms/responses generated at the long-offset range in the first (Fig. 3(i)) and third (Fig. 3(iii)) velocity models having LVL (e.g., Mesozoic sediments) hidden below the HVL (e.g., basalts/traps), as compared to no travel time skip observed in the second velocity model (Fig. 3(ii)), where the velocity increases with depth. The modeled refraction (P_i) and wide-angle reflection (P^i) phases are marked on the corresponding synthetic and observed seismic data (Fig. 3), where sub- or super-script of P indicates the respective layer numbers (1, 2, 3) or the corresponding velocity value (4.0 km/s) of each layer. The results are obtained from the ray-trace inversion of wide-angle travel time data generated from these 2D velocity models. Similar situation exists for other sub-surface geological models in the DVP, where LVL (e.g., Mesozoic sediments) is hidden below the HVL (e.g., basalts/traps). Several refraction/wide-angle seismic reflection and long-offset CDP seismic reflection profiles are carried out during last three decades (Fig. 1) with an aim of imaging sub-trappean Mesozoic sediments hidden below the Deccan traps for hydrocarbon exploration pursuit (NGRI, 1998, 2000, 2003, 2009).

Kutch Basin

The 2D long-offset CDP seismic reflection data acquired by CSIR-NGRI (Behera et al., 2011) along the profile AB in the onshore part of the Kutch sedimentary basin close to ABF and IBF (Fig. 1c). This profile is used for imaging Mesozoic sediments hidden below the basalt. Conventional seismic data processing method (Yilmaz, 2001) could not provide a better seismic image in this region due to low signal-to-noise ratio in the narrow angle range. However, with the help of non-hyperbolic moveout in the long-offset range by accommodating fourth-order term in the anisotropic velocity analysis and without muting the long-offset data (Behera et al., 2011), it is possible to image thick (0.5-1.0 km) column of southeast dipping hydrocarbon bearing sub-trappean Mesozoic sediments hidden below the basalts in the Kutch basin (Fig. 4a). The prominent geological structures like synclines, anticlines, faults (zoomed) favorable for hydrocarbon accumulation are imaged along the profile AB (Fig. 4a). The different layers with steep dipping basement and presence of shallow geological structures indicate a complex geological setting of the Kutch rift basin. The fault imaged (zoomed) in Figure 4(a) may be considered as extension of IBF (Fig. 1c), which may act as the potential site for hydrocarbon reservoir with presence of maximum thickness of the Mesozoic sediments imaged. On the other hand reflections below the syncline (zoomed in Fig. 4a) are not coherent due to basement upwarping, which resulted diffused reflectivity in the seismic image. This indicates hydrocarbon accumulation could be disrupted in this segment of the profile, although syncline and anticline structures are imaged towards left of the seismic section AB with thinning of the Mesozoic sediments due to basement upwarping.

The seismic refraction and wide-angle seismic reflection data acquired in the Kutch basin along Jakhau-Mandvi, Mandvi-Mundra, Mundra-Adesar and Hamirpur-Halvad seismic profiles (Fig. 1c) are modeled (NGRI, 2000). It has subsequently been reprocessed by Prasad et al. (2010). The presence of travel time skips in shot gather SP5 (Fig. 4b) is much clear and modeled along Jakhau-Mandvi profile. The first layer corresponds to the Tertiary sediments (2.0-2.2 km/s)

