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Delineation of the Trap and sub-trappean sediments in Kutch, Deccan syneclise and Bengal basins-An analysis

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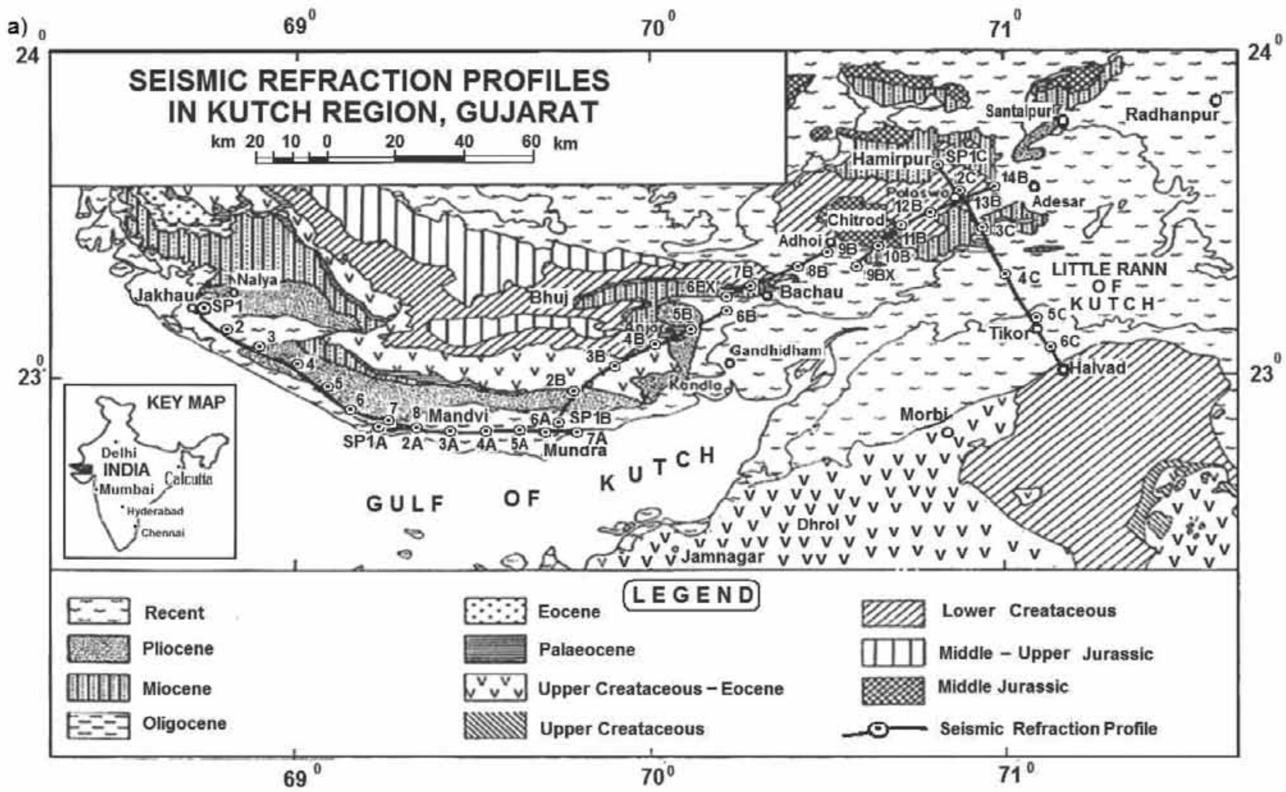
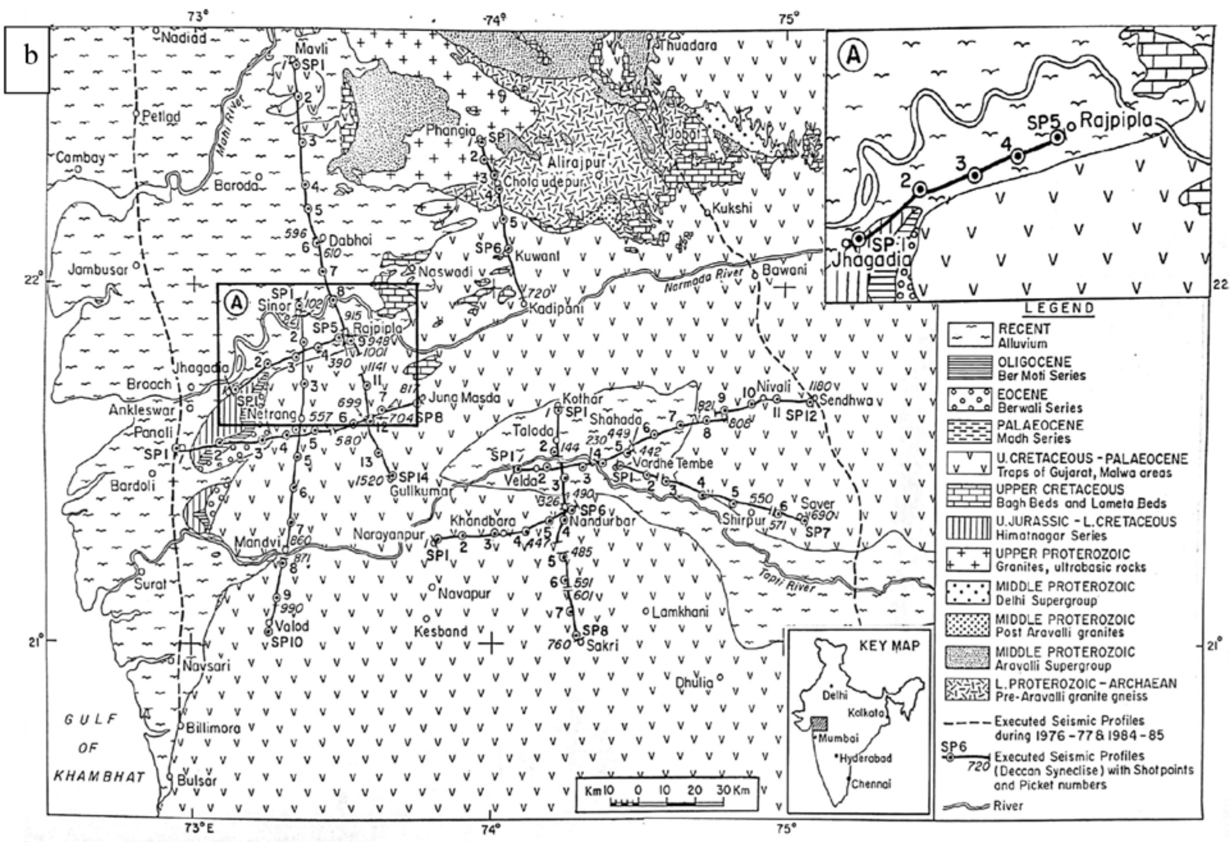
ABSTRACT
Conventional seismic reflection data are not well suited for imaging sub-trappean sediments. In this paper, we report on seismic imaging investigations that used large-offset refraction and wide-angle reflection data from three regions of India, namely, the Kutch basin, the Deccan syneclise, and the Bengal basin. We use travel time modeling of refracted and reflected phases to derive the basement configuration, including the Trap and subtrappean sediment thickness. Some of the record sections show sharp amplitude decays (attenuation) of the refracted phase from the high velocity Traps and travel time delays between the Trap and basement refracted phases, which can be diagnostic of the presence of a low-velocity zone (LVZ) consisting of sediments beneath basalt. We identify reflected phases from the top and bottom of the LVZ. Analysis of the refracted and reflected phases suggests that the relative thickness of the overlying high-velocity and underlying low- velocity sediments, play a major role in the seismic data quality. The sediment thickness also affects the magnitudes of the attenuation, the travel time delay, and the strength of the reflection. In the Kutch area, we find that the Deccan Traps are thin (about 100-800 m), and sub-trappean Mesozoic sediments are about 2 km thick. In the Deccan syneclise, the Traps are relatively thin in the north and Tertiary and sub-trappean Mesozoic sediments are thick in the southwest. Towards the east, the Trap and subtrappean Mesozoic sediments are about 1 km thick. Further east, near the Satpura basin, the Deccan Traps are about 1 km thick, and sub-trappean Gondwana sediments are quite thin (100-400 m). Similarly, in the west Bengal basin, the Rajmahal Traps are about 1 km thick, while the subtrappean Gondwana sediments are 1.8 km thick near Palashi. These results provide crucial information needed for more detailed hydrocarbon exploration in sub-trappean sediments.

