Assessment of Paleocene to lower Oligocene formations and basement to estimate the potential hydrocarbon reservoirs using seismic inversion: a case study in the Upper Assam Shelf, India

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Abstract

The upper Assam shelf is a self-slope basin in north-east India, filled with nearly 7 km of sedimentary rocks of tertiary period with the granite basement and various oil fields along the border of the Naga thrust. The major producing fields are structural and strati-structural. The study area is placed in between the Mikir hills and Naga thrust. The objective of the study is to identify potential hydrocarbon reservoir zones in the geologically complex south upper of the Assam shelf using estimates of acoustic impedance and porosity derived by 3D post-stack seismic inversion. Well data, such as sonic velocity and density logs, from two wells (namely, KA and TE) are used in the inversion and validation of results. Inversion results are used to build a geological model in the form of acoustic impedance from which we derive 3D porosity cube which are used for hydrocarbon potential in the Paleocene to lower Oligocene sands, and the Precambrian basement. Although the amplitude maps provide an indication of potential reservoirs, the extent of these zones are much better identified in the inverted impedance maps and the corresponding estimated high-porosity zones. The analysis predicted the potential reservoir rocks in the Sylhet, Kopili and Barail formations, in which the Sylhet and Kopili appear to have good potential zones. Near the vicinity of the Naga thrust belt, the proximity of potential reservoir is predicted in the Kopili, Sylhet formation and in the fractured basement, respectively.

Keywords 3D post-stack seismic data · Well log data · Model-based seismic inversion · Impedance · Porosity · Upper Assam Shelf

Introduction

Derivation of elastic parameters such as acoustic and shear impedance and density is the primary task of seismic inversion (e.g. Sen 2006). It involves iterative updating of elastic properties while reducing the misfit between the observed and synthetic data assuming that the source wavelet is known (normally derived from the seismic trace) (Latimer et al. 2000). Synthetic angle stack traces are computed by convolving the angle-dependent reflection coefficients with the source wavelet. Seismic inversion

is also known as iterative forward modelling because it relies on an initial model and perturbs the model parameters until it generates output with the minimum misfit between the original and synthetic one (Singha et al. 2019; Veeken and Silva 2004). However, different variants of seismic inversion exist. These include band-limited impedance inversion, maximum likelihood inversion, sparse spike inversion, Bayesian regularization, model based inversion, etc. (Berteussen and Ursin 1983; Hampson and Russell 1985; Russell 1988; Sacchi and Ulrych 1996; Ferguson and Margrave 1996). Compared to other methods, model-based seismic inversion is advantageous because of its higher correlation and the capability to generate the subsurface images beyond the seismic band limit and within the seismic band with the estimation of low-frequency model (Pendrel 2006; Russell and Hampson 1991; Lorenzen 2000; Latimer et al. 2000). In addition to deriving elastic parameter values, seismic inversion generally results in a higher-resolution image of the subsurface

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since the wavelet effect is deconvolved out of the seismic data (Das et al. 2017; Kumar et al. 2016). Acoustic impedances (it is the product of density and velocity–Russell 1988; Morozov and Ma 2009; Othman et al. 2015) are closely related to rock properties such as porosity; therefore, seismic inversion results can be used to obtain lateral information on petrophysical properties (Latimer et al. 2000; Dolberg et al. 2000; Helgesen et al. 2000; Marion and Jizba 1997). Prospect evaluation and determination of the quality of a hydrocarbon reservoir require estimation of petrophysical properties of a reservoir (Pandey et al. 2020; Chatterjee et al. 2016; Das and Chatterjee 2018). This is generally achieved by first establishing a relationship between the petrophysical properties and inverted seismic attributes at the well locations—this relationship is later used to estimate petrophysical properties in the entire volume (Rijks and Jauffred 1991; Lefeuvre et al. 1995; Russell 2004; Sancevero et al. 2005; Soubotcheva 2006). This commonly used method known as ‘seismic reservoir characterization’ or ‘quantitative seismic interpretation’ requires careful implementation of each step in areas of complex subsurface geology such as the upper Assam shelf, India—the area of our study.

The prime objective of this paper is to evaluate the hydrocarbon potential in the upper Assam basin by accurate estimation of acoustic impedance and porosity for Sylhet, Kopili and Barail formations and the granite basement in the study area (Zamanek et al. 1970; Hussain et al. 2017a,b). The shelf part of the upper Assam basin which is primarily in south-east (SE) dipping shelf (Gogoi and Chatterjee 2019; Kent and Dasgupta 2004) has spread over on the Brahmaputra and Dhansiri valley, and the slope part lies in Mikir hills and Naga thrust zone. The subsurface is structurally complex characterized by numerous faults. In this work, the 3D post-stack seismic volume in the south upper Assam shelf has been interpreted for better assessments for the underlying low acoustic impedance sand in the formations of Paleocene to lower Oligocene age, and the Precambrian basement rock as well as well data. The well logs recorded parameters such as sonic velocity and density log, from each used wells (KA and TE) which are used in the inversion and to validate the results. Both the wells are drilled to the basement depth and placed within the seismic volume. The wells are addressed the depth of the formations and used to extract the wavelet from each of them. Both the wavelets are used in the seismic-tie correlation. To understand rock properties away from the well location, the lateral and vertical variation can be inferred via the quantitative interpretation of the seismic data. Here, we combine the seismic inversion analysis with well data to successfully resolve the problem of prospect evaluation. A workflow is established here to infer the potential zones of reservoir rock in the basement and the sedimentary formations of Paleocene to lower Oligocene

ages. Within these formations, low-impedance and high-porosity properties are used as diagnostic of the presence of hydrocarbon.