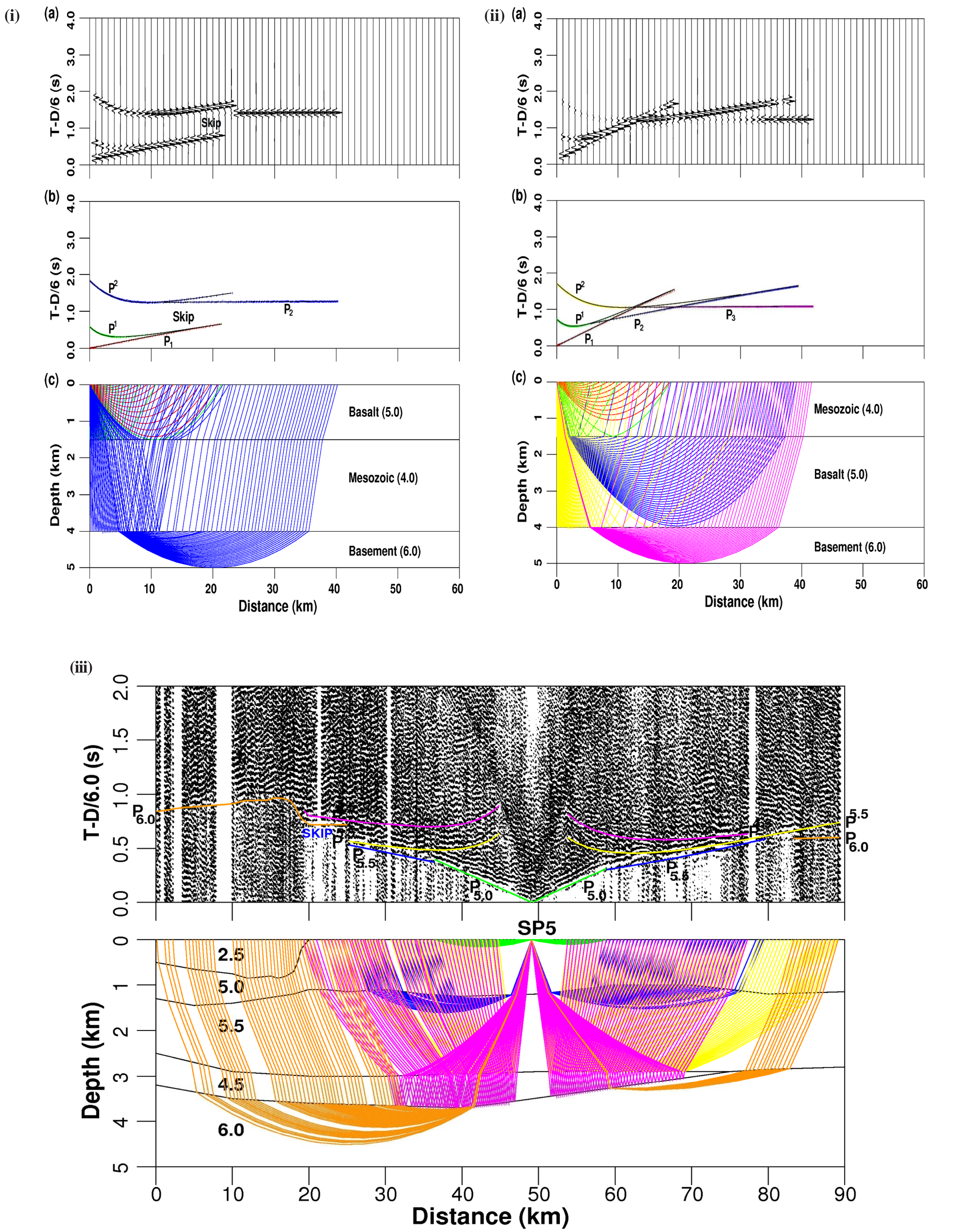

Fig.3. (i) Realistic experiment using ray-trace inversion to ascertain the presence of skips in the **(a)** synthetic seismic data and **(b)** travel time data generated from **(c)** a three layer velocity model having LVL Mesozoic sediments hidden below the HVL basalt lie above the basement. **(ii)** The same experiment show no travel time skip in (a) synthetic seismic data and **(b)** travel time data generated from **(c)** a three layer velocity model with increase of velocity with depth (i.e., no LVL lie below HVL). **(iii)** The presence of skip in the observed seismic data as an example (SP5) of the Deccan Syneclise region, modeled using same ray-trace inversion show LVL Mesozoic sediments lie below the HVL basalts (Behera and Sen, 2014). The data is plotted in reduced scale with reduction velocity 6.0 km/s.

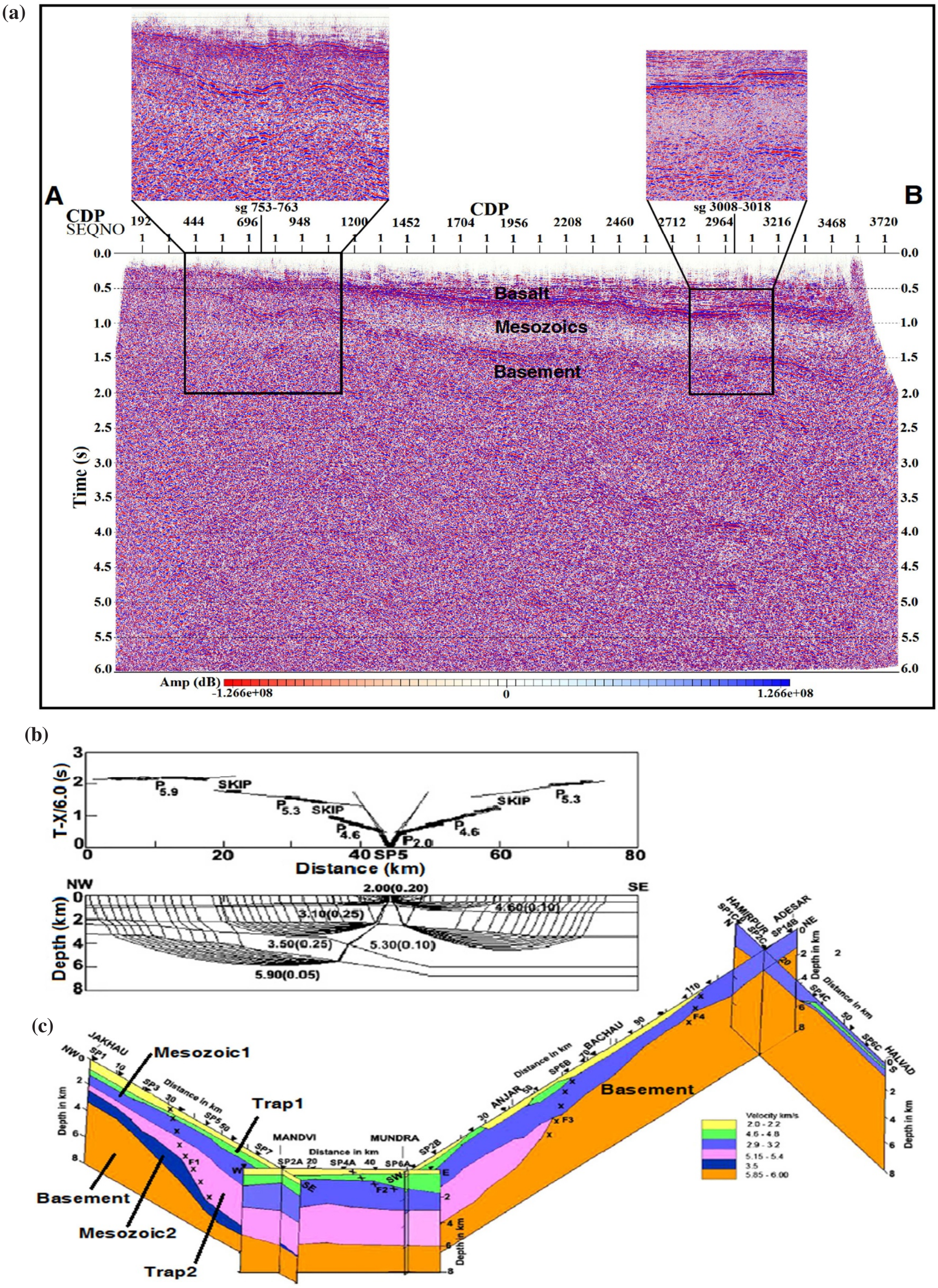

Fig.4. (a) The stack section using long-offset seismic data along the profile AB (Fig. 1) of the Kutch region is shown (Behera et al., 2011). The different structures imaged are zoomed and shown along with the layers of basalt, Mesozoic sediments and dipping basement. **(b)** The example wide-angle seismic data along the Jakhau-Mandvi seismic profile (Fig. 1) show traveltime skip indicates presence of LVL (Mesozoic sediments) below the HVL (basalts). **(c)** The corresponding velocity models obtained along four seismic profiles in the south of Kutch are represented as a fence diagram showing traps, Mesozoics, basement configuration along with deep basinal faults F1, F2, F3 forming large graben structure in the Kutch basin (Prasad et al., 2010).

