Tomographic imaging of sub-trappean Gondwana sediments for hydrocarbon potential and basement configuration using CDP seismic reflection data acquired in the south Rewa basin of Central India

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Keywords

Rewa basin; Gondwana sediments; Tomography; PSDM; Deccan basalts; Hydrocarbon

Summary

South Rewa basin of Central India is one of the poorly understood sedimentary basins in the world with potential hydrocarbon bearing sub-trappean Gondwana sediments deposited in a typical rift environment followed by masking due to basalt flows related to the Deccan volcanism (~ 65 Ma). To delineate the sub-trappean Gondwana sediments infested with several dykes and sills along with the basement configuration and complex subsurface geological structures, we have derived pre-stack depth migration (PSDM) seismic image with tomographic velocity model obtained along the 127 km long common-depth-point (CDP) seismic reflection data acquired for the N-S trending Kuvari-Shahdol profile in the Rewa basin. The stack section obtained using conventional velocity analysis and seismic data processing fails to provide good result as well as the pre-stack time migration (PSTM) although show some improvement but could not able to image the complex geological structures in this sedimentary basin. Hence, a robust tomographic velocity modeling approach being adopted to image the fine-scale subtle subsurface geological structures with smooth velocity variations, which clearly depicts the presence and extension of basaltic trap with numerous dyke intrusions, alternate horst and grabens with deposition of thick (>5.0 km) hydrocarbon bearing Gondwana sediments overlained by highly heterogeneous basalts (< 2.0 km thick). The PSDM image shows all the subsurface geological structures corroborated with the tomographic velocity model indicating highly fractured basement interspersed by Gondwana sediments due to intense tectonic activity in this rift basin. The seismic image is well constrained in which all the reflection events are flattened having minimum residual moveout (RMO) in the image gathers obtained with the help of tomographic imaging using constrained velocity inversion (CVI) and pre-stack depth migration. The presence of numerous faults cutting across the Gondwana sediments deposited with alternate horst and graben structures and basement undulations with fractures facilitate as the conduits for the emancipation of volcanic lavas forming dykes and sills in this region, which are considered as lower crustal mafic rocks due to the Deccan volcanism.

Introduction

Rewa basin (Fig. 1a) is an important Gondwana sedimentary basin of the Peninsular India largely effected by the Deccan volcanism as well as older igneous intrusives having sub- and intra-trappean Gondwana sediments. The Deccan volcanics (traps) of Late Cretaceous to Palaeogene period covers large part of the western and central India, which is considered as one of the largest basalt covered regions of the world formed due to outburst of tholeiitic lavas during Deccan volcanism (~65 Ma) forming the Late Cretaceous Volcanic Province (LCVP) of Central India. The E-W trending south Rewa basin is considered as a sub-basin of the NW-SE trending Son-Mahanadi rift basin having significant economic resources of huge coal reserves, which is also important for hydrocarbon exploration point of view due to its hydrocarbon potential (classified as Category IV sedimentary basins of India), presence of coal-bed-methane (CBM) and shale gas, as well as other economic mineral deposits like iron ore (hematite), massive Ni-Cu sulfide deposits, aluminium ore (Bauxite), mica, quartz, feldspar etc. There are four Gondwana sedimentary basins of India namely Pranhita-Godavari, Damodar, Satpura and Son-Mahanadi in which the Gondwana sediments deposited are mainly classified under two groups called Lower Gondawana and Upper Gondwana successions. This intra-cratonic south

Rewa basin is delimited by Deccan basalts (trap) in the west, Proterozoic Chhattisgarh group of rocks in the southwest, Precambrian basement rocks in the east and southeast, Palaeoproterozoic Mahakosal metavolcanics in the north and NW-SE trending Son-Mahanadi graben in the south.

