Imaging of sub-trappean Gondwana sediments and basement configuration using 2D long-offset seismic data of south Rewa basin, Central India

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Keywords

South Rewa basin; LVL; Gondwana sediments; Deccan basalt; Basement; Ray-trace Inversion

Summary

The south Rewa rift-basin has a deposition of thick column of sub-trappean Gondwana sediments important for hydrocarbon potential. To image the subsurface geological structures with basement configuration and obtain different rock compositions of this sedimentary basin, both P- and S-wave velocity models (V_P and V_S) are derived down to a depth of 15 km using ray-trace inversion of long-offset seismic refraction and reflection data along the155 km long N-S trending wide-angle seismic profile. The top layer indicates top soil and loose sediments (Pali-Tihki formations) having V_P varies from 3.20-3.40 km/s, V_S varies from 1.92-2.05 km/s, V_P/V_S variations of 1.570-1.719 and Poisson's ratio (σ) varies from 0.130-0.244 respectively. The high velocity basaltic flows (second layer) have V_P variations of 4.85-5.22 km/s, V_S varies from 2.70-2.90 km/s with corresponding V_P/V_S of 1.758-1.821 and σ of 0.261-0.284 mainly covers the 3.0-4.0 km thick low-velocity-layer (LVL) Gondwana sediments (third layer). From a prior information and 1-D velocity inversions of seven wide-angle shots, we have constrained the velocities of the LVL as 4.0 km/s for V_P and 2.36 km/s for V_S. The granitic basement (fourth layer) is highly undulated having V_P range from 5.95-6.10 km/s, V_S range from 3.43-3.60 km/s with corresponding V_P/V_S of 1.681-1.743 and σ of 0.226-0.259 respectively surrounded by the deep basinal faults. The sub-basement structure delineated show V_P variations of 6.45-6.52 km/s, V_S varies from 3.7-3.72 km/s with V_P/V_S of 1.732-1.751 and σ variations of 0.250-0.259 respectively. From the variations of the V_P/V_S and σ for each layer along with the V_P and V_S models derived in the south Rewa basin, we can infer complex geology having faults, horsts and grabens, dykes and sills, large-scale lithological changes of subsurface formations due to Gondwana rifting as well as late Cretaceous Deccan volcanism.

Introduction

The south Rewa sedimentary basin preserves large thickness of Permo-Triassic Gondwana sediments underlain by the basalt flows, which cause a major problem to delineate the subsurface geological structures of the sedimentary basin. Conventional seismic reflection method has poor penetration of seismic energy below the basalts due to attenuation, scattering, mode-conversion and other kind of loss of energy. However, long-offset seismic data (refraction and wide-angle reflection) has the advantage of penetrating below the basalts beyond the critical-angle of incidence of seismic waves and can able to delineate deep seated subsurface geological targets of interest underlain by the basalts (Behera et al., 2002). Therefore, it is necessary to model the long-offset seismic reflection and refraction data to address the velocity inversion problem, which are ubiquitously present in different regions of the world and most prominent in the Rewa sedimentary basin of Central India due to Deccan volcanism. The velocity inversion problems are more prominent in the long-offset seismic data due to the presence of traveltime skips or delays in the observed first-arrival traveltime data of different shot points (SPs). Hence, suitable traveltime inversion strategy can able to delineate the target LVL sediments hidden below the high-velocity-layer (HVL) basalts or traps. We know very well that V_P is sensitive to the bulk modulus (K), rigidity modulus (μ) and density (ρ) of rocks, whereas V_S is sensitive to only rigidity modulus (μ) and density (ρ). Hence, P-waves compress the volume of the rocks and S-waves modify their shapes (Farfour et al., 2016). Therefore, the analysis of both P- and S-wave seismic data can able to deal with the subsurface rock properties with an assessment of their compositions along with the subsurface velocity and geological structures of the study area. The main objectives of this study are (i) to obtain shallow subsurface geological structures, (ii) to image the LVL Gondwana sediments underlain by HVL Deccan basalts/traps along with the basement configuration, (ii) to derive V_P and V_S models, (iv) to understand compositions from V_P/V_S and Poisson's ratio (σ) estimates.

