Pre-drill pore pressure prediction and safe well design on the top of Tulamura anticline, Tripura, India: a comparative study

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Abstract

The Tulamura anticline falls in the state Tripura, Northeast India. The anticline is extended up to neighbour country Bangladesh. The region is characterized by huge anticlines, normal faults and abnormally pressured formations which causes a wide margin of uncertainties in wildcat well planning and design. These geological complexities of Tulamura anticline make the drilling engineers more challenging. Therefore, a proper well design is essential in such a region to prevent blow-out. Drilling engineer requires to maintain wellbore pressure between the pore pressure and fracture pressure to reduce the possibility of a kick and a formation damage. Pore pressure plays an important role to design a safe and economical well in such a high pressure and temperature reservoir. For wildcat drilling, only seismic data are available in the study area. There are various methods to predict pore pressure from seismic velocity data. Modified Eaton's method is widely used for the pore pressure prediction from seismic data in terms of the velocity ratio. Modified Eaton's equations may cause an error by manual selection of compaction trend line which is used to find normal compaction velocity. The main objectives of this study are to develop a new method to predict pore pressure and safe well design on the top of Tulamura anticline in terms of pore pressure. The new method is validated by a well-known method, modified Eaton's method, and RFT pressure data from offset wells. An excellent match with pore pressures estimated from RFT pressure data and predicted by new model along with modified Eaton's method is observed in this research work. The efficiency and accuracy level of the hybrid model is more as compared to other methods as it does not require compaction velocity data; thus, an error caused by manual compaction trend can be eliminated. Pore pressure predicted by new method indicates result up to the 6000 m, which is up to the basement rock. The predicted pore pressures by new method are used as an input to calculate the fracture pressure by Hubbert and Willis method, Mathews and Killy method and modified Eaton's method. Equivalent mud weight selection is carried out using median line principle with additional 0.3 ppg, 0.3 ppg and 0.2 ppg of swab pressure, surge pressure and safety factor, respectively, for calculation of all casing pipes. Casing setting depths are selected based on pore pressure gradient, fracture pressure gradient and mud weight using graphical method. Here, four types of casing setting depths are selected: conductor, surface, intermediate and production casings at 100 ft, 6050 ft, 15500 ft and 18,500 ft, respectively, by new methods, but the casing setting depths for intermediate are at 13500 ft in the case of modified Eaton's method. The casing policy is selected based on burst pressure, collapse pressure and tension load. For each casing, kick tolerance in bbl is determined from kick tolerance graph to prevent the blowout. Finally, comparative safe and economical wells are designed on the top of Tulamura anticline along with target depth selection, casing setting depth selection, casing policy selection and kick tolerance in consideration of collapse pressure, burst pressure and tension load which gives a clear picture of well planning on the top of anticline in pore pressure point of view.

Keywords Pore pressure prediction · Seismic data · Tulamura Tripura · New method · Well design

List of symbols

H Depth (ft)
 γ Poisson's ratio

K_i Stress ratio
 T Two-way travel time (μ s)
 PP, P_p Pore pressure (psi)
 PF, P_f Fracture pressure (psi)
 HP Hydrostatic pressure (psi)
 P_{ob} Overburden pressure (psi)
 $P_{pNormal}$ Normal pore pressure (psi)

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$GPP, \frac{P_p}{H}$	Pore pressure gradient (ppg)
$GPF, \frac{P_f}{H}$	Fracture pressure gradient (ppg)
$GOV, \frac{P_{ov}}{H}$	Overburden gradient (ppg)
$\frac{P_v}{H}$	Effective stress gradient (ppg)
$\frac{P_1}{H}$	Tectonic stress correction gradient (ppg)
R_{Normal}, V_{Normal}	Normal resistivity and normal interval velocity of the compacted core
$R_{observed}, V_{observed}$	Observed resistivity and observed interval velocity of a core sample

Introduction

Pore pressure and fracture pressure are important parameters for drilling engineering to design a safe well in the wildcat area. Pore pressure and fracture pressure play a very significant role in well design and reservoir modelling. Pore pressures are determined by prediction method and detection method. The pressure is measured directly by taking a fluid sample from the formation in the direct method. Based on the complexity, performance and cost of method, drill stem testing (DST), wireline formation testing (RFT) and production testing (PT) are the order of test carried out with respect to time. The objectives of this study are to develop a new method to predict pore pressure and hence to design a safe well on the top of Tulamura anticline, Tripura, India, from seismic velocity data.