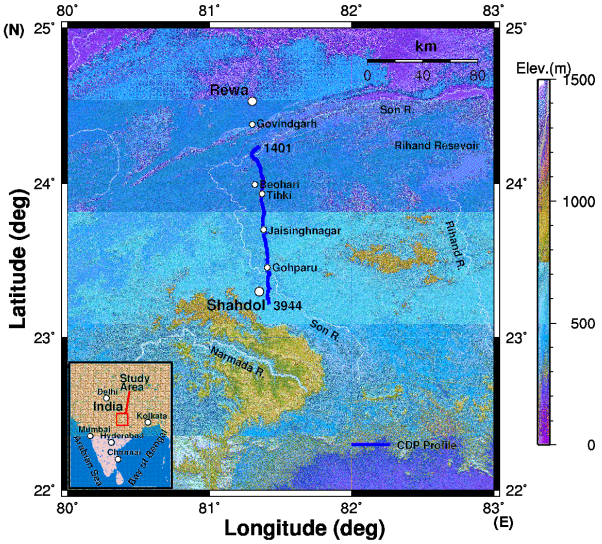

Figure 1: The topographical map of the south Rewa basin (marked as study area in the inset) in the Central India through which the 127 km long N-S trending long-offset CDP seismic profile (blue line) has been executed from Kuvari-Shahdol for imaging of sub-trappean Gondwana sediments. The average elevation of the study area is shown in color scale.

The imaging of hydrocarbon bearing Gondwana sediments hidden below the Deccan trap is a major challenge for the oil industry because conventional (near-vertical) seismic data acquisition and processing techniques fail to image the sub-trappean sediments hidden below the basalts/volcanic traps. Another important factor detrimental for fruitful imaging below the basalt is that the primary reflections are contaminated with severe noises like multiples, diffractions, scattering and multipathing due to large impedance contrasts at the sediment-basalt interfaces, presence of breccias and vesicles within the lava flows (Jarchow et al., 1994). The main objective of this study is to obtain for the first time 2-D comprehensive tomographic velocity model and Kirchhoff PSDM seismic image in the south Rewa sedimentary basin of central India, which is mainly effected by older igneous intrusives as well as infested by 65 Ma Deccan volcanism forming the major trapping mechanism for the Gondwana sediments hidden below the traps and its hydrocarbon potential with the help of long-offset CDP seismic data acquired in the south Rewa basin of Central India.

Seismic data acquisition

The 2-D long-offset (maximum ±12.0 km far-offset on either side of the shot point (SP) with symmetric split-spread configuration) CDP seismic reflection data acquired during 2014-2015 by CSIR-NGRI under the aegis of its XII-V plan project SHORE in the south Rewa basin of Central India along the 127 km long N-S trending Kuvari-Shahdol seismic profile (Fig. 1). The seismic data acquisition parameters are split-spread configuration having 481 active channels (240+1+240) for each spread of every shot taken with SP interval of 100 m and receiver group interval of 50 m. The CDP seismic reflection data acquired for this 127 km long profile by using the cable based line-telemetry seismic data acquisition system (SCORPION from INOVA Geophysical Pty., USA) of the CSIR-NGRI with maximum fold of 60. The seismic data acquisition technique (long-offset/wide-angle) have been adopted to overcome this serious problem of sub-basalt imaging for hydrocarbon exploration in the low-velocity Gondwana sediments hidden below the high-velocity basalts. The example raw seismic data (shot gathers) after application of field geometry for the long-offset CDP data acquired in the Rewa basin (Fig. 2) indicate presence of traveltime skips (SKIP), which is a direct evidence of the presence of thick low-velocity-layer (LVL) hidden below the high-velocity-layer (HVL) considered as basalts (Behera and Sen, 2014) and this is a proven and successful technique to image sub- or intra-trappean LVL sediments in the basalt covered regions of India with numerous examples (Sain et al., 2002; Behera and Sen, 2014). Sub-basalt imaging with the help of conventional near-vertical (coincident) seismic reflection data acquisition technique is very difficult because of the intrinsic properties of the basalt, which significantly obstruct the penetration of seismic energy due to heterogeneous high-velocity basalt layers, rugosity with highly reflective top of the basalts particularly where it is rough and scatters most of the incident seismic energy. It is also important to note that other different types of noises like short-period ringing, simple and peg-leg multiples, converted waves etc., obscure weak sub-basalt reflections with similar moveout.