Geological background of the study area

The Upper Assam shelf is an area of Upper Assam basin located in north-eastern India, and it is a self-slope basin shown in Fig. 1a, b (Bhandari et al. 1973; Kent and Dasgupta 2004). The basement rock is granite, and the sedimentation of ~7-km-thick sedimentary rocks has been reported in the shelf part of tertiary period (Kent and Dasgupta 2004). The basin evolved through the process of rifting and drifting of the Indian plate from super continent Gondwana. As mentioned in erstwhile studies, during the late Permian to early Mesozoic, a large number of structural features, such as Horst and Graben, were created on the granitic crust in the southern slope of the Dhansiri valley which is located in the south Assam Shelf (Singh et al. 2008; Evans 1964). South Assam Shelf is separated from the North Assam shelf by the east–west trending Jorhat fault. It has been also observed that most of the oil field in the Assam Shelf lies along the border of the Naga thrust, and major producing fields are basically structural and strati-structural (Bastia et al. 1993; Murty 1984; Ranga 1984; Singh et al. 2010). The block of the study area is placed nearby area of the Naga thrust fault. In the erstwhile research, the discovery of oil production has been reported and tested within the fractures of the basement, Basal sandstone and sand within Kopili and Sylhet formation; the steepening slope of the basement is identified towards SE direction (Saha et al. 2006; Pahari et al. 2008). The deposition of the sediments overlying transgressive Tura sandstone, Sylhet formation, and Kopili formation is tilted over on the fractured basement and created a favourable structural entrapment condition for hydrocarbons in the above-mentioned formations as shown in Fig. 2 (Singh et al. 2010; Ranga 1984). The block of the seismic survey area is located within Latitude 26° 14'N to 26° 22'N and Longitude 93° 56'E to 94° 2'E, and bounded by Mikir hills in the west and north-east (NE)–south-west (SW) trending Naga Schuppen belt which makes its eastern boundary (Fig. 1b).

The study decipheres that the structural evolution in the upper Assam basin exerted a major influence on hydrocarbon occurrence. Most likely, the source characteristic and trapping condition are identified in the Tura sandstone of lower Paleocene age, Sylhet formation of late Paleocene to Eocene age and Kopili formations of late Eocene age, whereas Barail formations of Oligocene age are found to be highly organic-rich among all other sequences (Fig. 2). In the Dhansiri valley, the effective source rock characteristics are identified in the shallow marine thick carbonaceous shale of Kopili formation of late Eocene age (Singh et al. 2008).

Fig. 1 **a** Country map of India; **b** location of the study area; the red area demarcates the location of the basin, **b** part of the basin, where study area (c- blue block) is located; **c** The 3D seismic survey area in

the block with two wells drilled in the survey area; **d** surveyed inline and crosslines

Fig. 2 General stratigraphic succession of the upper Assam basin (Wandrey 2004). The study area includes the presence of gas and oil production within the basement, Sylhet, Kopili and Barail formations, respectively, which are considered for our study

These studies demonstrated the presence of reservoir rocks not only in the fractured basement, but also in the overlying transgressive Sylhet limestone–Kopili interbedded sandstone of Eocene age and Tura sandstones of Paleocene age in the upper Assam shelf (Mandal and Dasgupta 2013; Gogoi and Chatterjee 2019).

The processed crosslines 205 and 214 seismic section are shown Fig. 3a, b as examples of subsurface structural complexity. These demonstrate the basement steepening slope direction to be NE–SW; the overlying deposition of Tura sandstone, Sylhet limestone, and basal part of the Kopili formation are indicated as anticlinal features as shown in Fig. 3a, b.

Data availability

In Fig. 1b, an 81 sq. km block is shown in the south upper Assam shelf in which the 3D seismic survey covered 34 sq. km which is used in this work (Fig. 1c). The study area is located in the east of Mikir hills and the west of Naga Schuppen belt. The general strike direction of the study area is in NE to SW direction. In the paper, processed 3D post-stack seismic data are used for the geological interpretation, which include 650-inlines and 621-crosslines in NE–SW and NW–SE direction, respectively, as shown in Fig. 1d. The orientation of the inline and crossline is 29.986 and 119.988 degree from north, respectively (Fig. 1d). The 3D seismic survey of sampling rate 2 ms are recorded for the time length of 5 s. The frequency content of the seismic data ranges from ~8 to 70 Hz. The study included the information of transit time from sonic log and density from density log from two

wells KA and TE from within the 3D seismic survey area. The location of well KA is within the seismic inline-285 and crossline-358, and drilled to the depth of 2338.3 m at the basement. The basement rock of the well KA is granitic rock overlying the deposition of sediments of Sylhet formation, Kopili formation, Barail formation, Bokabil formation, Tipam formation, respectively, and the well TE is located within the seismic inline-353 and crossline-267, and drilled to the depth of 2690.4 m, and contained similar stratigraphic succession with varying thickness as discussed in well KA.