Key Words: Seismic refraction, 2-D Travel time inversion, Mesozoic sediments, Deccan Traps, Saurashtra.

INTRODUCTION

Deccan volcanic rocks (Upper Cretaceous) cover large areas in western and central India (Kutch, Deccan syneclise (Figure 1a, b), whereas Rajmahal Volcanic rocks (Upper Jurassic-Lower Cretaceous) cover the eastern part (Bengal basin) (Figure 1c). Outcrops of Mesozoic and Gondwana sediments are present in the adjoining areas of Kutch, the western and eastern parts of Deccan syneclise, and in the west Bengal basin (Prasad et al., 2010, Murty et al., 2008, Kaila, 1988; Kaila et al., 1985, 1981, Mall et al., 2002). A significant amount of these sediments is reported to underlie the volcanic rocks (Traps) (NGRI, 1998, 2004, Murty et al., 2008, Mall et al., 2002)). The oil industry has been engaged in exploring Trap-covered regions for geologic and tectonic studies and hydrocarbon potential because Mesozoic sediments are source rocks for more than 50% of hydrocarbon reserves worldwide (Bois et al., 1982). Seismic imaging in the Trap-covered regions is a complex problem. Conventional seismic reflection methods have not been successful because of reverberations between high-velocity volcanic and low-velocity rocks. Large impedance contrasts within the volcanic sequences, caused by interbeds, breccia and vesicles, contaminate the primary reflections of interest with multiples and scattered noise in this range (Catchings and Mooney, 1988; Pujol et al. 1989, Jarchow et al., 1994; Sain et al., 2002). Subtrappean sediments form a low-velocity zone (LVZ) in seismic data sections because a high-velocity Trap layer is underlain by lower velocity sediments. Seismic refraction studies that used large energy sources can provide high-amplitude reflections from subtrappean interfaces at wide angles, where the noise is less dominant (Catchings and Mooney, 1988; Jarchow et al. 1994, Sain and Kaila 1996). Also, in certain favourable geological conditions, a high-velocity Trap layer that is underlain by low-velocity sediments causes seismic attenuation and travel time delays in the refracted first-arrivals; the magnitudes of the attenuation and delays being a function of the relative thickness of the two layers and their velocities (Catchings and Mooney, 1988; Tewari et al., 1995). Attenuation and travel time delays in the refracted phases and wide-angle reflected phases from top of the LVZ and basement, are indicative of low-velocity sediments beneath high-velocity volcanic rocks. Therefore, seismic refraction and wide-angle reflection data sets can be effectively used to constrain the subsurface velocity structure in Trap covered regions (Tewari et al., 1995; Fruehn et al., 2001; Murty et al., 2008; 2010; 2011).


a)
SEISMIC REFRACTION PROFILES
IN KUTCH REGION, GUJARAT
km 20 10 0 20 40 60 km
KEY MAP
Delhi
INDIA
Mumbai
Calcutta
Hyderabad
Chennai
Jakhau
SP1
Nalya
Bhuj
Mandvi
SP1A 2A 3A 4A 5A
Mundra
6A
SP1B
7A
2B
3B
4B
5B
6B
6BX
7B
8B
9B
9BX
10B
11B
12B
13B
14B
Bachau
Gandhidham
Kandla
Adhoi
Chitrod
Hamirpur
SP1C
2C
3C
4C
5C
6C
Santalpur
Radhanpur
Adesar
LITTLE RANN OF KUTCH
Tikor
Halvad
Morbi
Dhrol
Jamnagar
GULF OF KUTCH
LEGEND
Recent
Pliocene
Miocene
Oligocene
Eocene
Palaeocene
Upper Creataceous – Eocene
Upper Creataceous
Lower Creataceous
Middle – Upper Jurassic
Middle Jurassic
Seismic Refraction Profile


b
A
Nadiad
Petlad
Cambay
Baroda
Jambusar
Broach
Ankleswar
Panoli
Bardoli
Surat
Navsari
Billimora
Bulsar
GULF OF KHAMBHAT
Mahi River
Mavli
SP1
Dabhoi
Sinor
Rajpipla
Jhagadia
Netrang
Mandvi
Valod
SP10
Phangia
Chota udepur
Alirajpur
Kukshi
Thuadara
Jobat
Kuwant
Naswadi
Kadipani
Normada River
Bawani
Jung Masda
SP8
SP14
Gullkumar
Narayanpur
Khandbara
Navapur
Kesband
Kothar
Taloda
Shahada
Velda
Vardhe Tembe
Nandurbar
Sakri
Lamkhani
Dhulia
Nivali
Sendhwa
SP12
Shirpur
Saver
SP7
Tapti River
KEY MAP
Delhi
Kolkata
Mumbai
Hyderabad
Chennai
Km10 0 10 20 30 Km
LEGEND
RECENT Alluvium
OLIGOCENE Ber Moti Series
EOCENE Berwali Series
PALAEOCENE Madh Series
U. CRETACEOUS - PALAEOCENE Traps of Gujarat, Malwa areas
UPPER CRETACEOUS Bagh Beds and Lameta Beds
U. JURASSIC - L. CRETACEOUS Himatnagar Series
UPPER PROTEROZOIC Granites, ultrabasic rocks
MIDDLE PROTEROZOIC Delhi Supergroup
MIDDLE PROTEROZOIC Post Aravalli granites
MIDDLE PROTEROZOIC Aravalli Supergroup
L. PROTEROZOIC - ARCHAEAN Pre-Aravalli granite gneiss
Executed Seismic Profiles during 1976 - 77 & 1984 - 85
Executed Seismic Profiles (Deccan Syneclise) with Shotpoints and Picket numbers
River