Geology of the Study Area

South Rewa sedimentary basin is a NW-SE trending Gondwana rift-basin of the Son-Mahanadi rift system in Central India (Mukherjee et al., 2012; Chowdari et al., 2017). The study area is mainly confined between the latitude 23°-24° N and longitude 81°-82° E (Fig. 1). The basin has been tectonically disturbed with presence of numerous faults, horst and grabens as well as intrusions of several dykes/sills covered with conspicuous flows of Deccan basalts. The Rewa basin is relatively long in the ENE-WSW direction and the overall attitude of the basin-fill strata is low-dipping towards north (Mukharjee et al., 2012). A set of parallel faults along with the ENE-WSW trending Son-Narmada south fault bound the basin in the north defining the Malwa ridge, which show evidence of strike-slip movement. A set of ENE-WSW trending faults run along the middle of the Rewa basin dividing it into northern and southern compartments (Chakraborty et al., 2003). The basin configuration indicates major fault-controlled subsidence with exposures of many different rocks making this region very complex in geology and tectonic settings.

Data and Methodology

The 3-C wide-angle seismic data contains radial (R), transverse (T) and vertical (Z) components. Radial component shows high signal-to-noise-ratio (SNR) as it propagates along the direction of the seismic line. Thus, radial component seismic data has been chosen for modeling and inversion. Pre-processed radial-component wide-angle seismic data of SP3 is shown as an example in the top panel of Figure 2 for data quality. The 3-C wide-angle seismic data has been acquired by the CSS Group of CSIR-NGRI in the south Rewa sedimentary basin of Central India along the N-S trending 155 km long-offset seismic profile from Hardi to Samatpur during 2014-2015 under the aegis of XII-V Year Plan Project SHORE of CSIR. Seven wide-angle shot point seismic data have been recorded along the said profile using standalone 3-C Taurus Seismographs of Nanometric, Canada. The data was acquired with shot interval (SI) of 30 to 35 km and geophone group interval of 200 m by using explosives as charge. The explosives of minimum 100 kg to maximum of 1.8 Metric tons are blasted in pattern of holes (each hole of 25 m depth) drilled at each SP location (Fig. 1) depending upon the maximum offset coverage for each spread. The spread length is maintained for 24 km while recording the data by blasting each SP and the spread moves along the profile from Hardi to Samatpur (N-S).

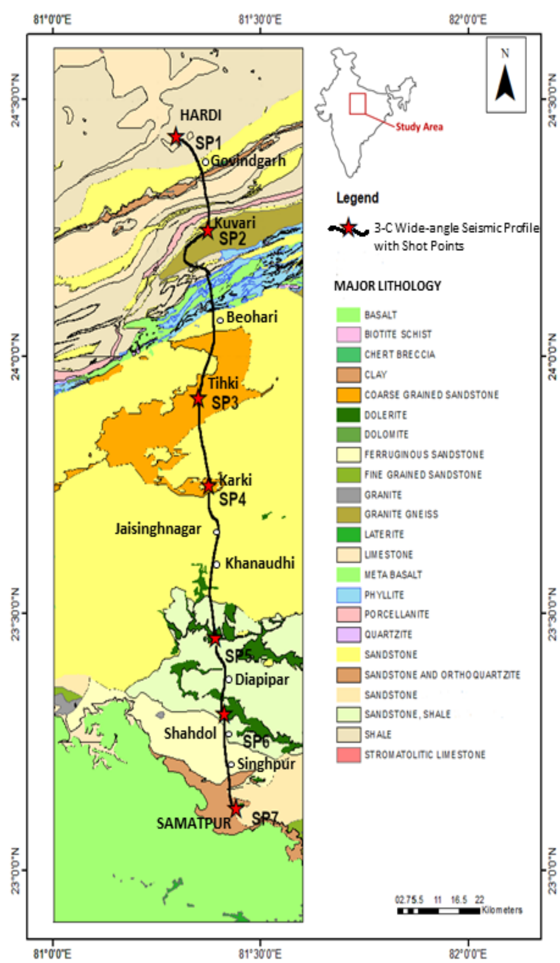

Figure 1. Geology map of the south Rewa basin of Central India showing 3-C wide-angle seismic profile from Hardi-Samatpur with shot points (SP1-SP7) marked.