Methodology

The workflow for inversion and rock property estimation is given below:

- Generation of 3D acoustic impedance (AI) model using model-based seismic inversion.
- Estimation of porosity volume for the formations using the extracted acoustic impedance model.
- Mapping of the top of Barail, Kopili, Sylhet and Basement to study the steepening slope of the formations using the inverted volume.
- Mapping of unconformable Isochronopach trend to study the deposition of sediments.
- Mapping of low acoustic impedance model, porosity model for the assessment of potential reservoir zone.

Fig. 3 Processed seismic section of crosslines **a** line-205 **b** line-214, demonstrates basement steepening slope direction to be NE–SW; the overlying deposition of Sylhet limestone and basal part of the Kopili formation is indicated as anticlinal features

Thus, the basic workflow comprises two distinct steps: acoustic impedance inversion and porosity mapping. We describe below each of these steps, in brief, for completeness.

Seismic inversion

The post-stack seismic data are modelled by convolution of a wavelet with a series of reflection events:

$$S(t) = W(t) * r(t) + n(t) \quad (1)$$

where $S(t)$ is the seismic trace amplitude as a function of two way reflection time t , $W(t)$ is the wavelet, $r(t)$ is the reflectivity (normal incidence reflection coefficient), and $n(t)$ is the noise.

Acoustic impedance is defined as the product of density and velocity given by equation (Lindseth 1979):

$$Z_i = \rho_i v_i \quad (2)$$

where Z_i is the acoustic impedance of i th layer, ρ_i is the density of i th layer, and v_i is the velocity of i th layer.

The reflectivity at the boundary between two homogeneous layers is given by (Lindseth 1979):

$$r_i = \frac{Z(i+1) - Z(i)}{Z(i+1) + Z(i)} \quad (3)$$

where r_i is the reflectivity of i th layer, $Z(i+1)$ is the acoustic impedance of $(i+1)$ th layer (Eq. 2), and $Z(i)$ is the acoustic impedance of i th layer (Eq. 2).

Given an acoustic impedance model, the reflection coefficient for each layer boundary is computed from Eq. 3. This results in a reflection coefficient time series, which is convolved with the given wavelet to generate a synthetic seismic trace. The model-based seismic inversion iteratively updates the impedance model while improving the fitness between the observed and the synthetic seismograms. At the convergence, the final impedance model is considered to be the subsurface impedance model at the trace location. The inversion is capable of generating a model of beyond and within the limit of seismic data by the addition of well log data (Russell and Hampson 1991; Austin et al. 2018). The suitable parameters are estimated in order to obtain minimum residual between synthetic inverted data and input seismic data by least square methods at well site, and those parameters are applied on the whole initial acoustic impedance model with the iteration based on generalized linear inversion (Cooke and Schneider 1983).

Mapping of density–porosity model in 3D seismic data

The main steps used to estimate the porosity are as follows:

1. In Eq. 2, it is required to obtain an accurate velocity model to get a density cube from the impedance. The general relationship is used to estimate the velocity model from the acoustic impedance model using Lindseth's approach is shown (Atat et al. 2020):

$$\log(\text{velocity}) = a + b * \log(\text{impedance}) \quad (4)$$

where $a = 0.272926$, and $b = 0.821244$.

2. Using the velocity model, the density model estimated from the acoustic impedance is calculated from Eq. 2.
3. The estimated density model is then used to estimate the porosity model. The general equation used to estimate the porosity from the density model is represented (Serra 1984):

$$\varphi = \frac{d_m - d}{d_m - d_f} \quad (5)$$

where φ is the porosity, d_m is the density of matrix, and taken the value ~ 2.71 g/cc, d is the density of the density model, d_f is the density of fluid, and taken value ~ 1.01 g/cc.

Model-based seismic inversion of 3D seismic volume

Derivation of acoustic impedance from seismic data by seismic inversion requires a wavelet and a low-frequency starting model. The steps for achieving these are described below:

Step 1 Seismic inversion as used here and described above requires that the wavelet be known (Cui and Margrave 2014; Edgar and Baan 2011; Yi et al. 2013). The wavelet is extracted using both the wells KA and TE keeping the phase constant and using the window length of 150 ms, and taper length of 20 ms. Given these parameters, an optimal wavelet is chosen for which the correlation between synthetic and real seismic trace is the highest. The first step, however, is to convert the well logs to time domain. This is achieved by using the following equation (Karim et al. 2016):

$$t(z) = t(0) + 2 \int_{z(0)}^z \frac{dz}{V(z)} \quad (6)$$

where $t(z)$ is the two-way travel time at depth z , $t(0)$ is the vertical two-way travel time at $z(0)$, and $V(z)$ is the two-way p-wave velocity, taken from log data.