with a thickness of 0.8 km to 0.5 km from northwest to southeast underlain by the Deccan trap of velocity 4.6-4.8 km/s, which is thin (0.2 km) in the northwest and gradually thickened (0.7-0.9 km) toward southeast of the profile. Below the Deccan trap, first Mesozoic sequence (Mesozoic1) is imaged with velocity 2.9-3.2 km/s using travel time skips observed in different wide-angle SPs (Prasad et al., 2010), which is thickened from 0.95 km in northwest to 2.0 km in the southeast part. The second Mesozoic (Mesozoic2) sequence (3.5 km/s) is imaged below the high-velocity (5.15-5.4 km/s) layer considered as limestone (Pandey et al., 2009), which is thin (0.4 km) in the northwest and thickened (2.4-2.6 km) along the southeast part of the profile. The Mesozoic2 layer is gradually thinning from southeast to northwest

(1.0 km to 0.5 km) and thickened in the middle of the profile (2.0 km) forming a ramp like structure as deep basinal fault overlying the basement (5.8-6.0 km/s). The modeling results along all the four seismic refraction profiles have been presented in the form of a fence diagram (Fig. 4c), which delineate shallow velocity layers with basement configuration in the southern part of the Kutch basin. The presence and extension of the LVL (3.2 - 3.5 km/s) corresponding to the Mesozoic sediments, hidden below the HVL (4.8 - 5.4 km/s) (e.g., basalts) are prominent along the Jakhau-Mandvi and Mandvi-Mundra profiles. Along Mundra-Adesar profile, these sediments are well exposed along the Hamirpur-Halvad sub profile. The thick (2-3 km) Mesozoic sediments with basement (6.0 km/s) depression in the Mandvi-Mundra-Anjar segment (Fig. 4c) form a large graben structure controlled by deep basinal faults (F1, F2 and F3), which can be considered as the major hydrocarbon potential zone in the Kutch basin.

Saurashtra Basin

Saurashtra basin is well covered with five refraction/wide-angle seismic reflection profiles along Jodia-Ansador, Tikor-Mangrol, Jogvad-Junagadh, Kurunga-Latipur and Dwarka-Madhavpur (Fig. 1b) during 1994-1996 by the CSIR-NGRI for exploration of sub-trappean Mesozoic sediments using integrated geophysical studies (NGRI, 1998). The ray-trace inversion (Zelt and Smith, 1992) of first-arrival travel time data of the 180-km long NW-SE Jodia-Ansador profile (Fig. 1b) identified LVL (4.3 km/s) sediments below the HVL (5.0-5.2 km/s) (Fig. 5a). The surface exposure of lower Cretaceous Dhrangdhara sandstones (Mesozoics) and borehole lithology of Lodhika-I and Dhanduka near the profile (Fig. 1b) indicate these sediments may be extended below the Deccan traps (Sarma et al., 1992; Singh et al., 1997). Thick Mesozoic sediments (1.5 km) of LVL (4.3 km/s) are imaged below the thin (0.5 km) HVL (5.0-5.2 km/s) basalts (Fig. 5b) underlain by the basement (5.9 km/s) along this profile. Towards Ansador along the southeast part of the profile, on the other hand, thin (0.2-0.5 km) basaltic trap (5.5 km/s) below the Mesozoic sediments underlain by the steeply dipping basement. The thickness of the top basalt is 1.5 km near to Ansador as compared to corresponding thinning (0.5 km) near Jodia along the northwest part of the profile. The velocity and thickness of the basaltic traps and the Mesozoic sediments imaged along the profile are constrained from the travel time skips observed from different SPs (Fig. 5a), which closely correlate with the results obtained from a small seismic refraction profile (Fig. 1b) cutting across the Lodhika-I exploratory well (Dixit et al., 2000; Sain et al., 2002). The basement is highly undulated showing gradual dipping along Jodia and steeply dipping near Ansador with significant upwarping in the middle part of the profile between SP11 to SP16 (Fig. 5b). The upwarping of basement may be attributed to upwelling caused by the volcanic plugs/dykes in this region. The velocity model (Fig. 5b) is derived based on the rays traced from all the shot points (SP1 to SP21) along the profile (Fig. 1b) with minimum RMS residual (0.042 s) between the observed data and computed responses having chi-square (χ^2) value close to one (1.08) with a fairly good ray coverage (Fig. 5a). The velocity-depth sections built for four seismic profiles including the Jodia-Ansador profile are shown as a fence diagram (Fig. 5c) depicting nature and extension of Tertiary sediments, basalts/traps, Mesozoic sediments and basement configuration. In general, the P-wave velocity within the trap is found to be 4.6-5.0 km/s for trap1 and 5.0-5.5 km/s as trap2 corresponding to two flows of Deccan volcanic. The trap2 delineated is confined only along the Jodia-Ansador profile in the southeast segment as steeply dipping intrusive. The Mesozoic sediments (3.2-4.0 km/s) delineated along all the four profiles (Fig. 5c) show thickening towards the northern part and gradual thinning in the southern part of the Saurashtra peninsula. The basement