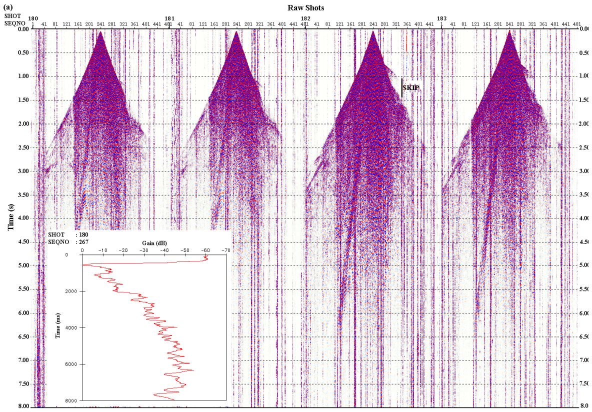

Figure 2: Example raw shot gathers (180-183) of the long-offset CDP seismic reflection data acquired in the south Rewa basin showing very good quality having significant traveltime skips in all the shots shown with the corresponding amplitude decay curve indicates fast decay and severe loss of energy in deeper data obtained after gain analysis (inset) for a single trace 267 of shot 180.

Conventional seismic data processing

The conventional seismic data processing flow (Yilmaz, 2001) have been adopted to process the long-offset CDP seismic reflection data (Fig. 2) acquired in the south Rewa basin. The standard pre-stack procedures involving editing of noisy traces, spherical divergence correction, static correction for elevation and near surface weathering, application of field geometry, filtering (notch, f-k and band-pass), deconvolution and finally sorted the data into common-mid-point (CMP) domain. The bad traces having spikes and glitches are manually edited (omitted) followed by geometrical-spreading or spherical-divergence correction of the data to enhance deeper reflections. Additionally the traces were scaled by 1 dB/s in order to account for inelastic attenuation as well as surface-consistent amplitude balancing is also performed by applying AGC of 2000 ms window length. The most important aspect of seismic data processing is increasing the temporal resolution of the seismic data by compressing the basic seismic wavelet into a spike thereby increasing the band-width of the seismic signal, which is mainly achieved by spiking deconvolution. After series of decon parameter tests for operator length (OL), prediction length (PL) and percent pre-whitening (PPW), the final deconvolution parameters applied to the shot gathers are OL = 0.320s, PL = 0.004s and PPW = 0.1% respectively (Yilmaz, 2001).

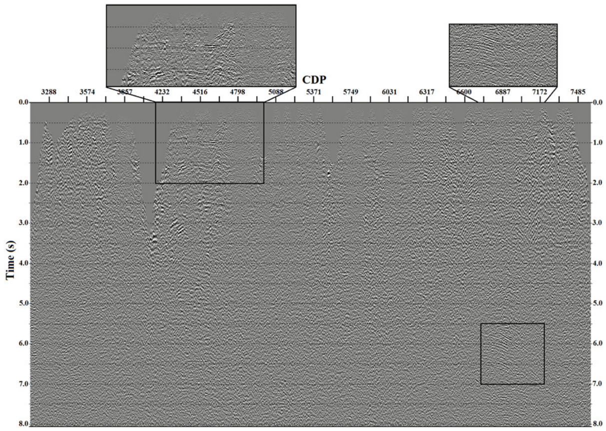

Figure 3: Conventional stack section of the seismic data shows structural features of dipping events, faults, diffused reflections, horizontal reflectors making this region very complex. The poor focusing and imaging problem persists throughout the region due to the presence of basaltic intrusives. The shallow reflections and dipping deeper reflections are zoomed (rectangles) and displayed as insets on the top of the stack section for clarity.