Step 2 The wavelet extracted from the well KA that gives a high correlation value between the synthetic trace and the

Fig. 4 Final wavelet extracted using well KA; amplitude shown in: **a** Time domain; **b** Frequency domain, and indicates the minimum phase of value -89

Fig. 5 Images display the cross-correlation between the synthetic seismogram (blue traces) and the original seismic traces (red traces). The correlation obtained: **a** at well KA location is ~0.732; **b** at well TE location is ~0.754

Fig. 6 Two-dimensional time slices at the top of each horizon: **a** Basement; **b** Sylhet; **c** Kopili; **d** Barail, in the study area, and the colour indicates the depth (two way time) of each horizon

original trace is shown in Fig. 4. The variation of amplitude of the wavelet with time and frequency is shown in Fig. 4a and b. In Fig. 4b, the red line is showing the average value of the minimum phase— 89° —for each of the frequency component.

Step 3 Figure 5a, b displays the cross-correlation between the synthetic seismogram and the original seismic traces. The traces of two different colours of blue and red are shown on the right panel of the image; the blue traces represent the synthetic seismogram, and the red traces represent the original seismogram; the correlation value obtained between these two traces at each well KA and TE locations are ~ 0.732 and ~ 0.754 , respectively (Fig. 5a, b).

Step 4 The depositional environments separated by imaginary lines are marked from the information given in well log

data (Faraklioti and Petrou 2004). The depth of the formations Barail, Kopili, Sylhet and Basement is extracted from both the wells KA and TE, and interpolated between the wells within the 3D seismic volume. The illustrative 2D time slice of the top of each horizons Barail, Kopili, Sylhet and Basement is shown in Fig. 6a, b, c, d.

Step 5 The current step is to compensate for the loss of low-frequency information from the seismic data which gives more realistic geological model (Oldenburg et al. 1983). The high cut filter of range $\sim 10/15$ Hz is used to build initial acoustic impedance along all the four horizons Barail, Kopili, Sylhet, and Basement with the p-wave velocity extracted from both the wells (Fig. 5). The acoustic impedance value extracted for each of the formations is shown in Fig. 7.

Fig. 7 High cut filter of range ~10/15 Hz is used to build an initial acoustic impedance model along all the four horizons. The acoustic impedance value: **a** Barail, Kopili, Sylhet formations, respectively;

b basement, extracted along the horizons from an initial acoustic impedance model. The locations of the wells are marked with asterisks

Step 6 The step is used for the analysis of misfit between synthetic acoustic impedance and the original acoustic impedance computed from the well data. All three formations and the basement are considered in the analysis window for each of the wells KA and TE as shown in Fig. 8. The analysis of minimum misfit is verified for the well KA as shown in Fig. 8a, and the analysis of minimum misfit is verified for the well TE as shown in Fig. 8b. Figure 8a, b displays the analysis of model-based seismic inversion at each well. There are two panels: the left panel of the display shows three impedance curves, namely the blue curve which

shows original impedance, the black curve which shows initial guess curve, and the red curve which shows the final inversion result, and the error between the real log impedances and inverted impedances is shown above the panel. At the location of well KA, the estimated error is ~1287.22 $(m/s)*(g/cc)$, and at the location of well TE, the estimated error is ~1209.97 $(m/s)*(g/cc)$. The second panel of the display is shown with two colours—red and black traces—the red traces are the synthetic traces calculated from the inversion results, and the black traces are the seismic traces. The correlation value between the synthetic trace and the seismic

Fig. 8 Quality control analysis, performed at each well KA and TE location, and the correlation obtained between inverted result (red traces) and the seismic traces (black traces) and the values: **a** well KA location ~ 0.978 ; **b** well TE location ~ 0.979

traces is mentioned above the panel which is estimated for the well KA and TE to be ~ 0.961 and ~ 0.971 , respectively. The third panel of the display shows the error between the second panel traces, and the errors estimated for well KA and TE are ~ 0.275 and 0.238 , respectively, which are closer to

zero, indicating the consistency of acoustic impedance trace with the wavelet and the input seismic trace (Fig. 8). In this study, we have used two wells simultaneously instead of one well for inversion, and the results are remarkably improved in the distributions of impedance.

Fig. 9 Images show the Isochronopach (time thickness) of the formations: **a** Sylhet; **b** Kopili; **c** Barail; the thickness increases are shown using colour key, placed on the right side of each time slice

Results and discussion

An acoustic impedance volume has been generated by seismic inversion using the 3D post-stack seismic data, the wavelet and the low-frequency acoustic impedance. In this section, we provide an interpretation of the inverted volume in terms of subsurface geology.