We have employed the ray-trace inversion method of Zelt and Smith (1992) based on model parametrization and ray-tracing suited to forward step of an inverse approach. For the model parametrization, each layer boundary is specified by arbitrary number of velocity and boundary nodes in which number and position of nodes may differ for each boundary. The layer boundary must cross the model from left to right with an irregular grid of velocity and boundary nodes, which are connected by linear interpolation of the chosen model parameters. The ray-trace inversion of traveltime data are used to obtain the velocity and interface structure simultaneously.

The integral form of a continuous velocity field $v(x,z)$ having traveltime t between a source and receiver along a ray path L can be expressed as (Zelt and Smith, 1992):

$$t = \int \frac{1}{v(x,z)} dl \qquad (1)$$

In discrete form Eq. (1) can be written as:

$$t = \sum_{i=1}^{n} \frac{l_i}{v_i} \qquad (2)$$

where l_i is path length of the i^{th} ray segment, v_i is velocity of the i^{th} ray segment. The traveltime is a linear combination of slowness, but the traveltime inversion is a non-linear problem because the ray-path is velocity dependent.

The traveltimes and their partial-derivatives with respect to the velocity and boundary nodes are calculated during ray-tracing. The forward response of the initial velocity model is compared with the observed data. To avoid scattering and focusing of ray paths, smooth layer boundary simulation is applied. Correction vectors are obtained from the damped-least-square inversion of the traveltime residuals followed by update of the model parameters. This iterative procedure has to be continued until satisfactory fit of the observed data and computed responses of the model are achieved (Zelt et al., 1992; Behera et al., 2002; Behera and Sen, 2014). The model is constrained by the RMS traveltime residual along with the chi-square (χ^2) fit of observed data and computed response from all the SPs (Zelt and Smith, 1992; Zelt, 1999).

The chi-square misfit can be expressed as:

$$\chi^2 = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{d_m^i - d_{obs}^i}{\sigma_d^i} \right)^2 \qquad (3)$$

where d_m^i is modeled data, d_{obs}^i is observed data and σ_d^i is the standard deviation. The picked phases and corresponding ray-trace for SP3 is shown in Figure 2. If the value of $\chi^2 \sim 1.0$ then the model is permissible. If χ^2 value is greater than 1.3, then the model corresponds to underfit and if less than 0.7 it indicates overfit.