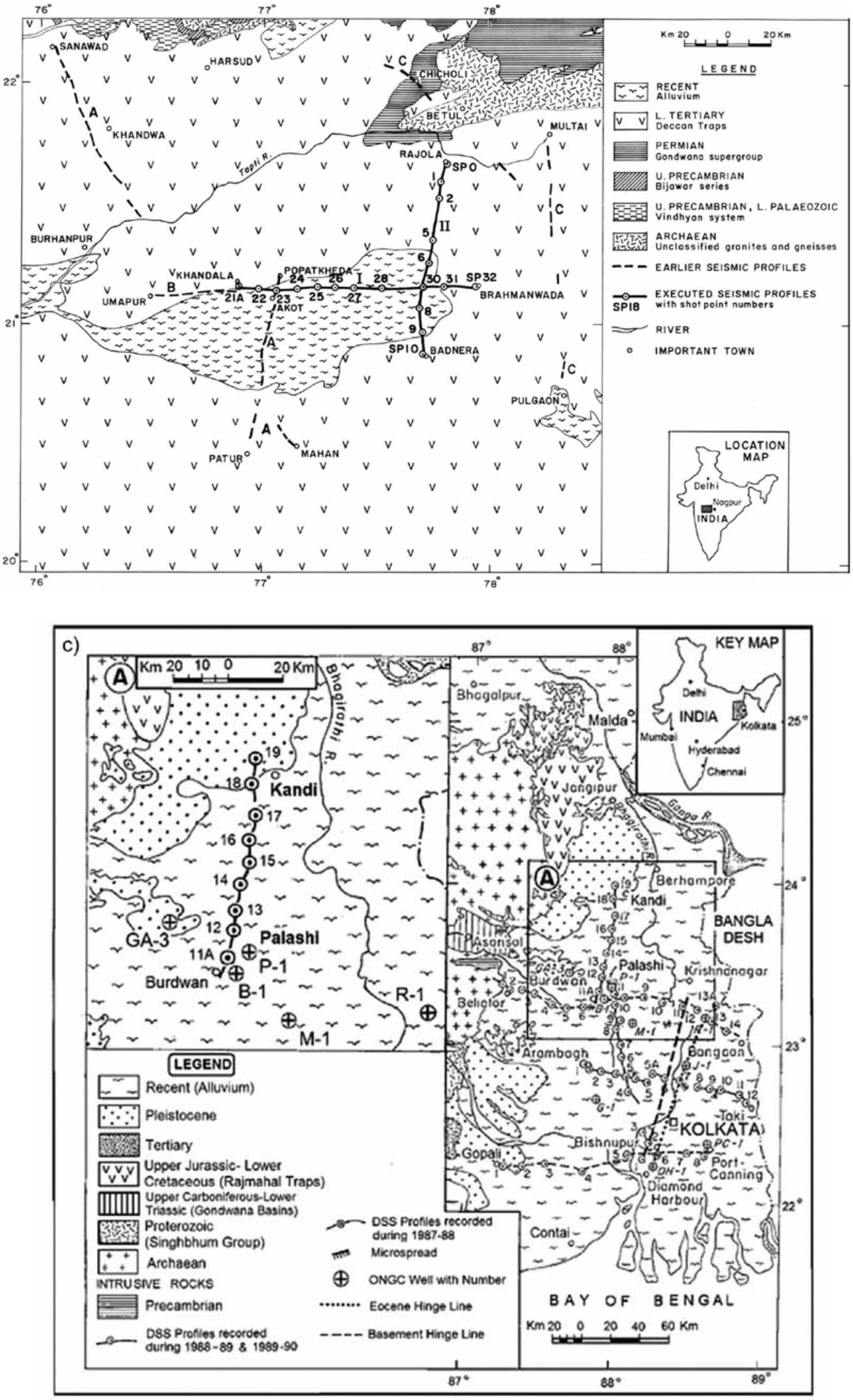


Figure 1. Location of the seismic profiles in (a) Kutch area, (b) Deccan Synclise and (c) West Bengal basin (after Rajendra Prasad et al., 2010, Murty et al., 2011a, 2011b, Murty et al., 2008).

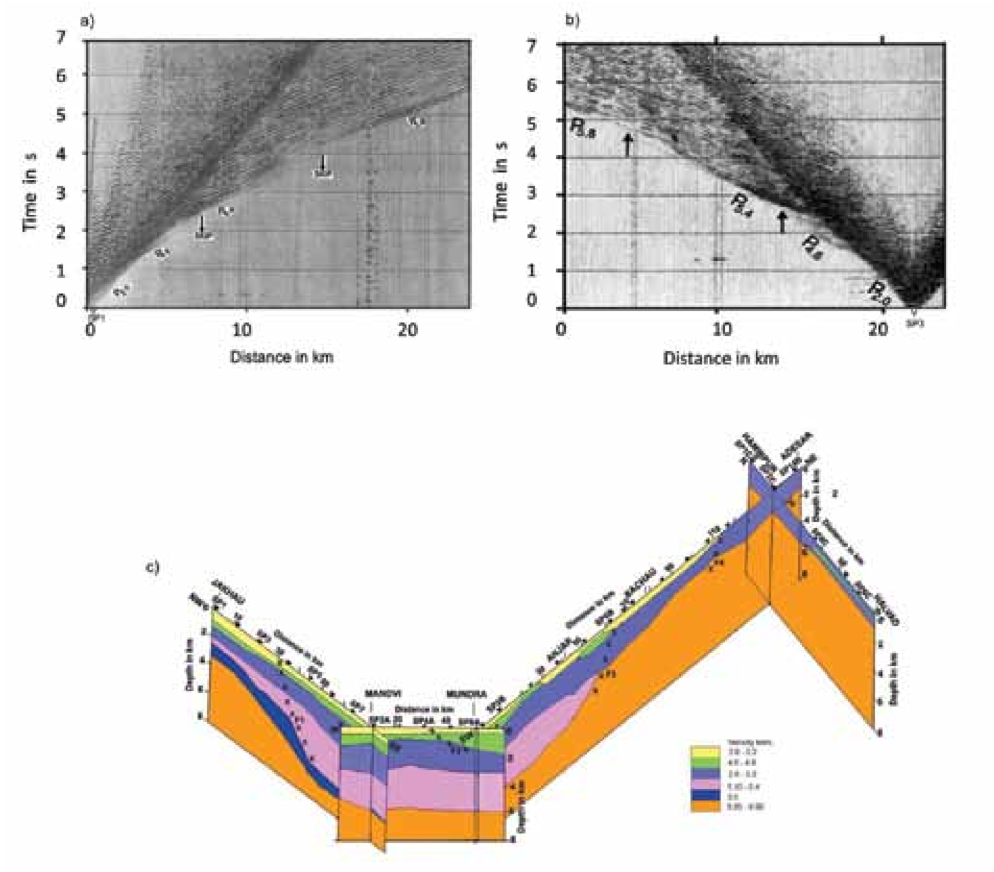


Figure 2. Record sections of reversing shot points (a) SP1 and (b) SP3 in the Kutch on-land basin plotted with distance (km) vs. time (s). $P_{2.0}$, $P_{4.6}$, $P_{5.4}$ and $P_{5.8}$ are first-arrival refracted phases. Amplitude decay in the Trap refracted phase ($P_{4.6}$) and the time skip between $P_{4.6}$ and $P_{5.8}$, indicate the presence of a low-velocity zone, (c) Shallow crustal velocity model along the four segments (Jakhau-Mandvi, Mandvi-Mundra, Mundra-Adesar and Hamirpur-Halvad) in the Kutch basin (after Rajendra Prasad et al., 2010).

Deep Seismic Sounding (DSS) studies in the Cambay-Narmada-Tapti region (Kaila et al., 1981, Sridhar and Tewari, 2001) indicate the presence of subtrappean Mesozoic sediments in grabens, separated by a horst. Similar studies in the eastern part of Deccan syneclise (Kaila, 1986, Mall et al., 2002), indicate the presence of Gondwana sediments beneath the Traps. Integrated geophysical studies were carried out by the National Geophysical Research Institute (NGRI) in Kutch (NGRI, 2000), the western part of Deccan syneclise (NGRI, 2004), which delineated Mesozoic sediments. The integrated studies in the eastern part of the Deccan syneclise (NGRI, 2009) between the Satpura basin (NE) and Godavari Gondwana (SE) graben in central India, also delineated Gondwana sediments beneath the Traps. Kaila et al. (1992) and Murty et al. (2008) further delineated subtrapppean Gondwana sediments beneath the Rajmahal Traps in west Bengal basin. In the present study, we analyze the seismic refraction and wide-angle reflection data sets of Kutch, the Deccan syneclise and the Bengal basins, primarily to delineate thickness variations of the Trap and subtrappean sediments.

SEISMIC DATA ANALYSIS

In all seismic record sections displayed in this paper, we use the term P_i as the P-wave refraction through layer i and P^i as the P-wave reflections from top of layer i.

Kutch basin: Using two DFS-V seismic acquisition systems, seismic refraction data were acquired (NGRI, 2000) along the Jakhau-Mandvi (NW-SE), Mandvi-Mundra (W-E), Mundra-Adesar (SW-NE) and Hamirpur-Halvad (N-S) profiles, which totalled 355 km in length (Figure 1a). All the shots were recorded to an offset of 48 km, with a shot interval of 8-12 km, and a receiver interval of 100 m, using 4-ms sampling interval. Data were recorded simultaneously in (a) analog form on photographic paper, and (b) digital form (SEG B) on magnetic tapes. First-arrival refraction data were picked from monitor records and travel time curves were prepared. Shot gathers of two reciprocal shot points (SP1 and 3) along the Jakhau-Mandvi profile is shown in figure 2a, b. Based on the slopes of the travel time curves, we identify four refracted phases $P_{2.0}$, $P_{4.6}$, $P_{5.4}$ and $P_{5.8}$. The direct wave ($P_{2.0}$) with a velocity