Pore pressure prediction equation from seismic data is given by the Karl (1996), Sayers et al. (2000), Matthews (1967), Eaton (1975), and Yan et al. (2013). Seismic interval velocities were estimated from the two-way seismic root mean square velocities (RMS velocity) by Dix's equation (Dix 1995). During seismic processing, seismic velocities are designed in such a way that the stack/migration is optimum with local fluctuation being smoothed and the velocity pic interval range is large for accurate pore pressure prediction.

Karl (1996) first estimated pore pressure from velocity using the simple experimental setup in 1948. This approach is working on effective stress, and it states that all measurable effects on the changes in stress are a function of effective vertical stress. This porosity-based approach is not working on the above abnormal pressure-causing mechanisms and leads to error formation pressure. Hottmann and Johnson (2007) estimated the formation of pressure by log-derived shale properties. This study was based on the logging data where the degree of compaction of shale is in response to compaction in axial stress. Pore pressure is related to the degree of compaction and burial depth. Hottmann and Johnson used shale acoustic and resistivity data to estimate

reservoir formation pressure. Here, standard deviation on acoustic and resistivity method is 0.020 and 0.22 psi/ft, respectively.

Matthews (1967) worked on pore and fracture pressure prediction and published an article in 1972. The purpose of that article was to show the relationship of lithologic properties indicated by logs that can be correlated to indicate pressure within the earth. Matthews and Kelly also presented a fracture pressure gradient equation. However, they introduced the concept of the variable horizontal-to-vertical stress ratio.

Eaton (1975) gave an equation for the prediction of over-pressure from well logs. Eaton's equations are derived from the drilling parameter and well log. All four theoretical-based equations give geo-pressure by the use of conductivity plot, resistivity plot, sonic travel time plot and D-exponent plot. The accuracy of geo-pressure by all equations is dependent on the quality of input data and method for the normal trend line.

Yan et al. (2013) gave the experiment-based equation for the pore pressure prediction from laboratory core measurement. In that study, pore pressure was predicted based on acoustic log and resistivity log data. Yan and Han's equation contained an effective stress coefficient which is estimated from laboratory measurement.

Brahma et al. (2013a, b) published an article on pre-drill pore pressure prediction using seismic velocity data on the flank and synclinal part of Atharamura anticline in the Eastern Tripura, India. They described the Atharamura anticline in eastern Tripura, which is the same in this study for validation and for further well planning. In that paper, they gave a proper flowchart to pore prediction from seismic velocity data and modified Eaton's equation was used to predict pore pressure and compare with RFT data.

In this work, modified Eaton's method and Yan method are studied thoroughly to predict pore pressure and derive an integrated approach for the pore pressure prediction. Pore pressure by the new method is validated by using RFT (repeat formation test) pressure data of the case study on the Tulamura anticline. Based on the new pore pressure from the integrated approach, the final well design is done on the top of the Tulamura anticline.

Fracture pressure was calculated by different methods based on an assumed Poisson ratio and stress anisotropy with depth and overburden pressure. Fracture pressure analysis is important for the well stimulation process. Hydrofracturing is necessary in order to increase production from conventional and non-conventional reservoir to increase mobility of fluid (Zhang et al. 2018; Dejam 2019a, b; Dejam and Hassanzadeh 2018; Dejam et al. 2018). Fracture pressure is calculated by Hubbert and Willis's equation (Hubbert and Rubey 1959), Matthews and Kelly's equation (Matthews 1967) and Eaton's equation

(Eaton 1969). From overburden pressure and pore pressure are used to find out fracture pressure gradient. Constant Poisson's ratio (0.25) is used in Hubbert and Willis's equation to find out fracture pressure. Matthews and Kelly's equation was used for fracture pressure calculation by using a matrix stress coefficient (0.33). Eaton and modified Eaton's equations were used for fracture pressure calculation with variable Poisson's ratio which is from Poisson's ratio curve given by Eaton.

Brahma and Sircar (2018) further worked on the Atharamura anticline, Tripura, to design a safe well using seismic data on the top of Atharamura. The main objective of their work was planning a safe well over Atharamura anticline to explore and exploit hydrocarbons. Planning an exploratory well from seismic velocities aims to produce: pore pressure prediction, establishing drilling mud window, target depth selection, optimal mud policy, kick tolerance guidelines and the final well with casing policy.

Elmahdy et al. (2018) gave an idea about pore pressure prediction in unconventional carbonate reservoir by using porosity and compressibility attribute of the rocks. The objective of their work was to predict the formation pore pressure by using a modified Atashbari prediction model upon the wireline logging data. This model is applied to the carbonated reservoir of Middle Eocene Apollonia formation, Abu El Gharadig basin, Egypt. That model had been calibrated with direct pressure measurement (MDT) from the well for the best result.