For weathering and elevation corrections, both shot and receiver statics are computed using seismic reference datum (SRD) of 400 m from the elevation data with replacement velocity (V_R) is 4000 m/s used for this profile (chosen as the sub-weathering velocity). The floating datum statics for each CDP gather along this profile is computed using the eq (1) as

$$Statics = \frac{2*1000*(SRD - Floating\ Datum\ (FD))}{Replacement\ Velocity\ (V_R)}\ \text{ms} \qquad (1)$$

and applied on the CMP sorted seismic data to bring the CDP gathers down to the floating datum. Floating datum is a smooth version of the topography, which should be close to the actual topography for better results. The velocity analysis is then performed, which plays an important role in seismic data processing and the final stack section derived (Fig. 3) depends upon how accurately the velocity analysis has been performed for the data. For this, the velocity-semblance (coherency) used in the velocity analysis. In order to improve quality of the velocity-semblance plots, they are often calculated by averaging over a few CMP gathers called supergathers (Sg). The supergather is basically a group of neighboring CMP gathers merged and averaged at each analysis location. In conventional velocity analysis, supergathers consisting of 3 to 5 CMPs are normally used to calculate velocity-semblance and the semblance quality often degrades if we use large number of CMPs than used for normal supergather. Here, the velocity-semblances are calculated from an 11-CMP supergather to achieve good control over the long-offset to see the effect of non-hyperbolic moveout terms. The velocity analysis produces set of vertical stacking/RMS velocities at regular intervals along the CDP profile called RMS-vertical velocity functions. This vertical stacking/RMS velocity analysis is routinely used for velocity model building. The set of RMS velocity values picked along the vertical time axis at a given lateral location is stored as an RMS vertical velocity function and can be converted to other velocities like interval, average and instantaneous velocities using the Dix (1955) conversion and computed at approximately every 1 km intervals (50 CMPs) along the 127 km long profile. The velocity analysis along the profile at different CDP locations show good estimation of the stacking velocity with velocity variations indicating presence of complex subsurface geological structures, which is used to obtain the conventional stack section (Fig. 3). The stack section (Fig. 3) has been improved by applying post-stack processing sequences such as coherency filter and F-X deconvolution, band-pass filtering, automatic-gain-control (AGC) and trace-equalization to enhance the amplitude of the coherent events. Since the stack section could not provide a better image inspite of incorporating the post-stack processing sequences, hence we have adopted the Kirchhoff pre-stack time and depth migrations (PSTM and PSDM) with robust tomographic velocity modeling to image the complex subsurface geological structures for establishing the hydrocarbon potential along the Kuvari-Shahdol profile of the south Rewa Gondwana sedimentary basin.

Seismic imaging with Kirchhoff pre-stack time and depth migrations (PSTM and PSDM)

Velocity model building using reflection tomography

The velocity modeling plays an important role for Kirchhoff PSTM and PSDM of the seismic data. Here, we have used the tomographic velocity modeling approach developed by Farra and Madariaga (1988) and suitably modified by Kosloff et al. (1996) to handle small perturbations in the slowness and layer depths by relating traveltime changes along a given ray and compute the velocity and interface depths based on tomographic inversion of migrated common-reflection-point (CRP) gathers. The tomographic principle is used to convert depth errors in migrated CRP gathers to time errors along a CRP ray pair and thus enable use of conventional traveltime tomography. It is also used to affect a very fast pre-stack migration and set up the tomography matrix.

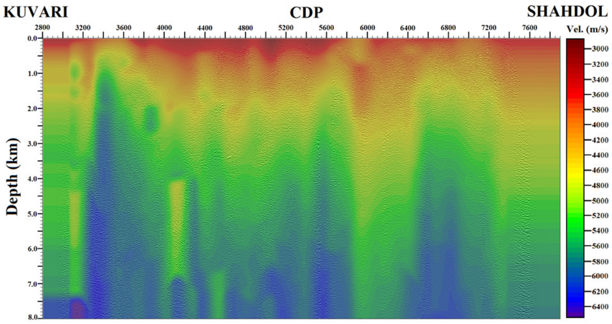

Figure 4: PSDM seismic image superimposed on the tomographic velocity model in the background derived along the Kuvari-Shahdol seismic profile in the south Rewa basin.