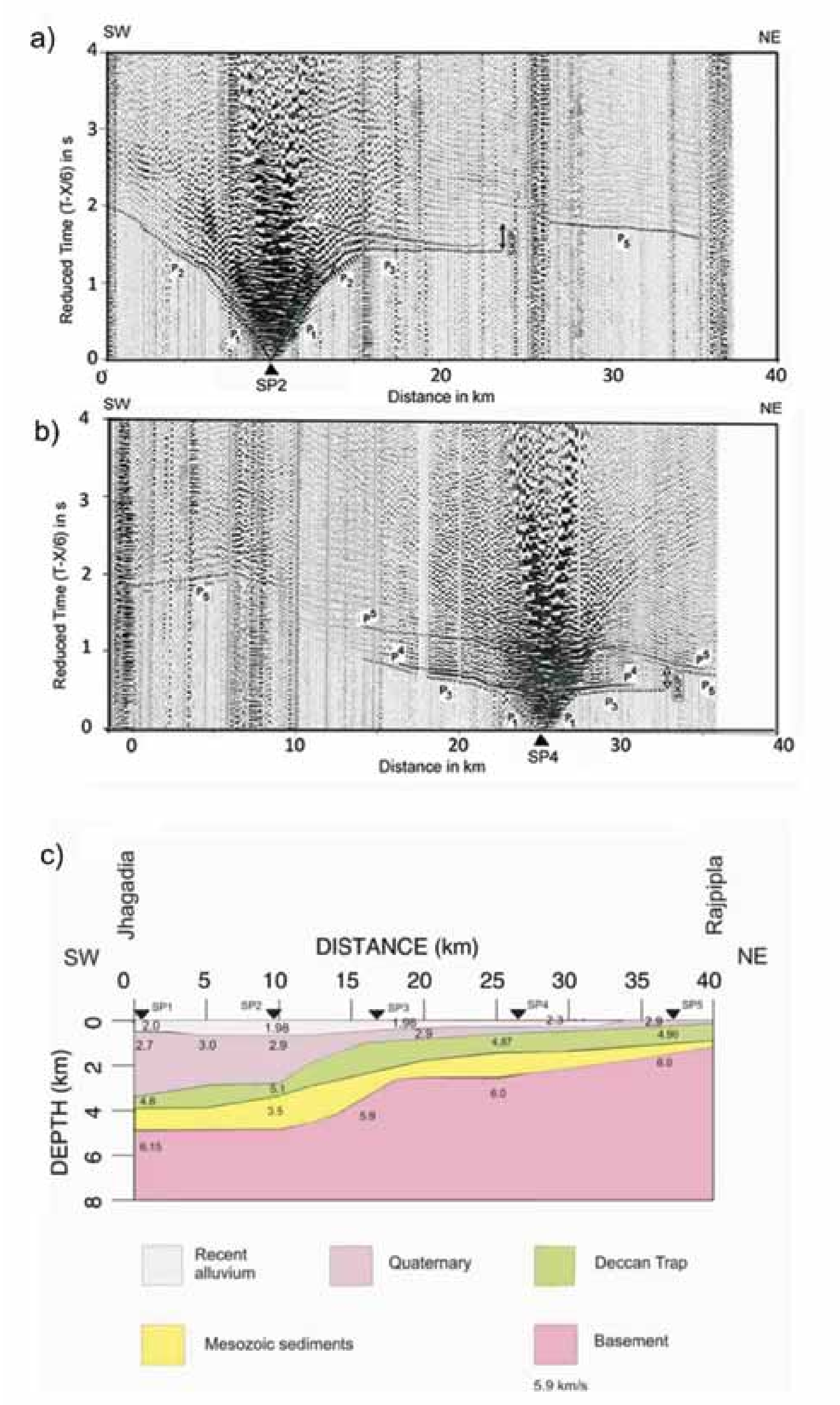


Figure 3. Record sections for shot points (a) SP2 and (b) SP4 from the western Deccan syncline, along the Jhagadia-Rajpipla (SW-NE) profile. P_1, P_2, P_3 and P_5 are first-arrival refracted phases. Amplitude decay in the Trap refracted phase (P_3) and time skip between P_3 and P_5 indicate the presence of a low-velocity zone. P^4 and P^5 are wide-angle reflected phases from the top and bottom of the low-velocity zone (c) Shallow crustal velocity model along Jhagadia-Rajpipla profile (after Murty et al., 2011a).

2.0 kms^{-1} propagates within the alluvium (Tertiary) layer that is observed at the surface. The velocities of the second, third, and fourth phases are 4.6, 5.4, and 5.8 kms^{-1}, respectively. These velocities are characteristic of Deccan Trap, limestone, and granitic basement rocks, respectively, in this region (Kaila et al., 1981). Shot gathers indicate amplitude decay in the $P_{4.6}$ and $P_{5.4}$ refracted phases and time skip between refracted phases $P_{4.6}$ - $P_{5.4}$ and $P_{5.4}$ - $P_{5.8}$ indicating the presence of low-velocity zones (LVZ) between $P_{4.6}$ and $P_{5.4}$ and $P_{5.4}$ and $P_{5.8}$. The low-velocity zones might be responsible for the decay of energy from the overlying high-velocity layer and the delay in arrival time of the refracted from the deeper high-velocity layer (Greenhalgh, 1977). The Trap refracted segment $P_{4.6}$ is short, indicating that the Deccan Trap layer is thin in this region. We observe the magnitudes of the amplitude decay and time skips to be a function of the relative thickness of both high- and low-velocity layers. Considering the prominent amplitude decay and time skips in the first-arrival refraction data, two LVZs are interpreted between $P_{4.6}$ and $P_{5.4}$ (Late Mesozoic) and $P_{5.4}$ and $P_{5.8}$ (Early Mesozoic) respectively along the Jakhau-Mandvi profile.

Deccan Syneclise

Seismic refraction studies were carried out along nine profiles, covering a total length of 700 km in the western part of Deccan syneclise (NGRI, 2004), and four profiles covering a total length of 600 km in the eastern part (NGRI, 2009) (Figure 1b). The data were recorded using RF Telemetry systems with a 100-m receiver interval, 8-10 km shot interval and 2 ms sampling interval. The data were recorded in SEG-D and converted to SEG-Y format. Record sections were generated from the SEG-Y data plotting the traces at their straight distance positions and band pass filtering (5-20 Hz); the traces were normalized and plotted in a reduced-time scale with a reduction velocity 6.0 km s^{-1}. Record sections of two shot points (SP2 and SP4) along the Jhagadia-Rajpipla profile (Figure 3a,b), two shot points (SP3 and SP4) along the Kothar-Sakri profile (Figure 4 a,b), in the western part, and two shot points (SP22, SP23) along the Khandala- Brahmanwada profile (Figure 5 a,b) in the eastern part of Deccan syneclise, are displayed. We picked refracted and reflected travel times from phases identified with pick uncertainties ranging between 20 to 100 ms, depending on the pick quality and S/N ratio. We used refraction data to derive an initial model, and computed reflected times from the model to pick a more reliable phase of the reflection band consisting two cycles. Reciprocal times of the identified phases were checked for every pair of shot points.

The record section of SP 2 (Figure 3a) along the Jhagadia-Rajpipla profile of the western Deccan Syncline, shows four first-arrival refracted phases P_1, P_2, P_3, P_5. From the velocities of the phases (1.95-2.0, 2.7-2.9 km s^{-1}) and the surface geology, P_1 and P_2 represent phases from the Tertiary (Recent and Quaternary respectively) sediments. The velocities of P_3 and P_5 are 5.1 and 6.15 kms^{-1} – a characteristic of Deccan Traps and granitic basement, respectively. There exists an amplitude decay at 14 km offset from SP2 NE and also a time skip between the two refracted phases (P_3 and P_5), indicating the presence of a low-velocity zone (LVZ) beneath the trap layer. The same phenomena of attenuation and travel time delay is observed in SP 4 (Figure 3b). Record sections for shot points 2 and 3 also show a wide-angle reflected phase (P^4), just above first-arrival refracted phase (P_3). The strong reflected phase immediately after the first-arrival; Trap refracted phase indicates the existence of a large velocity contrast. An apparent travel time delay and amplitude decay in the high-velocity refracted phase and the presence of a strong reflected phase just above the refracted phase (due to large velocity contrast), strengthens our argument for a LVZ beneath the Trap cover. We interpret this reflected phase as arising from the top of the LVZ. Similarly, we interpret another reflected phase (P^5) seen from SP 4, but we lack reversed coverage for that phase. We interpret P^5as a wide-angle reflected phase from the bottom of the LVZ. We observed the Trap refracted phase (P_3) from SP2, occurs at ~ 5 km offset from shot point 2 NE (SP 2, Figure 3a), whereas the refracted phase (P_2) observed as far as 10 km towards the SW does not include a high-velocity refracted (P_3) phase. This indicates that the high-velocity Trap layer is deeper in the SW direction. Based on the above observations and on the exposures of Mesozoic sediments near Rajpipla, we infer that a low-velocity layer corresponding to Mesozoic sediments lies between the basement and the Deccan Traps.

The reversing shot points (SP3 and SP4) along the Kothar-Sakri (N-S) profile (Figure 4a,b) are located east of the Jhagadia-Rajpipla profile, in the western part of the Deccan syneclise. The first two phases (P_1 and P_2) with apparent velocities of 4.5-4.7 km s^{-1} and 5.0-5.2 km s^{-1}, respectively, may represent two flows of Deccan Traps, and the third phase (P_3) with an apparent velocity 6.0 km s^{-1}, may correspond to the basement. (P_2) extends to large offsets, indicating that the Deccan Trap layer is thick in this part of the profile. We observe amplitude decay in the Trap refracted phase (P_2) and a travel time delay between the Trap and basement refracted phases (P_2 and P_3 in SP 4). Record sections show a reflected phase, which we designate as P^2 just above the Trap refracted phase (P_2); we interpret P^2 as a reflection from the top of the LVZ. We interpret another reflected phase (P^3) as a reflection from the bottom of the LVZ. P^3 is relatively weak, probably due to attenuation of the seismic wave that propagates through thick Trap and LVZ layers.