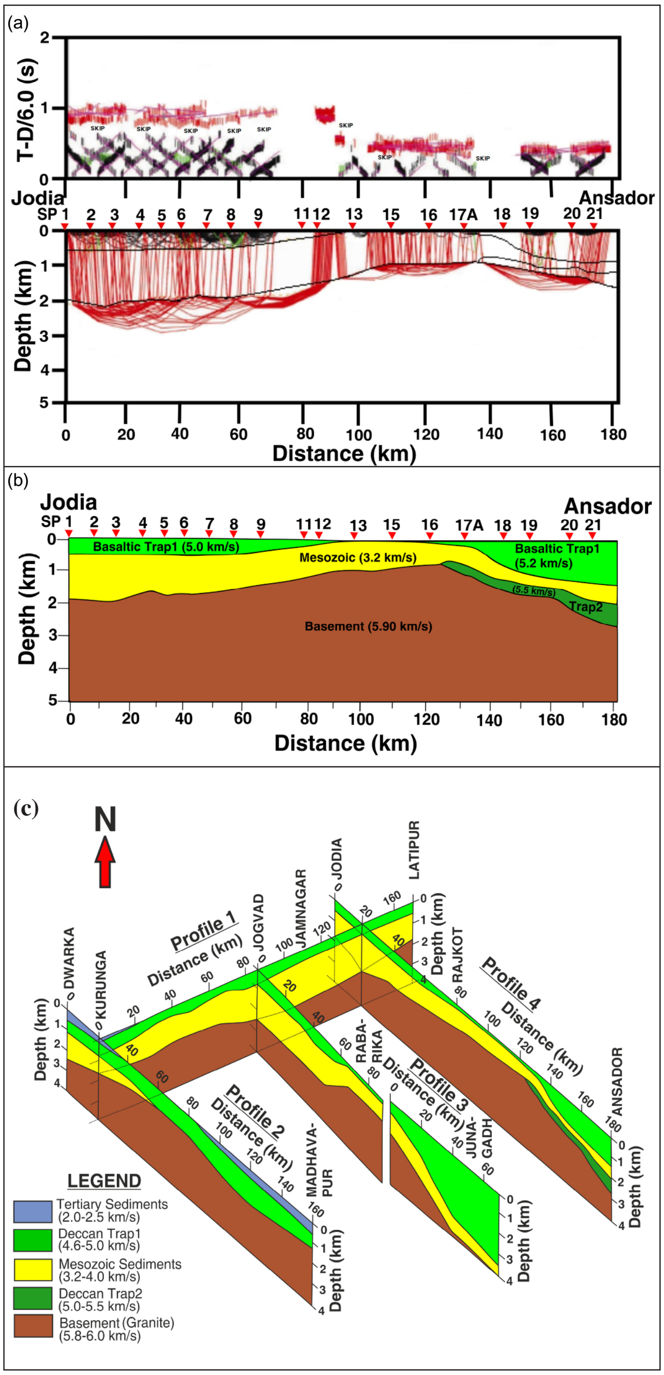

Fig. 5. (a) Ray-trace inversion (bottom), corresponding travel time fit (top) of the observed data (vertical bars) and synthetic response (pink line) from the derived velocity model **(b)** along Jodia-Ansador seismic profile. The travel time skips are marked on the observed data (a), which are plotted in reduced scale with reduction velocity 6.0 km/s. The velocity model (b) shows the presence of thick LVL (3.2 km/s) corresponding to the Mesozoic sediments lie below the HVL (5.0-5.2 km/s) of basalt as Trap1. Another layer of dipping intrusive as Trap2 (5.5 km/s) is underlain by the Mesozoic sediment overlying the basement (5.9 km/s) toward Ansador. The basement is dipping both sides of the profile with significant upwarping in the middle between 90-125 km profile distance. **(c)** The fence diagram show the overall depth-velocity structures obtained from inversion of refraction and wide-angle seismic reflection data covering four seismic profiles including the Jodia-Ansador profile results (b) indicate presence of thick (3 km) sub-trappean Mesozoic sediments in the Dwarka and Jamnagar basins of Saurashtra peninsula. (Modified after NGRI, 1998).

(5.8-6.0 km/s) is highly undulated forming horst and graben structures. In building up the velocity-depth sections as fence diagram (Fig. 5c), the litholog and velocity information available from deep borehole at Lodhika (Fig. 1b) is used. The velocity model along Jodia-Ansador profile shows basement uplift in the southeast of Rajkot and a significantly different subsurface structure in the southeast and northwest of Rajkot. The progressive increase of trap thickness towards Ansador from 0.2-3.0 km along 120-180 km profile distance (Fig. 5b and 5c) has inhibited any categorical identification of sub-trappean Mesozoic sediments in this region. The data suggests possibility of a mixed sediment-volcanic layer at the lower part of the trap or presence of a thin sedimentary column sandwiched between two layers of the traps (e.g., trap1 and trap2) forming a wedge structure (Fig. 5c). The velocity-depth section along Jogvad-Junagadh profile indicates once again a distinct structural variation between the regions northeast and southeast of Rabarika. The basement uplift at Rabarika along this profile and also the one near Porbandar along Dwarka-Madhavapur profile could be attributed to an upwelling introduced by prominent dykes. The Kurunga-Latipur profile show presence of thick (2-3 km) sub-trappean Mesozoic sediments with thickest (3.0 km) column closer to Dwarka, in and around Jamnagar and Jodia, which suggest that the northwest part of Saurashtra could be considered as an important zone of hydrocarbon prospect, which need further detailed investigations (Fig. 5c). The detail descriptions of the presence and extension of sub-trappean Mesozoic sediments, basalts/traps and basement configuration along these five profiles (Fig. 1b) in the Saurashtra peninsula are discussed with two different fence diagrams (NGRI, 1998). The fence diagrams built using all the five profiles decipher the velocity and thickness of different layer structures, which has provided useful input for integration of overall results (NGRI, 1998).