The velocity-depth determination method uses the available offsets of all CRPs and inverts for the parameters of all layers simultaneously (Kosloff et al., 1996). Here, the subsurface velocity model is represented by a number of layers separated by horizons over which the velocity can change discontinuously. The input for the inversion is 2-D pre-stack depth migrated variable offset CRP gathers. The tomography updates such as slowness and layer depth changes from an initial model. The slowness change allowed in a layer is vertically uniform and laterally variable in a smooth manner as well as the vertical time changes also vary laterally within the medium. The parameter changes of all the layers are solved for simultaneously and not by layer stripping method to avoid accumulation of errors (both velocity and interface) in deeper targets arise due to shallow targets, which have an adverse affect of the results in the deeper layers.

Pre-stack time and depth migration

The tomographic velocity modeling is applied to the 2-D seismic data acquired in the south Rewa basin. The first step in the tomographic velocity modeling is to develop an initial model. For this objective, Kirchhoff pre-stack time migration (PSTM) was performed on the seismic data using the same RMS velocity model developed along the profile by smoothing the velocity contours. The PSTM yield better image than the stack section with good focusing and continuity of the reflection events in the subsurface. But the PSTM seismic image has its own limitations because it is in time domain and hence interpretation for the subsurface geological structures leads to ambiguous results, which are mainly positioned in the depth domain. Hence, robust velocity model building using the tomographic principle is necessary followed by Kirchhoff PSDM of the seismic data and the key for its success is to establish a reliable velocity depth model.

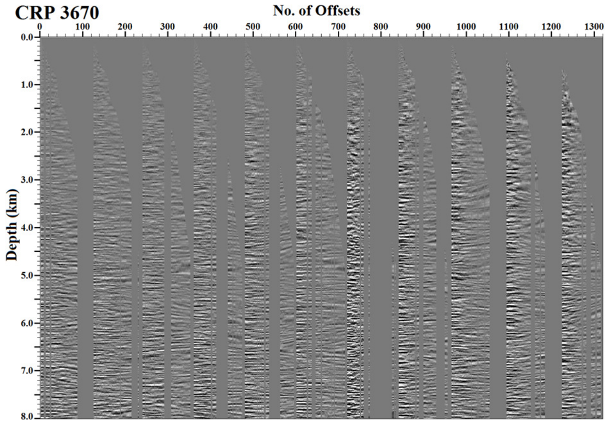

Figure 5: The preconditioned image gathers obtained after automatic residual velocity analysis of the PSDM image with the tomographic velocity model update and CVI shown at same CRP 3670 for different offsets. Each image gather show significant flattening of the events from shallow to deeper parts for which residual moveout are minimum, which are displayed with 12.0 km maximum offset.

A stable constrained velocity inversion (CVI) procedure (Koren and Ravve, 2006) based on the tomographic velocity model building approach as mentioned above is used to derive the pre-stack velocity model. The initial velocity model for CVI processing is normally a set of stacking (RMS) vertical velocity functions. However, there are large variations in the RMS velocity functions, and this velocity model produced unstable results, which cannot be used to provide reliable results during inversion. Therefore, an initial velocity model with a low-velocity surface layer is constructed based on the velocity gradient extracted from a smoothed RMS velocity input using Dix conversion. A Kirchhoff PSDM algorithm is then used for the iterative grid-based tomographic CVI velocity model building and updating using seismic migration (Fig. 4). A migration aperture of 8 km is used in the processing of the seismic data. The corresponding depth migrated gathers (image gathers) obtained are iteratively checked for flattening of the events (Fig. 5) to provide the final updated tomographic velocity model dealing with very small scale subtle velocity variations. Kirchhoff PSDM is one of the most reliable and accurate seismic imaging techniques for finding subtle subsurface geological structures because of its ability to focus and position reflections in areas of strong lateral velocity variations with complex geology as well as can able to handle steeply dipping reflectors as obtained for the Kuvari-Shahdol profile of Rewa basin (Fig. 4). The different small-scale structural features like horsts and grabens, dykes, faults, deposition of sub-trappean Gondwana sediments in the rift basin along with basement configuration imaged along this profile indicate complex geological setting of the study region. The thick column of sub-trappean Gondwana sediments imaged is plausible for hydrocarbon potential in the south Rewa sedimentary basin of Central India with suitable trapping mechanism due to overlying basalts. The newly acquired seismic data allowed us to image steeply dipping structures in this basalt covered Gondwana sedimentary basin with seismic signatures attributed to the basement undulations with fractures as well as overlying volcanic rocks (basalts) from robust tomographic update of velocity modeling (Fig. 6).