Shot gathers from reversing shot points (SP 22 and 23) along the Khandala-Brahmnawada profile in the eastern

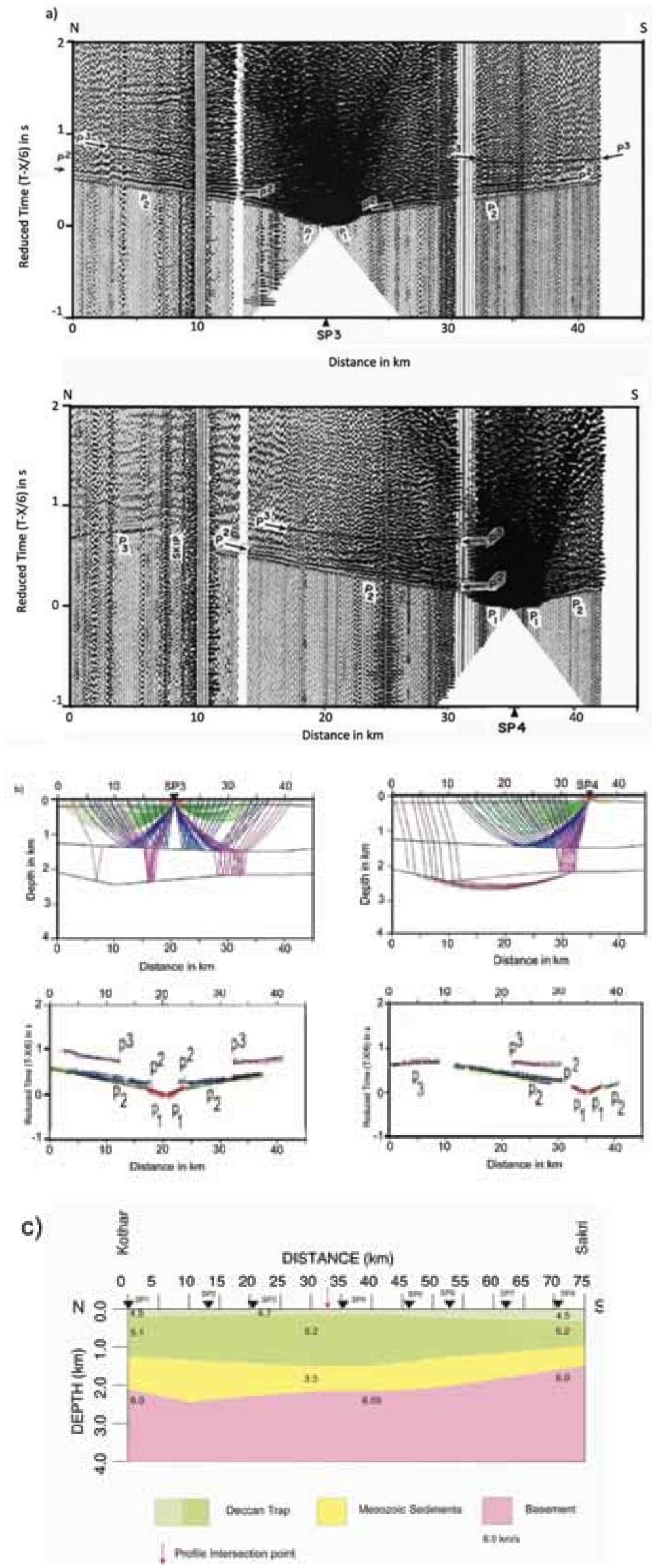


Figure 4. Record sections of shot points (a) SP3 and SP4 in western Deccan syneclise, along Kothar-Sakri (N-S) profile. P_1, P_2, and P_3 are first arrival refracted phases. Amplitude decay in Trap refracted phase (P_2) and time skip between P_2 and P_3 indicate presence of low velocity zone. P^2 and P^3 are wide-angle reflection phases from top and bottom of the low velocity zone, (b) corresponding ray diagrams and travel time fit for SP3 and SP4, (c) shallow crustal velocity model along Kothar-Sakri profile (after Murty et al., 2010).

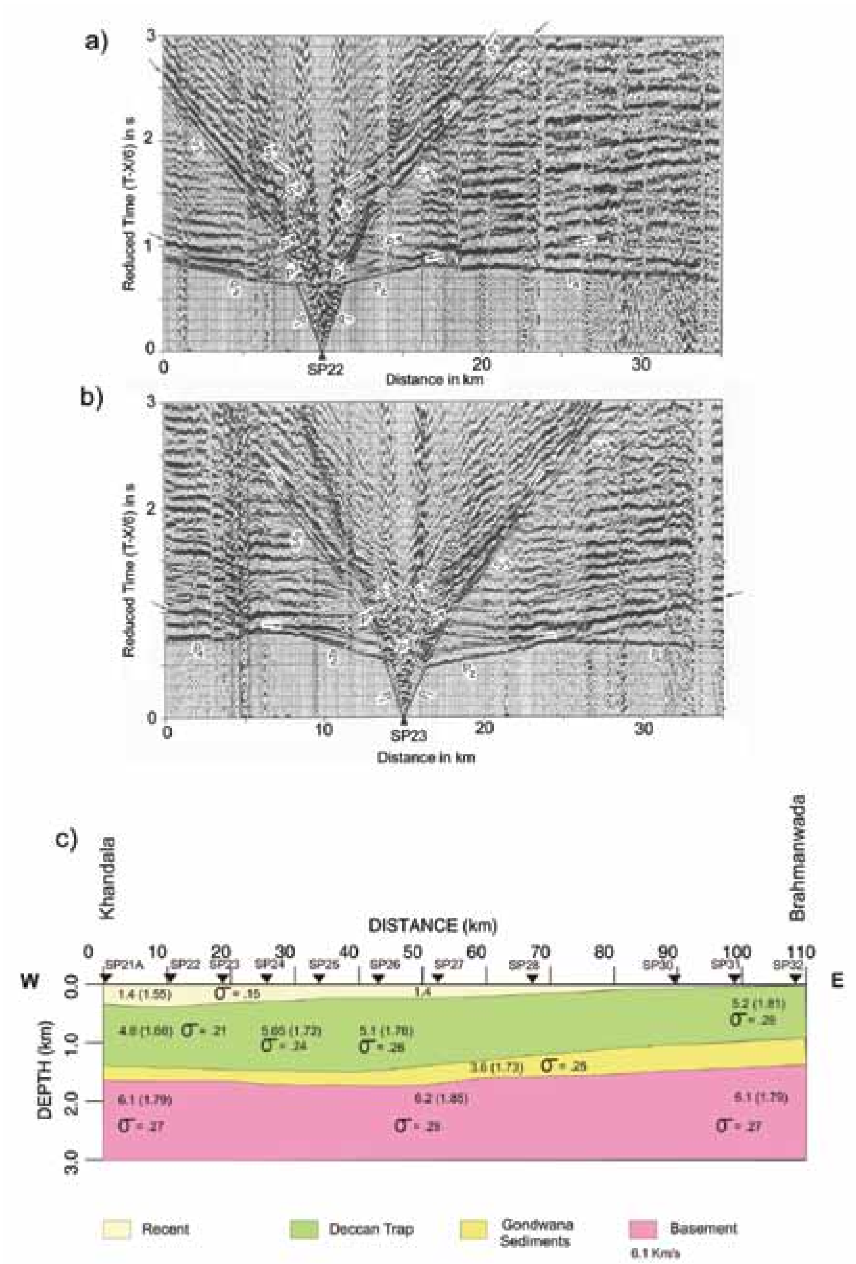


Figure 5. Record sections of shot points (a) SP22 and (b) SP23 in eastern Deccan Syneclise, along Khandala-Brahmanwada profile. P_1, P_2 and P_4 are first-arrival refracted phases. P^3 and P^4 are wide-angle reflected phases from the top and bottom of the low-velocity zone. S_2 and S_4 are S-wave refracted phases. S^3 and S^4 are wide-angle reflected phases from the top and bottom of the low-velocity zone, (c) Shallow crustal velocity model along Khandala-Brahmanwada profile (σ-Poisson's ratio) (after Murty et al., 2011b).