Deccan Syneclise

The Deccan Syneclise region of central India is covered with eight refraction/wide-angle seismic reflection profiles (Fig. 1d) executed by the CSIR-NGRI in the Narmada-Tapti region of the DVP with the help of integrated geophysical method (NGRI, 2003). The extension of Mesozoic sediments in the Deccan Syneclise is difficult to ascertain because of the presence of thick column of Deccan basalts/traps (Fig. 1). A robust tomographic imaging of refraction/wide-angle seismic reflection data is carried out by Behera et al. (2014) to image the sub-trappean Mesozoic sediments along the 90-km long Sinor-Valod seismic profile (Fig. 6). It successfully imaged the presence of thin (<0.75 km) LVL Mesozoic sediments (4.3-4.5 km/s) forming a pinchout structure toward Valod underlain by the basement (5.9-6.1 km/s). The thick (2-3 km) column of HVL basalts (5.0-5.5 km/s) imaged along the profile lie above the Mesozoic sediments correspond to different flows of Deccan lava. These lava flows are spreaded laterally all along the profile forming traps and exposed at some places on the surface as dykes. The velocity variation contours are shown for different small scale geological structures (Fig. 6c), which could not be imaged by conventional velocity modeling using ray-trace inversion (Fig. 6a). A large graben structure imaged extending from 0 to 20 km in the north, called Narmada graben with thick (~1.0 km) Quaternary and Tertiary sediments (2.5 km/s). Another small graben structure (70 to 75 km) imaged to the south, called the Tapti graben, which is devoid of sediment deposits as observed in the tomographic imaging (Fig. 6c). These two grabens are formed due to flow of Narmada and Tapti rivers in this region (Fig. 1). Presence of alternate horst and graben with basement undulations and Mesozoic sediments below the Deccan trap are imaged in this region (Fig. 6c and 6d). The tomography velocity model along the Sinor-Valod profile is well constrained (Fig. 6c) using a starting velocity model (Fig. 6b). The starting velocity model is obtained from the preferred velocity model (Fig. 6a) derived

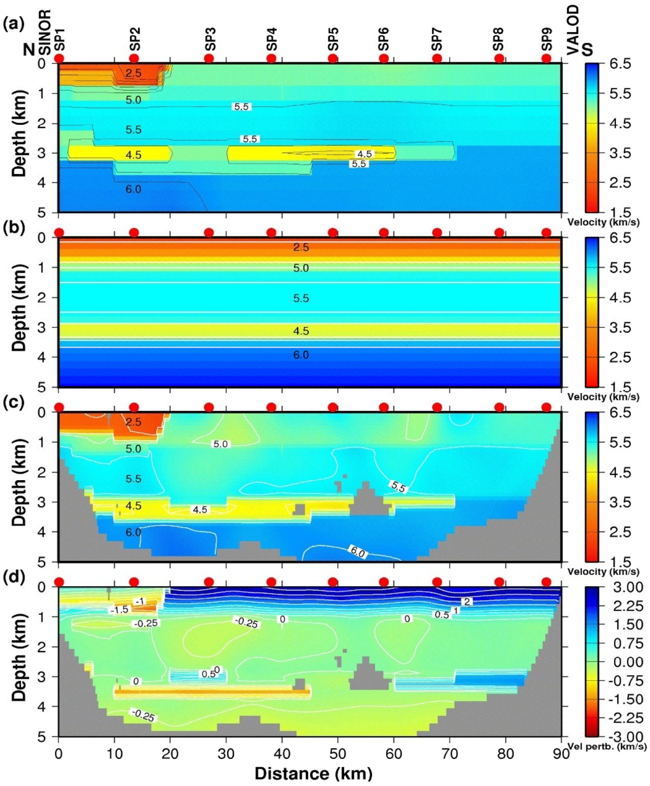

Fig.6. (a) The preferred velocity model derived along Sinor-Valod seismic profile in the Deccan Syneclise region (Fig. 1) using ray-trace inversion of refraction/wide-angle seismic reflection data. **(b)** Starting velocity model obtained by smoothing the velocities of different layers in the preferred velocity model (a) used for the first arrival-travel time tomography. **(c)** The tomographic velocity model derived from the first-arrival travel time data along the Sinor-Valod profile. **(d)** Velocity perturbation obtained along same profile. The regions not sampled by rays in the tomographic velocity model and velocity perturbation plot are left blank. The SP locations (red dots) and the colour scale with contours shown for each plot indicate the nature of velocity variations (5.0 km/s) or the velocity perturbations (0.5 km/s) along the profile (Behera and Sen, 2014).

from the ray-trace inversion of wide-angle seismic data along the Sinor-Valod profile (Behera and Sen, 2014). The ray-trace inversion through the preferred velocity model is shown for an example shot gather SP5 in Figure 3(iii). For tomographic inversion, the model is defined on a uniform 0.25 km grid extending from 0 to 90 km in the x-direction and 0 to 5 km in the z-direction for all forward calculations. A 0.5 km lateral and 0.25 km vertical cell size was used in the inverse step, which is twice the horizontal and equal to the vertical forward node spacing, resulting 3600 independent model parameters. A suitable cell size is one that allows the required data fit with a normalized misfit of 1.0 (Zelt, 1999). The tomographic velocity model (Fig. 6c) is able to image both small- and large-scale subsurface geological structures, which correlate with the preferred velocity model (Fig. 6a). The lateral and vertical extensions of the basalt flows are prominent in the tomographic image (Fig. 6c) as well as in the velocity perturbation (Fig. 6d). The large positive velocity perturbation (+3.0 km/s) within the 20-90 km distance extending from 0 to 1 km depth indicates that the high-velocity (5.0 km/s) basalts are almost exposed on the surface and devoid of any sediments on the surface forming the first flow of the Deccan trap. Subsequently, there is a second large flow of thick basalts (1.5 km) and increase in velocity (5.5 km/s) as compared to the first flow. On the contrary, toward Sinor there is a large negative velocity perturbation of -1.5 km/s within 0-20 km distance representing