In our study area, the strike direction is marked in NE–SW direction based on geological information. Our goal is to identify potential reservoir zones within formations. The extracted horizons for Barail, Kopili, Sylhet and Basement shown in Fig. 6a, b, c, d, respectively, show the steepening slope directions of the formations to be NW–SE, towards the Naga Schuppen belt. The Isochronopach between the top of

Fig. 10 Preparation of porosity cube from density section to velocity cube which is further derived from impedance cube. IVT: impedance-to-velocity transformation, VDT: velocity-to-density transformation, DPT: density-to-porosity transformation

two formations governs the thickness of the above formations. The Isochronopach for the Sylhet formation increases subsequently towards SE direction as shown in Fig. 9a. Maximum Isochronopach in range ~462 ms to ~546 ms demonstrates the presence of a plunging syncline structure around the NE and as well as, Isochronopach of range ~41 ms to ~104 ms demarcates the presence of a plunging anticline structure around the area containing the TE well in the study area (Fig. 9a). Transgressive Sylhet deposition is demarcated with the presence of plunging anticline and syncline structures in Paleocene and lower Eocene ages, to which it prompted the pressure around the study area due to local and regional tectonic activity in the Paleocene and lower Eocene age. The Kopili formation unconformities of upper Eocene age overlays the Sylhet formation. The subsidence

and sedimentation is more or less continuous towards SE direction, and the maximum areal coverage of the accommodation of SE sediment is thickening towards the north direction of the study area, as shown in Fig. 9b. The maximum and minimum values of Isochronopach in the proximal region draw the presence of accommodations of sedimentation space in plunging syncline and anticline structure, to which it prompted the occurrence of tectonic events, regional and local sediment transport, climatic controls and the effect of eustasy in the Upper Eocene era (Fig. 9b). The Isochronopach of Barail formation demarcates lower Oligocene age. The Isochronopach map indicates that the variation in accommodation throughout the volume of study is in the lower Oligocene era as shown in Fig. 9c.

Next, we examine the high reflectivity zone of the formations and the areal extent of low-impedance sand and the availability of maximum porosity in each formation for the assessment of reservoir in the formations.

Fig. 11 Illustrative diagram is the assessment of the presence of high-reflectivity seismic amplitude in the basement of the study area: **a** the encircled zone indicates the high reflectivity zone in the acquired seismic data; **b** model-based seismic inversion is used to extract the acoustic impedance model, and low impedances ~3000 to ~4667

(m/s)*(g/cc) correspond to high reflectivity zones; **c** the porosity model: encircled porosity ranges from ~12 to ~20% at high reflectivity zone. The study is the assessment of the presence of low-impedance sand reservoir inside the fractured basement

The porosity cube has been transformed from density cube which is extracted from velocity cube, as shown in Fig. 10. The velocity has been extracted from inverted impedance data using Eq. 4 (Fig. 10).

The high reflectivity zone encircled in seismic amplitude slice is shown in Fig. 10a which indicated the presence of low-impedance sand of ranges ~2000 to ~5000

Fig. 12 Illustrative diagram is the assessment of the presence of high-reflectivity seismic amplitude in Sylhet formation: **a** the encircled zone indicates the high reflectivity zone in the seismic data; **b** model-based seismic inversion is used to extract the acoustic impedance

(m/s)*(g/cc) encircled in Fig. 11b to show the presence of reservoir rock in the Sylhet formation; the porosity extracted for the similar low-impedance zone ranges from ~28 to 38% which is encircled in Fig. 11c. In Fig. 11 b, c, we identify proximal variation of reservoir rock more or less in the NE and SE directions around the location of both the wells KA and TE. Larger areal extent of the reservoir rock is found in the SE part of the study area in the Sylhet formation. In Fig. 12b, the low-impedance sand of ranges ~2000 to 4000 (m/s)*(g/cc) is encircled to show the presence of reservoir rock in the high reflective zone (Fig. 12a) within Kopili formation; the porosity

model, and encircled the low impedances ~2000–~5000 (m/s)*(g/cc) at high reflectivity zone; **c** the porosity model encircled the porosity ~28–~38% at high reflectivity zone. The study is the assessment of the presence of low-impedance sand reservoir in the Sylhet formation

extracted for the similar low-impedance zone is ~31% to ~39% which is encircled in Fig. 12c. In Fig. 13b, the zone of the reservoir low-impedance sand ranges from ~2000 to 4000 (m/s)*(g/cc) which is encircled with the high reflectivity zone (Fig. 13a), and the porosity of ranges ~37% to 41% estimated in the Barail formation is shown in Fig. 13c.

Figure 14b displays the top of the basement with 10 ms window, and the encircled low impedance of range ~3000 to ~4667 (m/s)*(g/cc) within the high reflectivity zone (Fig. 14a) demarcated the presence reservoir with the porosity of ranges ~12% to 21% which is encircled in Fig. 14b. In

Fig. 13 Illustrative diagram is the assessment of the presence of high-reflectivity seismic amplitude in Kopili formation: **a** the encircled zone is indicated the high reflectivity zone in the seismic data; **b** model-based seismic inversion is used to extract the acoustic impedance model, and encircled the low impedances ~2000– ~4000

(m/s)*(g/cc) at high reflectivity zone; **c** the porosity model encircled the porosity ~31–~39% at high reflectivity zone. The study is the assessment of the presence of low-impedance sand reservoir in the Kopili formation

Fig. 14b, the nonzero value of porosity indicates the presence of fractures in the basement.