part of Deccan syneclise (Figure 5a, b), show there are three refracted phases (P_1, P_2, P_3) with velocities 1.4, 4.9-5.2, and 6.0-6.2 km s^{-1} that correspond to alluvium, Deccan Traps, and granitic basement, respectively (Figure 5a,b). Attenuation of the high-velocity Trap refracted phase and a travel time delay between the Trap (P_2) and basement refracted (P_4) phases, are not seen from these shot points, whereas the same are clearly observed from the shot points at large offsets along this profile. There is a reflected phase (P^3) that follows the P_2 refracted phase, which likely results from a LVZ beneath the Traps, which results in a large velocity contrast. There is a strong reflection (designated as P^4) in the 10-15 km distance range. Considering the attenuation and travel time delay between the refracted phases (P_2 and P_4) at larger offsets, we interpret the wide-angle reflected phases (P^3 and P^4) from SPs 22 and 23 as

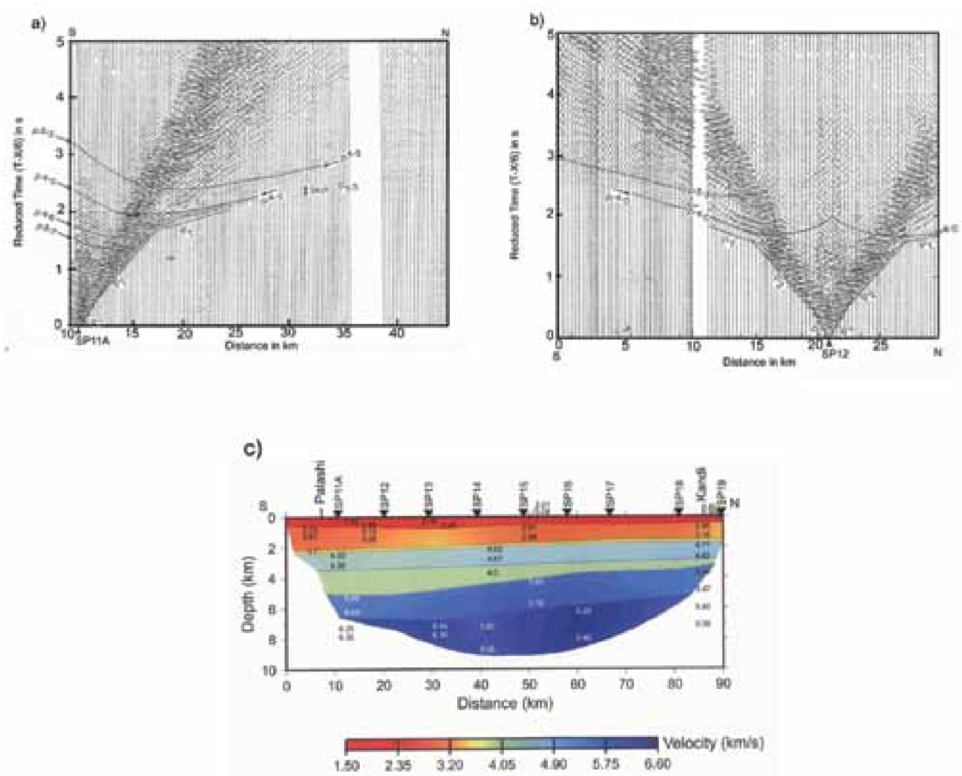


Figure 6. Record sections of reversing shot points (a) SP11A and (b) SP12 in the West Bengal basin, along the Palashi-Kandi (N-S) profile. P_1, P_2, P_T and $P_{5.3}$ are first-arrival refracted phases. Amplitude decay in the Trap refracted phase (P_T) and traveltime delays between P_T and $P_{5.3}$ are indicative of a low-velocity zone. $P^{4.0}$ and $P^{5.3}$ are wide-angle reflected phases from top and bottom of the low-velocity zone. (c) Shallow crustal velocity model along Palashi-Kandi profile is shown at the bottom (after Murty et al., 2008).

reflected phases from the top of a LVZ and basement. The reflected phase (P^4) is strong, with a high-amplitude phase that infers a large velocity contrast. We do not observe significant energy loss associated with the reflected wave propagating between basement and the overlying layer, which is also indicative of a thin LVZ. In general, we have noticed that the strength of the reflection phase from the bottom of the low velocity zone, varies considerably based on the thickness of the high-velocity trap and low-velocity sediment layers. In the case of large trap and sub-trappean sediment thickness (Figure 4c), reflection phase is weak and in the case of thin trap and sub-trappean sediments (Figure 5c) the reflection phase emerges strong and the data quality is better.

West Bengal basin

Record sections from reversing shot (SP11A and SP12) along the Palashi-Kandi (N-S) profile in the west Bengal basin are shown in figure 6a, b. The profile was acquired during 1989-90, using a DFS-V seismic system with 80 m receiver intervals, ~10 km shot intervals, and a 4-ms sampling rate. All shots were recorded with up to 80 km offset. To show the reflected phases clearly, we use low-gain data at near offsets. We picked travel times of the first-arrival refracted and reflected phases from the monitor records. We observe three refracted phases (P_1, P_2 and P_T) in the near offset. Our interpreted refracted phases correlate well with data obtained by the Oil and Natural Gas Corporation (ONGC) in a drilled well at Palashi. We infer the refracted phases (P_1 and P_2) to correlate with Tertiary sediments, and the refracted phase (P_T) to correlate with the Rajmahal Traps. We observe an amplitude decay in the Trap refracted phase (P_T) and travel time delay between the Trap refracted phase and $P_{5.3}$, as seen in the seismic record from SP 11A. We also observe a strong reflected phase ($P^{4.0}$) just above the Trap refracted phase and another reflected phase ($P^{5.3}$). Amplitude decays, travel time delays, and strong reflections are indicative of a low-velocity zone between the Trap and $P_{5.3}$ layer. We interpret the two reflected phases ($P^{4.0}$ and $P^{5.3}$) to be reflections from the top and bottom of a low-velocity zone. Low-velocity Gondwana sediments, observed in the nearby Palashi well, are likely to comprise our observed LVZ.

MODELLING RESULTS

Shallow crustal velocity models were derived from first-arrival refraction and wide-angle reflection data for Kutch, the Deccan syneclise, and the west Bengal basins (Murty et al., 2008, 2010, 2011a,b ;Prasad et al., 2010), using the travel time inversion method of Zelt and Smith (1992) and the ray tracing program, Rayamp-PC (1987). In the Kutch basin, we infer a five-layer model (Figure 2c) that overlies granitic basement between SP 1 to 6, and a four-layer above-basement model between Jakhau-Mandvi profile-I (Rajendra Prasad et al., 2010). The first layer is unconsolidated Tertiary sediments, which are varying between 0.8 to 0.5 km in thickness from the NE to SW (velocity of 2.0 kms^{-1}). We interpret the second layer to be Deccan Traps, with a velocity of 4.6 km s^{-1}. The Trap is thin (0.2 km) between SP 1 and 5 and increases in thickness to 0.7-0.9 km between SP 6 and 8. We interpret about 1 km of Mesozoic sediments (3.1 kms^{-1}) to underlie the Traps near SP1, increasing in thickness to about 2 km near SP8. The third layer is underlain by a 0.4-km-thick high-velocity layer (5.4 km s^{-1}) at SP 1 that increases in thickness to about 2.5 km between SP 5 and 8. Between the high-velocity (5.4 km s^{-1}) layer and basement (5.9 km s^{-1}), we interpret another low-velocity layer (3.5 km s^{-1}). Basement is at 3.2 km near Jakhau, deepening to about 6.5 in km near Mandvi.