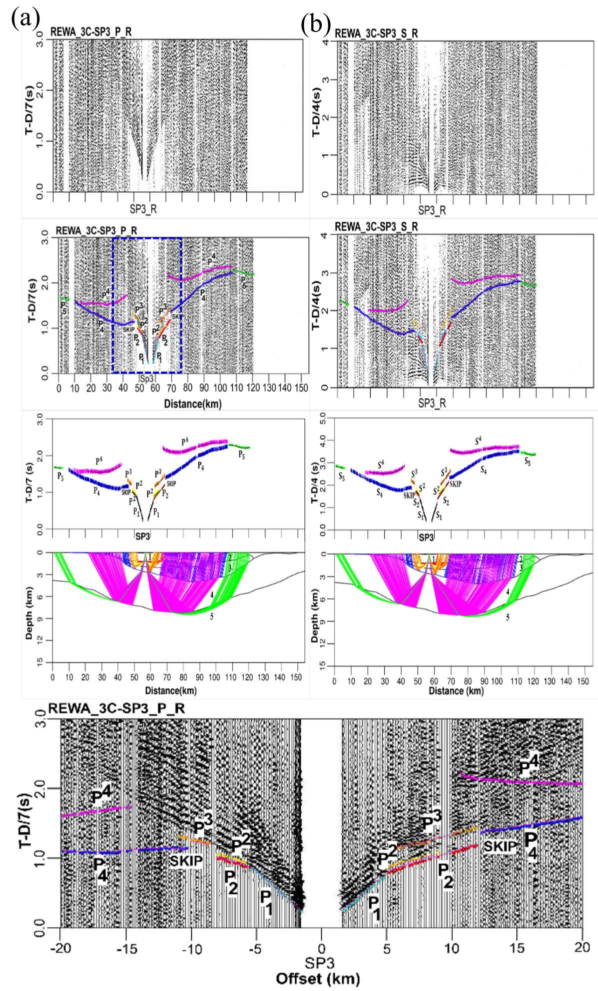

Figure 2. (a) Shows pre-processed radial-component seismic data (top panel) and the corresponding phases picked (middle panel) for the P-waves of SP3. The ray-trace inversion of first-arrival refraction phases (P_1, P_2, P_4, P_5) and reflection phases (P^2, P^3, P^4) along with corresponding traveltime fit is shown in the bottom two panels. (b) Shows pre-processed radial-component data (top panel) and picked phases (middle panel) of the S-waves for same shot point SP3 with corresponding ray-trace inversion of first arrival refraction phases (S_1, S_2, S_4, S_5) and reflection phases (S^2, S^3, S^4) along with the traveltime fit (bottom two panels). SP3 shows traveltime skip due to lowering of amplitude. The corresponding zoomed data (marked in blue rectangle) of SP3_P_R for the different phases picked is shown in the bottom panel for clarity.

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2-D Seismic Modeling and Inversion

Identification and phase picking are the crucial steps of forward modeling and inversion of seismic data. We have picked both P- and S-wave refraction and long-offset reflection phases of all the seven wide-angle SPs along the Hardi-Samatpur profile of south Rewa basin. The first-arrival refraction and reflection phases were picked with picking uncertainties of 25 ms assigned for phases P_1, P_2, P^2 and 50 ms for P_4, P^4, P_5 respectively for the seven shot points (SP1-SP7). The 1-D velocity models are derived separately for each SP using P-wave seismic data. The pseudo 2-D velocity model is obtained by smoothly joining the 1-D velocity models derived. The forward response of the initial model is compared with the observed data and the inversion procedure is repeated until a good fit with the observed data is obtained. The final V_P model is constrained by the RMS residuals of traveltime data for all the SPs and the corresponding chi-square fit. The final V_P model is the input for initial S-wave velocity modeling. Traveltimes of first-arrival refraction and reflections were picked with assigned picking uncertainties of 50 ms for S_1, S_2, S^2 phases and 75 ms for S_4, S^4, S_5 phases respectively for all the seven SPs along the profile. The same procedure is repeated for S-wave modeling to derive the final V_S model along the profile of study. It is to be noted that the third layer of the model is LVL and hence refraction phases (P_3 and S_3) through this layer are absent due to traveltime skip phenomena (Fig. 2).

Results and Discussion:

Ray-trace inversion of all SPs for P- and S-waves are shown in Figure 3. The shallow upper-crustal V_P and V_S models are derived from the ray-trace inversion of the radial-component of P- and S-wave seismic refraction and reflection traveltime data along the Hardi-Samatpur profile (Fig. 4). The velocity variation within the V_P and V_S models are shown with their respective color scales along with localized average velocity (km/s) values for each layer. The SPs are indicated by red dots on the top of the models (Fig. 4).

We have derived shallow basement and upper-crustal velocity structure down to 15 km depth along with the estimates of the compositions of different sub-surface rock types from the inversion of both P- and S-wave seismic data. The top layer indicates presence of loose sediments with sporadic deposits of upper Gondwana sediments (Pali-Tihki formations) having lateral velocity variations V_P (3.20-3.40 km/s), V_S (1.92-2.05 km/s), V_P/V_S (1.570-1.719) and Poisson's ratio (σ) of 0.130-0.244. The models also indicate presence of thick (1.5-2.0 km) column of LVL Gondwana sediments having relatively low values of V_P (4.0 km/s) and V_S (2.36 km/s) with corresponding relatively high values of V_P/V_S (1.695) and σ (0.233) respectively. The LVL is hidden below the HVL basalt flows. There is strong lateral and vertical velocity variation of the basalt flows having V_P (4.85-5.22 km/s), V_S (2.70-2.90 km/s), V_P/V_S (1.758-1.821) and σ (0.261-0.284). The basement is highly undulated forming horst and graben features with large lateral velocity variations of V_P (5.95-6.10 km/s), V_S (3.43-3.60 km/s), V_P/V_S (1.681-1.743) and σ (0.226-0.259) showing deep basinal faults. The sub-basement structure is delineated forming a large depression with corresponding variations of V_P (6.45-6.52 km/s), V_S (3.70-3.72 km/s), V_P/V_S (1.732-1.751) and σ (0.250-0.259) respectively, extended to a depth of 15 km within the upper-crust of the south Rewa basin of Central India (Fig. 4).