Oligocene Barail shales, which act as a source rock in the Oligocene to Miocene of the petroleum system, have higher porosity as observed in time section of the porosity of Fig. 13c. This higher porosity in the Barail formation could be associated with the higher rate of sedimentation in the Middle Miocene period in fluvio-deltaic conditions. The Eocene Kopili formation has fine-grained sand during a marine transgression and contains huge amounts of lower-impedance sand reservoir with higher porosity but lesser than Barail formation. The lower Eocene Sylhet which is made of limestone with interbedded fine shale and sand layers has lower porosity than the Kopili formation.

Conclusions

Inversion of a 3D seismic volume in the upper Assam shelf was carried out, and the resulting impedance and porosity volumes were examined to identify potential reservoir zones. The data and the corresponding inverted volume clearly highlight the basement, and the formations of Paleocene to lower Oligocene age of the upper Assam shelf and the steepening slope of the basement. It also displays that each formation dips towards the SE direction, approaching the Naga thrust fault. The maximum and minimum values of Isochronopach in the proximal region demarcate the presence of accommodations of sedimentation in the plunging syncline and anticline structures, to which it prompted the

Fig. 14 Illustrative diagram is the assessment of the presence of high-reflectivity seismic amplitude in Barail formation: **a** the encircled zone indicates the high reflectivity zone in the seismic data; **b** model-based seismic inversion is used to extract the acoustic impedance

model, and encircled the low impedances $\sim 2000\text{--}4000$ (m/s)*(g/cc) at high reflectivity zone; **c** the porosity model encircled the porosity $\sim 37\text{--}41\%$ at high reflectivity zone. The study is the assessment of the presence of low-impedance sand reservoir in the Barail formation

occurrence of tectonic events, regional and local sediment transport, climatic controls and the effect of eustasy in Paleocene to lower Oligocene. Considering the thickening sediments displaying low impedance and high porosity, we identify the most prospective zones for reservoir rocks in the formations. The study identifies the potential reservoir rock in the Sylhet, Kopili and Barail formations, in which the Sylhet and Kopili show good potential zones of reservoir rock which are found to be consistent with the well log data. As the area approaches the vicinity of Naga thrust belt, the proximity of the potential reservoir is predicted in the Kopili formation, Sylhet formation and in the fractured basement. The analysis of porosity modelling reveals that the higher porosity values reach 41% in the Barail formation, and the distributions of porosity in the granite basement clearly indicate potential sand reservoirs.

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Declarations

Conflict of interest It is hereby informed that we do not have any conflict among authors and regarding data for possible publication the manuscript in the Journal of Petroleum Exploration and Production Technology. I would like to inform you that we have used one 3D seismic data and three well log data in the Assam upper shelf. The data

were collected from the Oil India with the help of Prof Rima Chatterjee who is one of the co-author of this manuscript. The results of the manuscript were not published to any other journal previously.

Ethical approval We, three authors (Neha Rai, Dip Kumar Singha and Rima Chatterjee), have maintained all the ethical transparency and professional conducts during research analysis, data sharing and preparing the manuscript. We have mentioned the data source Oil India in the acknowledgement section of the manuscript.