Murty et al. (2011a) interpreted four layers above basement along the Jhagadia-Rajpipla profile in western part of Deccan syneclise (Figure 3c). All the layers, including the basement, are deepest below shot point 1 (near Jhagadia in the southwest) and are shallowest towards northeast, near Rajpipla. Near-surface sediments range in velocity between 1.95-2.3 km s^{-1} and ranges in thickness from about 300 m near Jhagadia to 700 m near SP 2; this layer gradually thins towards the northeast and pinches out near shot point 5. We interpret ~ 2.9 km of Quaternary sediments (2.7-3.05 km s^{-1}) to underlie the near-surface recent sediments beneath SP 1 near Jhagadia. The Quaternary sediments layer rapidly decreases in thickness between SP 2 and SP 3 and is only about 150 m thick near Rajpipla. Deccan Traps (4.8-5.1 km s^{-1}) are about 1 km thick near SP 3, thinning to 500 m to the northeast and southwest. The top of the Trap layer dips steeply between shot points 2 and 3, resulting in a thickened deposit of Mesozoic sediments overlying the Trap layer southwest of SP 2, near Jhagadia. The Mesozoic sediments vary in thickness from about 1 km near Jhagadia (at SP 1) to 1.7 km near SP 2. The depth of basement (5.9-6.15 km s^{-1}) decreases from 4.6 km near shot point 2 to 2.6 km near SP 3 and further thins down to about 1.2 km near Rajpipla. Murthy et al. (2010) interpret three layers above basement (Figure 4c) along the Kothar-Sakri profile in western part of Deccan synclise They interpret the first two layers (4.5-4.7 and 5.1-5.2 km s^{-1}), with layer thickness 0.15-0.30 km and 0.65-1.35 km respectively, as various flows of the Deccan Traps. The total Trap thickness is 1-1.50 km. The underlying low-velocity Mesozoic sediments (3.5 km s^{-1}) are 0.55-1.1 km thick along the profile, and basement (6.0 km s^{-1}) varies in depth from 1.5-2.45 km, dipping towards north. Murty et al. (2011b) modelled three layers above basement along Khandala-Brahmanwada profile (Figure 5c) in the eastern part of Deccan syneclise. The first layer (1.4 km s^{-1}) represents alluvium, which is about 350 m thick at SP21A (near Khandala) that gradually thins towards the east before surfacing near Brahmanwada. The second layer (4.8-5.2 km s^{-1}) corresponds to Deccan Traps, with an average thickness of 1 km along the profile which is underlain by a thin layer (250-400 m) of Gondwana sediments (3.6 km s^{-1}). Basement (6.1-6.2 km s^{-1}) is about 1.6 km deep in the NW near SP 0, decreasing to 1.35 km near Brahmanwada.

Murty et al. (2008) also modelled six layers above basement along the Palashi-Kandi profile (Figure 6c) in the west Bengal basin. The first two layers (1.9-2.1and 2.8-3.1 kms^{-1}) correlate with alluvium and shale which are 0.3-0.75 km and 1.0-1.7 km thick, respectively. The third layer corresponds to Sylhet limestone (3.7 kms^{-1}) and is only a few hundred meters thick and is underlain by a ~ 1-km-thick layer of Rajmahal Traps (4.5-4.7 kms^{-1}). About 1.8 km of Gondwana sediments (4.0 kms^{-1}) underlies the Rajmahal Traps near Palashi, shallowing to about 400 m near Kandi. Murty et al. (2008) interpret Sighbhum group of Meta volcanic rocks (5.4-5.6 kms^{-1}) to underlie the Gondwana sediments and overlie the crystalline basement (5.8-6.25 kms^{-1}), which varies in depth between 4.9 to 6.8 km, dipping towards the south.

DISCUSSION AND CONCLUSIONS

The velocity models derived along various seismic profiles in the Kutch area, the Deccan syneclise, and the west Bengal basin, delineate variations in the Traps and sub-trappean sediments and the basement depth. In the Kutch basin, Recent/Tertiary sediments overlie the Trap along the Jakhau-Mandvi profile. Shot records show near-surface refracted arrivals are followed by a shadow zone (travel time delay), a higher velocity layer, and a second shadow zone before the basement refraction. We correlated well data with our refraction/reflection data and interpreted the shallow crust along the Jakhau-Mandvi profile as Mesozoic sediments. We interpret high-velocity layer between the two low-velocity layers as limestone within Mesozoic sediments. From the derived velocity models along the four segments (Figure 2c), we infer a sedimentary graben between faults F1 and F3. The model shows that basement is 3.3 km deep near Jakhau, increasing to 6.7 km depth at Mandvi. Overlying the basement are five layers, with velocities of 2.0, 4.6, 3.1, 5.4, 3.5 kms^{-1}, which we interpret as Tertiary sediments, Traps, Late Mesozoic sediments, Mesozoic limestone, and Early Mesozoic sediments, respectively. The model changes toward the northeast. The Traps are almost absent in the north, consisting of an older Mesozoic sequence. The basement shallows to about 3 km from Bachau north-eastward, and the limestone layer discontinues. Across the Little Rann, sediments (2.8 kms^{-1}) overlie the shallow (2 km) basement. The thick Mesozoic sediments in the southern Kutch basin are likely an extension of the thick Mesozoic rocks inferred in north-western Saurashtra, across the Gulf of Kutch.

The velocity models for the western part of Deccan syneclise (Murty et al., 2011a, 2010) are shown in figures 3c and 4c. The Mesozoic sediments in western India occupy a large portion of Rajasthan, Gujarat, and Madhya Pradesh, and the sediments are mostly of marine origin; thus, they are important to the oil industry. On the south-eastern margin of the Cambay basin and the western part of the Deccan syneclise near Rajpipla, a 600-m-thick section of the Cretaceous Bagh beds (Mesozoic) is exposed. Poddar (1964) suggested the presence of suitable facies and favourable prospects for hydrocarbon-bearing Mesozoic sediments below the Deccan Traps towards the Ankleswar oil field. From these considerations and the presence of a relatively thin trap, the thick (~1.7 km) Mesozoic sediments near SP 2 of the Jhagadia-Rajpipla profile (Figure 3c) are significant. Deep seismic sounding studies (DSS) across the Narmada-Son lineament revealed Deccan Traps and subtrappean sediments in the Naramada-Tapti region (Kaila, 1988; Sridhar and Tewari, 2001). The area in the western part of the Deccan syneclise lies between two DSS profiles, the Mehmadabad-Billimora profile in Cambay basin and the Thuadara-Sindad profile to the east. Along the Thuadara-Sindad profile, the Trap thickness is about 900 m, and south of Sendhwa (up to Tapti river), Mesozoic sediments are approximately 1.9 km thick. Sridher and Tewari (2001) observe evidence for a graben between the Narmada and Tapti rivers. Within the graben, basement is 5.0-5.5 km deep between Sendhwa and the Tapti river and contains 1.0-2.8 km Mesozoic sediments beneath the thick (2.0-2.7 km) Trap cover. From the present study of profiles in the western part of the Deccan syneclise, Tertiary and subtrappean sediments are relatively thick in the southwest (Figure 3c). Further east (Figure 4c), the Trap and subtrappean sediments are about 1 km thick. On the basis of isopach contour maps of the Mesozoic sediments in the Narmada-Tapti region, Kaila (1988) hypotheses a Mesozoic basin in the Narmada-Tapti area that formed within a Mesozoic sea. Seismic profiles in the western part of the Deccan syneclise show evidence for a Mesozoic basin in the region.

In the eastern part of the Deccan syneclise, Deccan Traps are about 1 km thick, and subtrappean Gondwana sediments vary in thickness from 100-400 m (Figure 5c). Seismic profiles in the eastern part of Deccan syneclise (Murty et al., 2011b, Kaila, 1988, Kaila and Koteswara Rao, 1985, Mall et al., 2002) indicate a large variation in the thickness of the Deccan Traps in the E-W direction. The variation in the thickness of the Traps arises from the presence of volcanic plugs. Although Gondwana sediments outcrop north of the seismic profile, these sediments are relatively thin in the area of the Satpura horst. A Bouguer gravity low in the area suggests that the Godavari Gondwana graben and the Tapti-Purna fault extend northward of Nagpur. This Tapti-Purna fault is believed to bound the Satpura graben (Mishra, 1992). The entire region of the eastern Deccan syneclise, combined with the Gondwana rocks of the Wardha coal field, constitutes the elongated Godavari Gondwana basin, which extends towards the Satpura basin. Such a linear extension of Gondwana sediments might have resulted from some deep-seated tectonics, such as lithospheric upwelling associated with a plume or a hot spot trace (Curray and Munasinghe, 1991), which, in turn, gave rise to the extensional tectonics that produced the rift valleys in this region.