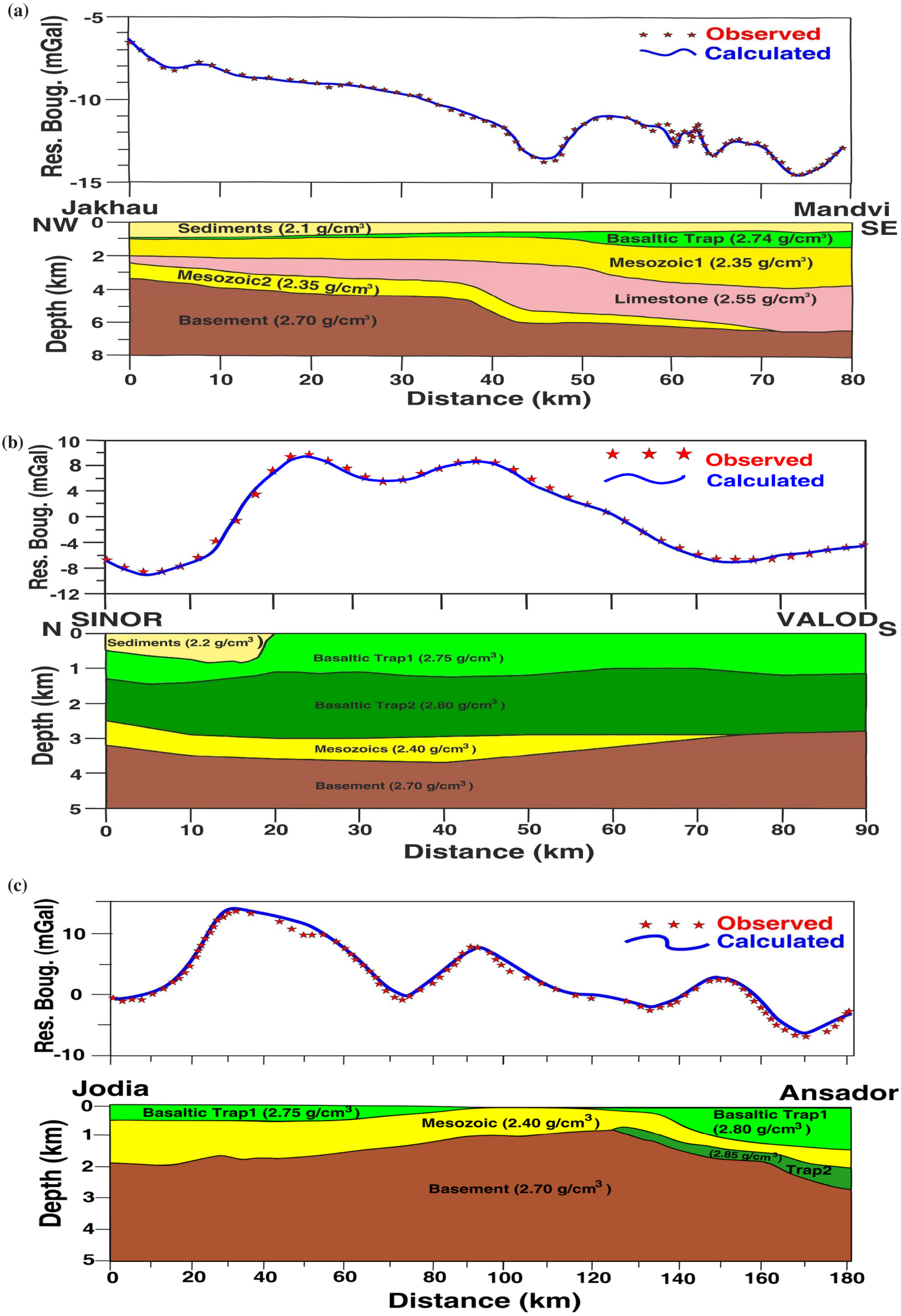

Fig.7. The density models derived using residual Bouguer gravity anomaly data along **(a)** Jakhau-Madvi, **(b)** Jodia-Ansador and **(c)** Sinor-Valod seismic profiles in the Kutch, Saurashtra and Deccan Syneclise regions respectively. The observed residual Bouguer gravity anomaly data (red stars) are superimposed by the corresponding calculated gravity responses (blue lines) obtained from the gravity inversion using the velocity models (Figs. 4-6) along these profiles for velocity-to-density conversions (Table 1) keeping the same interface structures of the derived velocity models. The corresponding final density values for each layer are marked (2.7 g/cm^3) in the respective density models derived with optimum fit of the observed and computed residual Bouguer gravity anomaly data along the three selected profiles in the different study regions of the DVP (Fig. 2).

the presence of thick sediments forming a graben structure and clear demarcation of sediment-basalt contact by the deep basinal fault at 18-20 km distance. The velocity perturbations in the deeper part from 1 to 5 km depth show both positive and negative perturbations (±0.5 km/s) (Fig. 6d) that reveal some of the structures not apparent in Fig. 6a or in Fig. 6c. The length-scales of the perturbations are a function of the resolution provided by the data, and reveal the subsurface geological structures. The presence of Mesozoic sediments imaged could be potential for hydrocarbon accumulation in this region, because the Cambay basin oil field is located to the west of this profile (Fig. 1d).

Table 1. Average density values of different rocks in the DVP obtained from velocity-density relationships (Barton, 1986; Brocher, 2005)

Rock types	Velocity (V_p) in km/s	Density (ρ) in g/cm^3
Sandstones	2.0-4.5	1.95 - 2.45
Shales	1.8-4.0	1.85- 2.38
Limestones	4.0-5.4	2.38-2.55
Basalts/Volcanics	5.0-5.5	2.74-2.90
Granites	5.8-6.0	2.67-2.70

GRAVITY MODELING OF DECCAN VOLCANIC PROVINCE

The shallow velocity models derived along different seismic profiles (Figs. 3-6) for imaging sub-trappean Mesozoic sediments and basement configuration in the DVP (Fig.1) can further be constrained using residual Bouguer gravity anomaly data of this region (Fig. 2). The residual Bouguer gravity anomaly maps of the Kutch, Saurashtra and Deccan Syneclise region (Fig. 2) are derived from the Bouguer gravity anomaly maps (NGRI, 2006) after removing the isostatic regional component corresponding to near zero free-air anomalies (Subba Rao, 1996) so as to depict the shallow subsurface geological structures in these sedimentary basins. The residual Bouguer gravity anomaly maps (Fig. 2) show prominent gravity highs and lows as well as linear gravity trends corresponding to horsts, grabens and faults or lineaments in these regions of DVP. To obtain a better constrain of the shallow velocity models along the selected refraction/wide-angle seismic reflection profiles of Jakhau-Mandvi, Jodia-Ansador and Sinor-Valod in the Kutch, Saurashtra and Deccan Syneclise regions respectively (Figs. 1 and 2), we have derived the corresponding density models along these seismic profiles using the residual Bouguer gravity anomaly maps (Fig. 2).