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References

- Atat JG, Akankpo AO, Umoren EB, Horsfall OI, Ekpo SS (2020) The effect of density-velocity relation parameters on density curve in TAU field, Niger delta basin. *Malays J Geosci* 4(2):54–58. <https://doi.org/10.26480/mjg.02.2020.54.58>
- Austin EO, Onyekuru Samuel I, Ebuka OA, Abdulrazzaq TZ (2018) Application of model-based inversion technique in a field in the coastal swamp depo belt, Niger delta. *Int J Adv Geosci* 6(1):122–126. <https://doi.org/10.14419/ijag.v6i1.10124>
- Bastia R, Naik GC, Mahapatra P (1993) Hydrocarbon prospects of Schuppen belt Assam Arakan basin in Biswas SK et al. (eds.) Proceeding second seminar on petroliferous basin of India, ONGC, Dehradun 18–20 December 1991, 1 (East Coast, Andaman and Assam-Arakan basin), 493–506
- Berteussen AK, Ursin B (1983) Approximation computation of the acoustic impedance from seismic data. *Geophysics* 48:1305–1414. <https://doi.org/10.1190/1.1441415>
- Bhandari LL, Fuloriya RC, Sastri VV (1973) Stratigraphy of Assam valley, India. *AAPG Bull* 57(4):642–654. <https://doi.org/10.1306/819A4310-16C5-11D7-8645000102C1865D>
- Chatterjee R, Singha D, Ojha M, Sen MK, Sain K (2016) Porosity estimation from pre-stack seismic data in gas-hydrate bearing sediments, Krishna-Godavari basin, India. *J Nat Gas Sci Eng* 33:562–572
- Cooke DA, Schneider WA (1983) Generalized linear inversion of reflection seismic data. *Geophysics* 48:665–676
- Cui T, Margrave FG (2014) Seismic Wavelet Estimation. *CREWES Res Rep* 26:1–16
- Das B, Chatterjee R (2018) Well log data analysis for lithology and fluid identification in Krishna-Godavari Basin, India. *Arab J Geosci* 11:231–242. <https://doi.org/10.1007/s12517-018-3587-2>
- Das B, Chatterjee R, Singha DK, Kumar R (2017) Post-stack seismic inversion and attribute analysis in shallow offshore of Krishna-Godavari Basin, India. *J Geol Soc India* 90:32–40. <https://doi.org/10.1007/s12594-017-0661-4>
- Dolberg DM, Helgesen J, Hanssen TH, Magnus I, Saigal G, Pedersen BK (2000) Porosity prediction from seismic inversion, Lavrans Field, Halten Terrace Norway. *Lead Edge* 19(4):392–399. <https://doi.org/10.1190/1.1438618>
- Edgar AJ, Baan VM (2011) How reliable is statistical wavelet estimation. *Geophysics* 76(4):v59–v68
- Evans P (1964) The tectonic framework of Assam. *Geol Soc India* 5:80–96. <https://doi.org/10.1190/1.3587220>
- Faraklioti M, Petrou M (2004) Horizon picking in 3D seismic data volume. *Mach Vis Appl* 15:216–219. <https://doi.org/10.1007/s00138-004-0151-8>
- Ferguson RJ, Margrave GF (1996) A simple algorithm for band-limited impedance inversion. *CREWES Res Rep* 8(21):1–10
- Gogoi T, Chatterjee R (2019) Estimation of petrophysical parameters using seismic inversion and neural network modeling in upper Assam basin, India. *Geosci Front* 10:1113–1124. <https://doi.org/10.1016/j.gsf.2018.07.002>
- Hampson D, and Russell B (1985) Maximum-likelihood seismic inversion. In: Proceeding of the 12th annual national Canadian Society of exploration geophysicists (CSEG) meeting abstract no. SP-16, Calgary, Alberta, May 7–10
- Helgesen J, Magnus I, Prosser S, Saigal G, Aamodt G, Dolberg D, Busman S (2000) Comparison of constrained sparse spike and stochastic inversion for porosity prediction at Kristin field. *Lead Edge* 19(4):400–407. <https://doi.org/10.1190/1.1438620>
- Hussain M, Chun WY, Khalid P, Ahmed N, Mahmood A (2017a) Improving petrophysical analysis and rock physics parameters estimation through statistical analysis of Basal sands, Lower Indus Basin, Pakistan. *Arab J Sci Eng* 42:327–337
- Hussain M, Ahmed N, Chun WY, Khalid P, Mahmood A, Ahmad SR (2017b) Reservoir characterization of Basal Sand zone of lower Goru Formation by petrophysical studies of Geophysical logs. *J Geol Soc India* 89:331–338
- Karim US, Islam SMD, Hossain MM, Islam Md (2016) Seismic reservoir characterization using model based post-stack seismic inversion: in case of Fenchuganj gas field, Bangladesh. *J Jpn Petrol Inst* 59(6):283–292. <https://doi.org/10.1627/jpi.59.283>
- Kent NW, Dasgupta U (2004) Structural evolution in response to fold and thrust belt tectonics in northern Assam. A key to hydrocarbon exploration in the Jaipur anticline area. *Mar Petrol Geol* 21(7):785–803. <https://doi.org/10.1016/j.marpetgeo.2003.12.006>
- Kumar R, Das B, Chatterjee R, Sain K (2016) A methodology of porosity estimation from inversion of post-stack seismic data. *J Nat Gas Sci Eng* 28:356–364. <https://doi.org/10.1016/j.jngse.2015.12.028>
- Latimer R, Davison R, Van RP (2000) An interpreter's guide to understanding and working with seismic-derived acoustic impedance data. *Lead Edge* 19(3):242–256. <https://doi.org/10.1190/1.1438580>
- Lefevre FE, Wrostad KH, and Zou KS, Smith LJ, Maret JP, Nyein UK (1995) Sand-shale ratio and sandy reservoir properties estimation from seismic attributes: an integrated study. SEG annual meeting 1995, USA, Houston p. 1623. Doi: <https://doi.org/10.1190/1.1887627>
- Lindseth RO (1979) Synthetic sonic logs—a process for stratigraphic interpretation. *Geophysics* 44(1):3–26. <https://doi.org/10.1190/1.1440922>
- Lorenzen RJL (2000) Inversion of multi component time lapse seismic data for reservoir characterization of Vacuum Field, New Mexico: Ph.D. Thesis, Colorado School of Mines
- Mandal K, and Dasgupta R (2013) Upper Assam basin and its basinal depositional history. 10th biennial international conference and exposition, Society of petroleum geophysicists, Kochi, 292
- Marion D, Jizba D (1997) Acoustic properties of carbonate rocks: use in quantitative interpretation of sonic and seismic measurements. In: Palaz I, Marfurt KJ (eds) Carbonate seismology. Society of Exploration Geophysicists, Tulsa, pp 75–94
- Morozov IB, Ma J (2009) Accurate poststack acoustic-impedance inversion by well-log calibration. *Geophysics* 74(5):59–67. <https://doi.org/10.1190/1.3170687>