Seismic profiles in the West Bengal basin (Kaila et al., 1996. Murty et al., 2008) delineate the Traps and subtrappean Gondwana sediments. The Rajmahal Traps are about 1.0 km thick, and Gondwana sediments are about 1.8 km thick in the south near Palashi but decreases to 0.4 km northward near Kandi (Figure 6c). Wells in the west Bengal basin show a large variation in velocity of the Eocene limestone formation, varying from 5.8 km s^{-1} at the Diamond Harbour (0.9 km thick) to 3.2 km s^{-1} (0.2 km thick) at the Palashi -1 well (Kaila et al., 1996). The limestone formation was not found further north in the Purnea well, where basement is shallow near Jangipur and Malda (Chowdhury and Datta, 1973). We suggest that the shallow basement might have limited the northward extension of the early Tertiary Seas towards Purnea and acted as an effective structural barrier to the deposition of Sylhet limestone in the Early Tertiary. According to Chowdhury and Datta (1973) the basement high, while acting as a structural barrier in the early Tertiary period, did not interrupt the continuity of the Gondwanas from south to north. We infer that there was continuous deposition of the Gondwanas from south to north in local basement depressions at the initial stage of the break-up of Gondwana land during the Permocarboniferous period.

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REFERENCES

Bois, C., Bouch, P. and Pelet, R., 1982. Global geologic history and distribution of hydrocarbon reserves, AAPG Bulletin, 66, 1248-1270.

Chowdhury, S.K. and Datta, A.N. 1973. Bouguer gravity and its geologic evolution in the western part of the Bengal basin and adjoining area, India, Geophys. 38, 691-700.

Curray, J.R. and Munasinghe, T., 1991. Origin of Rajmahal Traps and the 85^0 E ridge: preliminary reconstruction of the trace of the Crozet hot spot. Geology, 19, 1237-1240.

Fruehn, Juergen, Moritz M. Fliendner and Robert S. White, 2001. Integrated wide-angle and near – vertical sub salt study using large-aperture seismic data from the Faeroe-Shetland region, Geophys, 66(5), 1340-1348.

Greenhalgh, S.A., 1977. Comments on "The hidden layer problem in seismic refraction work", Geophys. Prospect., 25, 179-181.

Jarchow, C.M., Catchings, R.D. and Lutter, W.J., 1994. Large explosive source, wide-recording aperture, seismic profiling on the Columbia Plateau, Washington, Geophysics, 59, 259-271.

Kaila, K.L. and Koteswara Rao, P., 1985. Crustal structure along Khajuriakalan-Pulgaon profile across the Narmada-Son lineament from Deep Seismic Soundings, I: Deep Seismic Soundings and Tectonics, Editors: K.L. Kaila and H.C. Tewari, AEG publication, India, 43-59.

Kaila, K.L., 1986. Tectonic framework of Narmada-Son lineament-a continental rift system in central India from deep seismic soundings. In: Barazanki, M. and Brown, I. (Eds.), Reflection seismology: a global perspective, Geodyn. Ser., 13, AGU Washington DC, 133-150.

Kaila, K.L., 1988. Mapping of the thickness of the Deccan Trap flows in India from deep seismic sounding studies and inferences about a hidden Mesozoic basin in Narmada-Tapti region. Geol. Soc. India, Mem. No. 10, 91-116.

Kaila, K.L., Krishna, V.G. and Mall, D.M., 1981. Crustal structure along Mehmadabad-Billimora profile in the Cambay basin, India from Deep Seismic Soundings. Tectonophysics, v. 76, pp: 99-130.

Kaila, K.L., Reddy, P.R., Dixit, M.M., and Koteswara Rao, P., 1985. Crustal structure across Narmada-Son Lineament, central India from Deep Seismic Soundings, J. Geol. Soc. India, 26 465-480.

Kaila, K.L, Reddy, P.R., Mall, D.M., Venkateswarlu, N., Krishna, V.G. and Prasad, A.S.S.S. R.S., 1992. Crustal structure of the west Bengal basin, India from deep seismic sounding investigations, J. Int., 111, 45-66.

Kaila, K.L., Murty, P.R.K., N. Madha Rao, I.B.P. Rao, P.K. Rao, A.R. Sridher, A.S.N. Murty, V.Vijay Rao, and B.R. Prasad., 1996. Structure of the crystalline basement in the west Bengal basin, India, as determined from DSS studies, Geophys, J., Int.,124, 175-188.

Mall, D.M., Sarkar, D. and Reddy, P.R., 2002. Seismic signature of Sub-Trappean Gondwana Basin in Central India. Gondwana Research, 5(3), 613-618.

Mishra, D.C., 1992. Mid continental gravity 'High' of central India and the Gondwana tectonics, Tectonophysics, 212, 153-161.

Murty, A.S.N., Kalachand Sain and Rajendra Prasad, B., 2008. Velocity structure of the West-Bengal sedimentary basin, India along the Palashi-Kandi profile using a travel-time inversion of wide-angle seismic data and gravity modeling-An update. Pure and Applied Geophysics, 165, 1733-1750.

Murty, A.S.N., Prasad, B.R., Koteswara Rao, P., Raju and S., Sateesh, T., 2010. Delineation of Subtrappean Mesozoic Sediments in Deccan Syneclise, India, Using Travel time Inversion of Seismic Refraction and Wide-angle Reflection Data. PAGEOPH, 167, 233-251.

Murty, A.S.N, Rao, P.K., M.M. Dixit, G. Kesava Rao, M.S. Reddy, B. Rajendra Prasad and D. Sarkar., 2011a. Basement configuration of the Jhagadia-Rajpipla profile in the western part of Deccan syneclise, India from travel-time inversion of seismic refraction and wide-angle reflection data, India. Journal of Asian Earth Sciences, 40, 40-51.

Murty, A.S.N, M.M. Dixit, B. Mandal, S. Raju, Sanjay Kumar, P. Karupanan, K. Anitha and D.Sarkar., 2011b. Extension of Godavari Gondwana sediments underneath Trap covered region of Satpura basin as evidenced from seismic studies in Deccan Syneclise, India. Journal of Asian Earth Sciences, 42, 1232-1242.

NGRI Technical Report, 1998. Integrated geophysical studies for hydrocarbon exploration, Saurashtra, India. NGRI Technical Report No. NGRI-98-Exp-237.

NGRI Technical Report, 2000. Integrated geophysical studies in Kutch on land to delineate subsurface sedimentary basins structure and Basement configuration-Seismic refraction results, NGRI Technical Report No. NGRI-2000-Exp-281.

NGRI Technical Report, 2004. Integrated geophysical studies for hydrocarbon exploration, Deccan Syneclise, India. NGRI Technical Report No. NGRI-2003-Exp-404.

NGRI Technical Report, 2009. Integrated Geophysical studies for hydrocarbon exploration in eastern part of the Deccan Syneclise, central India. NGRI Technical Report No. NGRI-2009-Exp-679_Volume II.

Poddar, M., 1964. Mesozoic of western India-their geology and possibilities. In: 22nd Int. Geol. Cong., New Delhi, Sect.1-part1. Geology of Petroleum, 126-143.

Pujol, J., Fuller, B.N., and Smithson, S.B., 1989. Interpretation of a vertical seismic profile conducted in the Columbia Plateau basalts. Geophysics, 54, 1258-1266.

Rajendra Prasad, B., Venkateswarlu, N., Prasad, A.S.S.S.R.S., Murty, A.S.N. and Sateesh, T., 2010. Basement configuration of on-land Kutch basin from seismic refraction studies and modeling of first arrival travel time skips, Journal of Asian Earth Sciences, 39, 460-469.

Rayamp-PC, 1987. 2 D Ray tracing\Synthetic seismogram. Version 2.1, Geophys, Laboratory, Mc-Gill University.

Sain, K., and Kaila, K.L., 1996. Interpretation of first arrival traveltimes in seismic refraction work. Pure Appl. Geophys., 147, 181-194.

Sain, K., Zelt, C.A. and Reddy, P.R., 2002. Imaging of subvolcanic Mesozoics in the Saurashtra peninsula of India using travel time inversion of wide-angle seismic data, Geophys., J. Int. 150, 820- 826.

Sridhar, A.R. and Tewari, H.C., 2001. Existence of a sedimentary graben in the western part of Narmada zone: Seismic evidence. Joul. Geodynamics, 31, 19-31.

Tewari, H.C., Dixit, M.M., and Murty, P.R.K., 1995. Use of traveltime skips in refraction analysis to delineate velocity inversion. Geophys. Prospect., 43, 793-804.

Zelt, C.A., and Smith, R.B., 1992. Seismic travel time inversion for 2-D crustal velocity structure. Geophys. J. Int., 108, 16-34.

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