Density structure derived from the modeling of gravity data is invariably non-unique due to the fact that different sub-surface density distributions provide the same gravity responses. To ameliorate the density and sub-surface geological structure of the causative bodies, which are the two critical parameters that govern the inherent non-uniqueness in the gravity modeling, it is necessary to constrain the density model from the available seismic velocities or borehole lithology. Since the boreholes are very rare, the gravity modeling will make use of available seismic velocity structure to constrain the corresponding density model using Nafe-Drake curve and other empirical velocity-density relationships for velocity-to-density conversions of different rock types of subsurface Earth (Nafe-Drake, 1957; Ludwig et al., 1970; Barton, 1986; Behera et al., 2004; Brocher, 2005). The velocity and density values of different rock types prevalent in the DVP are shown in Table-1 used for velocity-to-density conversions while modeling the residual Bouguer gravity data.

The residual Bouguer gravity anomaly map of Kutch with 2 mGal contour intervals (Fig. 2a) show prominent gravity highs in the north as compared to gravity lows mainly confined along the southern coast, which is a direct indication of the presence of thick sediments toward south. The northern and southern borders of the central gravity high (G1 and G2) in the north and the south show sharp gradients indicating presence of horst structure with faulted margins. The other gravity gradients marked as G3 and G4 are also indicative of faults, which may represent basement uplift along north controlled by faults. The basement uplift between G1 and G2 may be due to a horst structure bounded by faults G1 and G2 or may represent a folded structure with an anticline between G1 and G2. To obtain clear insight of the shallow geological structures with an aim to image sub-trappean Mesozoic sediments in the Kutch basin, we have derived the density model (Fig. 7a) along the selected Jakhau-Mandvi seismic profile close to the southern coast constrained by the corresponding velocity model derived by Prasad et al. (2010). While obtaining the density model from the inversion of residual Bouguer gravity data (Fig. 2a), we keep the same interface structure of the velocity model derived along the Jakhau-Mandvi seismic profile (Prasad et al., 2010). The density values obtained from the corresponding velocity values (Table 1) are updated iteratively using the empirical relationship of Nafe and Drake (1957) and Ludwig et al. (1970). The layers at the edges of the model are extended to long distances to reduce the edge effects. The gravity inversion method of Nielsen and Jacobsen (2000) is used and the absolute density values of each block are updated automatically during inversion. An optimum fit of observed and computed response of residual Bouguer gravity anomaly with normalized χ^2 of 1.4 is obtained after twelve iterations. The final residual Bouguer gravity model is shown (Fig. 7a) with the corresponding average density values of each layer and optimum data fit having RMS residuals of observed and computed residual Bouguer gravity response of the order 1.6 mGal. The final density model show six layers with corresponding average density values of 2.10, 2.74, 2.35, 2.55, 2.35 and 2.70 g/cm^3 depicting top sedimentary cover of Tertiary sediments, basaltic Deccan trap, Mesozoic1 sediments, middle to late Jurassic limestones, Mesozoic2 and basement respectively, with deep basinal faults and basement upwarping along northwest segment of the profile (Fig. 7a). The two sequences of sub-trappean Mesozoic sediments imaged along the Jakhau-Mandvi profile from the integrated seismic and gravity modeling may bear fair chance of obtaining hydrocarbon reserve in this segment of Kutch basin.

The residual Bouguer gravity anomaly map of Saurashtra with 2 mGal contour intervals (Fig. 2b) show prominent concentric circular gravity highs corresponding to intrusive plugs of Deccan volcanism. It also depicts prominent gravity low along the northeast part of Saurashtra covering Jodia, Rajkot, Jasdan, Ansador and Dhanduka. This broad gravity low (Fig. 2b) may represent presence of a large sedimentary basin with thick sediments below the Deccan trap with an excellent exposure of Mesozoic sediments as Dhrangadhra sandstone along the northeast segment of Saurashtra peninsula (Fig. 1b). To obtain a clear insight of the shallow subsurface geological structures and delineate both vertical and lateral extent of the Mesozoic sediments hidden below the Deccan trap corroborating the seismic velocity model (Fig. 5b), we have derived the corresponding density model (Fig. 7b) along the 180-km long Jodia-Ansador seismic profile cutting across the broad gravity low in the northeast part of Saurashtra basin using the residual Bouguer gravity anomaly map of this region (Fig. 2b). To derive the density model along the Jodia-Ansador profile, same gravity inversion method of Nielsen and Jacobsen (2000) as mentioned above is used by conversion of corresponding velocity-to-density (Table-1) with the help of the empirical relationship of Nafe and Drake (1957) and Ludwig et al. (1970). The layers at the edges of the model are extended to long distances to reduce the edge effects while keeping the same interface structures of the derived velocity model (Fig. 5b). The absolute density values of each block are updated automatically during inversion so that an optimum fit of observed and computed response of residual Bouguer gravity anomaly with normalized χ^2 of 1.2 is obtained after ten iterations. The final residual Bouguer gravity model is shown with the corresponding average density values of each layer and optimum data fit having RMS residuals of 1.4 mGal between the observed and computed residual Bouguer gravity response. The final density model show four layers with corresponding average density values of 2.75-2.80, 2.40, 2.85 and 2.70 g/cm^3 depicting top basalt of Deccan trap, Mesozoic sediments, thin (0.3-0.8 km) basaltic intrusive along Ansador underlain by the basement with presence of deep basinal faults and basement upwarping having exposoures of Mesozoic sediments in the centre of the profile between 90-120 km distance. The Mesozoic sediments lie below the thick (2.0 km) cover of Deccan trap along Ansador may provide a good prognosis for hydrocarbon reservoir because of both top and bottom seals with presence of deep basinal faults (Fig. 7b). However, a very detailed study is necessary to provide a quantitative estimate of the hydrocarbon potential in this region.