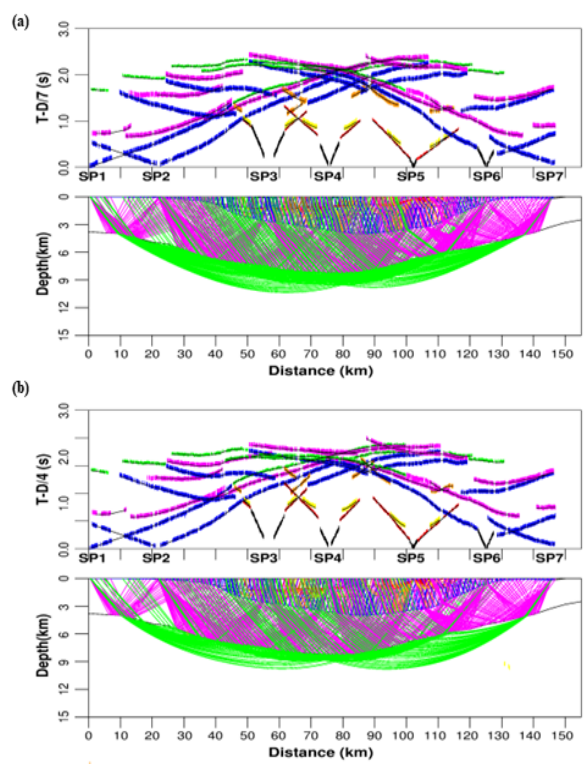

Figure 3. The ray-trace inversion of (a) P-wave and (b) S-wave seismic data picked for all the seven shot points along seismic profile in the south Rewa basin.

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The granitic basement is exposed along the north of the profile from 0-20 km and some parts towards south of the profile from 140 km onwards (Fig. 4). upper Gondwana (Pali-Tihki) formations are exposed on the surface along the profile from 20-110 km. Deccan basalt flow have been intruded through the Gondwana sediments forming dykes and sills. Thick column (1.5-2.0 km) of lower Gondwana sediments are imaged below the high velocity Deccan basalts as trap (Fig. 4).

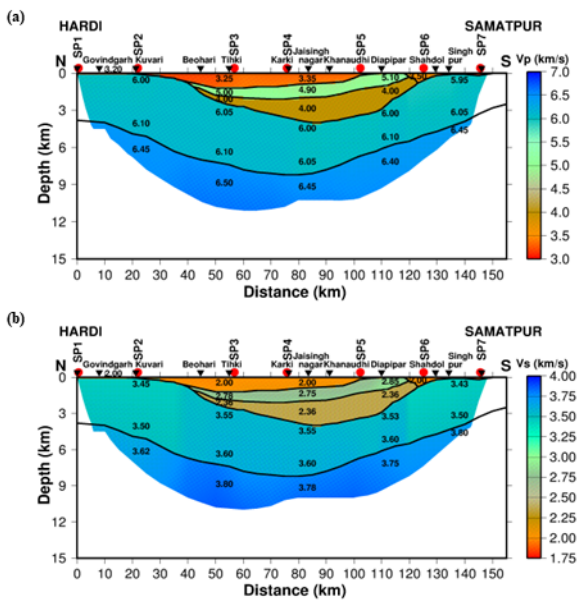

Figure 4. Upper crustal velocity model (a) P-wave velocity (V_p) and (b) S-wave (V_s) of radial component.

Conclusions

From the modeling and inversion of long-offset seismic data along the Hardi-Samatpur profile of south Rewa basin, the following conclusions can be inferred.

- The top layer is maximum 1.2 km thick forming mainly upper Gondwana sediments, which corresponds to Pali-Tihki formation.
- HVL basalt flows (0.5-1.0 km thick) are intruded through the Gondwana sediments and most of the Deccan basalts are exposed in the south of the profile.
- Within the 50-120 km profile distance, maximum 1.5-2.0 km thick LVL Gondwana sediments are imaged, which are mainly confined within the graben potential for hydrocarbon accumulation.
- Basement is highly undulated forming horst and graben structures confined by deep basinal faults.

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