Conclusions

The robust tomographic velocity modeling and Kirchhoff PSDM of the CDP seismic data acquired along the N-S trending 127 km long Kuvari-Shahdol profile in the south Rewa rift basin for the first time brings out smooth and minimum structure seismic image in this highly complex geological terrain of Central India for imaging hydrocarbon bearing Gondwana sediments. Since this rift basin has been affected due to widespread Deccan volcanism, the basalts acts as major constrain for deeper penetration of seismic energy using conventional seismic data acquisition and processing techniques adopted by the oil industries in India for significant discovery of oil and gas.

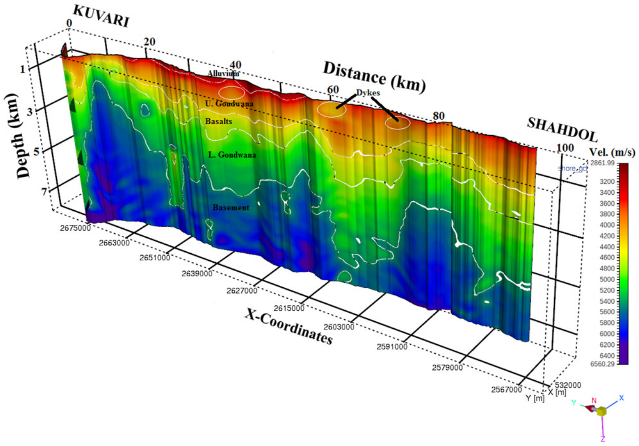

Figure 6: The final updated tomographic velocity model obtained after automatic residual velocity analysis with CVI along the Kuvari-Shahdol seismic profile in the Rewa basin showing subtle velocity variations (shown in color scale) indicating presence of basement fractures, dykes, sills, deep basinal faults with other prominent geological structures as shown in the PSDM image.

However, with the help of state-of-the art seismic data acquisition in the long-offsets (±12 km) using large charge sizes (50 kg) could able to obtain deeper penetration of seismic energy and corresponding reflections from deeper targets below the basalts. With the help of CVI and tomographic update of the velocity model and PSDM could able to delineate subtle velocity variations, which are mainly responsible for imaging small scale structures like fractures, dykes and sills along with deep basinal faults responsible for migration and entrapment forming hydrocarbon reservoir in this Type 1 rift basin. The presence of alternate horst and graben structures with basement upwarping provides an excellent insight about the tectonic activity this sedimentary basin has experienced during rifting of Gondwanaland as well as subsequent reworking for deposition of thick Gondwana sediments for generation of coal seams as well as hydrocarbon reservoir.

Acknowledgments

We thank the Director, CSIR-NGRI to accord permission for publication of this paper. LB thanks Council of Scientific and Industrial Research (CSIR), Govt. of India for funding and support through the XII-V Year Plan Project PSC0205 (LB) SHORE for seismic data acquisition in the Rewa basin of Central India. The seismic data processing was performed using Seismic Unix (SU) of CWP, Colorado School of Mines and Paradigm Geophysical seismic data processing softwares.

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