- Murty KN (1984) Geology and hydrocarbon prospect of Assam shelf-recent advances and present status. *Petroleum Asia Jour* 6(4):1–14
- Oldenburg DW, Scheuer T, Levy S (1983) Recovery of the acoustic impedance from reflection seismograms. *Geophysics* 48(10):1318–1337. <https://doi.org/10.1190/1.1441413>
- Othman AAA, Ewida HF, Fathi MM, Embaby M (2015) Seismic inversion for reservoir characterization in Komombo Basin, upper Egypt, (Case study). *IJSET-Int J Innov Sci Eng Technol* 2(9):654–666
- Pahari S, Singh H, Prasad VS, Singh RR (2008) Petroleum system of upper Assam shelf. *Geohorizon*, India, p 14
- Pandey AK, Chatterjee R, Choudhary B (2020) Application of neural network modeling for classifying hydrocarbon bearing zone, water bearing zone and shale with estimation of petrophysical parameters in Cauvery basin, India. *J Earth Syst Sci*. <https://doi.org/10.1007/s12040-019-1285-4>
- Pendrel J (2006) Seismic inversion-still the best tool for reservoir characterization. *CSEG Recorder* 31(1):5–12
- Ranga Rao A (1984) Geology and hydrocarbon potential of a part of Assam-Arakan Basin and its adjacent Region petrol. *Petroleum Asia J* 6(4):127–158
- Rijks EJK, Jauffred JCEM (1991) Attribute extraction: an important application in any detailed 3-D interpretation study. *Geophys Lead Edge Explor* 10(9):11–19. <https://doi.org/10.1190/1.1436837>
- Russell BH (1988) Introduction to seismic inversion methods. Society of Exploration Geophysicists. <https://doi.org/10.1190/1.9781560802303>
- Russell B, Hampson D (1991) Comparison of poststack seismic inversion methods. *Soc Explor Geophys Expand Abstr*. <https://doi.org/10.1190/1.1888870>
- Russell BH (2004) The application of multivariate statistics and neural networks to the prediction of reservoir parameter using seismic attributes. (Unpublished doctoral thesis), University of Calgary, Calgary, AB. Doi: <https://doi.org/10.11575/PRISM/24453>
- Sacchi MD, Ulrych TJ (1996) Bayesian regularization of some seismic operators. In: Hanson KM, Silver RN (eds) *Maximum entropy and Bayesian methods. Fundamental theories of physics* (An international book series on the fundamental theories of physics: their classification, development and application), 79. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-5430-7_55
- Saha T, Chowdhury KB, Chakraborty D, Prusty KS, Khatri LB, Reddy VG (2006) Understanding structural configuration on the basis of 3D seismic attributes in Dhansiri valley, Assam. *Geohorizon* 2:28–31
- Sancevero SS, Remacre AZ, Portugal RS, Mundim EC (2005) Comparing deterministic and stochastic seismic inversion for thin-bed reservoir characterization in a turbidite synthetic reference model of Campos Basin Brazil. *Lead Edge* 24(11):1168–1172. <https://doi.org/10.1190/1.2135135>
- Sen MK (2006) Seismic inversion. Society of Petroleum Engineers
- Serra O (1984) Fundamentals of well-log interpretation, 1. The acquisition of logging data. *Developments in Petroleum Science*, Elsevier Science Publisher, Amsterdam, 15A:201
- Singh RK, Bhaumik P, Akhtar MS, Siawal A, and Singh HJ (2008) Deeper (paleogene) hydrocarbon plays and their prospectivity in south Assam Shelf, A and A A basin, India. 7th Biennial International Conference and Exposition on Petroleum Geophysics, SPG, Hyderabad, 2008, p-442
- Singh RK, Bhaumik P, Akhtar MS, Singh HJ, Mayor S, and Asthana M (2010) Major Hydrocarbon Trap Types in Dhansiri valley, Assam and Assam Arakan Basin, India. 8th Biennial International Conference and Exposition on Petroleum Geophysics, SPG, Hyderabad, 2010, p-161
- Singha KD, Shukla KP, Chatterjee R, Sain K (2019) Multi-channel 2D seismic constraints on pore pressure and vertical stress related gas hydrate in the deep offshore of the Mahanadi Basin, India. *J Asian Earth Sci*. <https://doi.org/10.1016/j.jseae.2019.103882>
- Soubotcheva N (2006) Reservoir property prediction from well-logs, VSP and multi component seismic data. Pikes peak heavy oilfield. Saskatchewan. M.Sc Thesis. Department of Geology and Geophysics. University of Calgary, Calgary, Alberta. Doi: <https://doi.org/10.11575/PRISM/360>
- Veeken CHP, Silva DM (2004) Seismic inversion methods and some of their constraints. *First Break* 22(6):47–70. <https://doi.org/10.3997/1365-2397.2004011>
- Wandrey CJ (2004) Sylhet-Kopili/Barail-Tipam composite total petroleum system, Assam geological province, India. USGS open file report, 2208-D
- Yi BY, Lee GH, Kim HJ, Jou HT, Yoo DG, Ryu BJ, Lee K (2013) Comparison of wavelet estimation methods. *Geosci J* 17(1):55–63. <https://doi.org/10.1007/S12303-013-0008-0>
- Zamanek J, Glenn EE, Norton LJ, Caldwell RL (1970) Formation evaluation by inspection with the borehole televiewer. *Geophysics* 35:254–269. <https://doi.org/10.1190/1.1440089>

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