The residual Bouguer gravity anomaly map of the Deccan Syneclise region with 2 mGal contour interval (Fig. 2c) show prominent large gravity lows in the western and eastern part with large gravity high in the southwest corner of the study region. There are prominent linear gravity gradients separating the highs and lows representing presence of alternate horst and graben features separated by deep basinal faults with thick sediment cover in the western and southeast part of the Deccan Syneclise region. Since the Mesozoic sediments of Bagh and Lameta beds are exposed near Rajpipla (Behera and Sen, 2014), the sub-surface extension of these sediments below the Deccan basalts are not ruled out. To validate this proposition, we choose the north-south trending 90-km long Sinor-Valod seismic profile (Fig. 1) to derive the corresponding density model (Fig. 7c) using the residual Bouguer gravity anomaly map of the study region (Fig. 2c). Same gravity inversion method of Nielsen and Jacobsen (2000) as mentioned above is used by conversion of corresponding velocity-to-density (Table 1) with the help of the empirical relationships of Nafe and Drake (1957) and Ludwig et al. (1970) to derive the shallow density model along the Sinor-Valod profile (Fig. 7c). We keep the same interface structure of the tomographic velocity model derived along the Sinor-Valod profile (Fig. 6c) by smoothing the different layers for corresponding ray-race inversion (Fig. 3 (iii)), which is used for obtaining the density model (Fig. 7c). The density values of different blocks are updated automatically during inversion to obtain optimum fit of observed and computed response of residual Bouguer gravity anomaly with normalized χ^2 of 1.12 after eight iterations. The final residual Bouguer gravity model is shown with the corresponding average density values of each layer with optimum data fit (Fig. 7c) having RMS residuals of observed and computed residual Bouguer gravity response of the order of 1.25 mGal. The final density model represent five layers with corresponding average density values of 2.20, 2.75, 2.80, 2.40 and 2.70 g/cm^3 depicting Tertiary sediments in the graben toward Sinor, basalts of Deccan trap1, basalts of Deccan trap2, sub-trappean Mesozoic sediments pinching out along Valod underlain by the basement respectively, with basement upwarping in the south of the profile between 75-90 km distance corroborating the derived velocity model (Fig. 6c). The Mesozoic sediments hidden below the basalts form the major hydrocarbon reservoir in this part of the Deccan Syneclise region, which is very close to the most prolific oil and gas producing Cambay basin of India.

CONCLUSION AND FUTURE PERSPECTIVES

The large extension and ubiquitous presence of Deccan trap in the DVP bears significant hindrances and masking for imaging hydrocarbon bearing Mesozoic sediments hidden below the basalts. However, the robust seismic imaging techniques using tomography, ray-trace inversion and advanced seismic data processing of long-offset CDP seismic reflection data and refraction/wide-angle seismic reflection data could able to image LVL Mesozoic sediments hidden below the HVL basalts in the DVP covering large span of Kutch, Saurashtra and Deccan Syneclise regions of India (Figs. 3-6). The important geological structures such as faults, synclines, anticlines and pinchouts are imaged toward the northeast part of the Kutch basin along the CDP seismic profile (Fig. 4a). It shows presence of maximum 1.0 km thick hydrocarbon-bearing Mesozoic sediments extending toward south of AB, which is dipping upward and pinching out toward north of the profile AB (Fig. 1c) with basement upwarping (Fig. 4a). The Jakhau-Mandi, Mandvi-Mundra and Mundra-Bachau segment of the seismic refraction and wide-angle reflection profiles in the southern part of Kutch basin also show promising potential for hydrocarbon reserve with thick (1-3 km) sub-trappean Mesozoic sediments (Mesozoic1 and Mesozoic2) deposited in a large graben structure confined by deep basinal faults F1, F2 and F3 with basement depression (> 5 km) as shown in the fence diagram of the velocity model (Fig. 4c) obtained in this region. The Jodia-Ansador seismic profile in the Saurashtra (Fig. 1b) also shows 0.5-1.5 km thick sub-trappean Mesozoic sediments (Fig. 5b) with plausible hydrocarbon reserve toward Ansador due to its entrapment by top and bottom basalts forming excellent seal with significant upwarping of the basement. The details of the layer thickness and velocity variations showing horsts and grabens, faults, Mesozoic sediments, basalts/traps and basement configuration constrained from all the five refraction and wide-angle reflection profiles were developed in the form of two fence diagrams (NGRI, 1998). The fence diagram covering four seismic profiles (Fig. 5c) including the Jodia-Ansador profile show significant results of the presence of thickest (3 km) sub-trappean Mesozoic sediments. This is suitable for hydrocarbon exploration in the Saurashtra peninsula covering two important basins such as Dwarka and Jamnagar basins (Fig. 5c), which provide useful input for integration of overall results. The Deccan Syneclise region (Fig. 1d) is infested by very thick trap cover, which poses major impediment for imaging Mesozoic sediments. But with the help of wide-angle seismic data and robust tomographic inversion approach, 0.75 km thick sub-trappean Mesozoic sediments are imaged below the 3.0 km thick Deccan trap cover along the Sinor-Valod profile, which forms a deep seated hydrocarbon reservoir in this region close to the Cambay basin (Fig. 6). Further, all the velocity models derived in the DVP are corroborated by the corresponding density models derived using residual Bouguer gravity anomaly data (Figs. 2 and 7), which vindicate the presence and extension of sub-trappean Mesozoic sediments hidden below the basalts forming excellent hydrocarbon bearing reservoirs in the Kutch, Saurashtra and Deccan Syneclise regions of India. However, more analysis of available geophysical (seismic, gravity, magnetic, magneto-telluric, deep-resistivity, well-logs) and geological data along with state-of-the-art advanced new data acquisition, processing and interpretation techniques of both geological and geophysical data with their integration can able to provide a quantitative assessment of the potential hydrocarbon bearing target zones of the hidden Mesozoic sediments in the DVP of India.

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