Radwan et al. (2019) published an article on pore and fracture pressure modelling using direct and indirect methods in Badri Field, Gulf of Suez, Egypt. Objective of that work was to find out pore and fracture pressure prediction by direct and indirect method and to identify the overpressure zones in subsurface. All the pressure predictions were based on well logging data like resistivity, density, sonic and gamma-ray from offshore well in the Badri field. They used the Amoco overburden equation for calculation of overburden stress, while Eaton's equations are used for the pore pressure and fracture pressure prediction from sonic and resistivity logs.

A comparison of fracture pressure predicted by various methods is shown in results and discussions. Modified Eaton's method gave more realistic results for fracture pressure. Tectonic correction is very important for the geologically complex area to get an accreted fracture pressure. Modified Eaton's method considered tectonic correction so it gives the most accurate result for fracture pressure gradient. In this paper, we used modified Eaton's method for the further process of designing a safe well on the top of the Tulamura anticline. Finally, two exploratory wells are designed on the top of the Tulamura anticline based on the pre-drill pore pressure prediction and fracture pressure, drilling mud

window, optimal mud policy selection, propose of safe casing policy with kick tolerance guidelines.

We proposed a new method for the pore pressure prediction based on seismic data. Previously, all the methods for the pore pressure prediction are dependent on the two-way travel time and normal compaction trend line velocity data. In this new method, pore pressure is not dependent on the normal compaction trend data so error caused by normal compaction trend data is eliminated and procedures of pore pressure prediction are the simple and actual representation of subsurface formation pressure.

In this work, the first part indicates the study area for a case study on the top of Tulamura anticline, Tripura, India. All geological and petrophysical properties are discussed and used for target depth selection and casing policy selection. After that, detailed methodology is described for proposed new method and methodology for the design of a well from pore pressure and fracture pressure is given in detail. After pore pressure prediction, new method is validated with RFT pressure data on the top of Tulamura anticline, Tripura, India. A comparison of two well design policies proposed by considering pore pressure by new method and modified Eaton's method is discussed in detail (Fig. 1). Finally, summary and conclusion give all the ideas about the new method, their advantages–disadvantages and proposed design of a safe well.

Study area

Tripura is a non-coastal state in Northeast India surrounded by six states: Assam, Mizoram, Arunachal Pradesh, Manipur, Nagaland and Meghalaya which are jointly known as the Seven Sister States. It spreads over 4050.86 m² (10,491.69 km²). It ranges from 24° 32' N to 22° 56' N, and 92° 20' E to 91° 09' E. The physical geography of Tripura is categorized by plains, hill ranges and valleys. Tripura has five anticlinal ranges of peaks from north to south: Baramura in the west, through Atharamura, Longtharai and Shakhani, and Jampui Hills in the east. The intervening synclines are the Udaipur–Agartala, Teliamura–Khowai, Ambasa–Kamallapur, Kailasahar–Manu and Kanchanpur–Dharmanagar valleys (Development 2007).

The airborne gravity survey leads to the delineation of fourteen large closed anticlinal structures, viz., Langtarai, Gojalia, Skham, Baramura, Tichna, Atharamura, Tulamura, Machlithum, Batchia, Harargaj, Langai, Khubal, Rokhia, and Jampai anticlines, as shown in Fig. 2. A series of long and narrow anticlines with north–south-trending axial traces separated by board intervening synclines are present in Tripura fold belt thrust (FBT). In most of the anticlines, Middle Bhuvan formation is capped by Upper Bhuvan, Bokabil and Tipam formations (Fig. 3). High abnormal to superpressures

Fig. 1 Problem statement

are observed from Middle—Lower Bhuban, practically in all the structures of the Cachar area with pressure gradient reaching almost geostatic or even exceeding it. Compaction disequilibrium, aided partly by clay diagenesis and tectonic activity, has been found responsible for the generation of overpressures in the Tripura area (Bhagwan et al. 1998).

The Tripura subbasin is constituted by a huge tertiary sedimentary sequence of post-Cretaceous to Pleistocene age (Momin and Choudhury 1999). The generalized stratigraphic section in the study area is indicated in Figs. 2, 3. All the wells drilled so far in Tripura have penetrated only up to Surma group of rocks. The Lower to Middle Miocene Surma group, consisting of the Bhuban formation and the overlying Bokabil formation, was deposited during repeated transgressions and regressions. These widespread units together reach more than 4500 m thickness in the Tripura fold belt and the deeper part of the Bengal basin. The sequence appears to thicken towards south and east and appears to have its depocenter in Mizoram (Chakravorty and Gupta 2011). Out of the three units within the Bhuban formation, the lowermost and the uppermost are mainly siltstones and fine-grained sandstone, alternating with mud rock, whereas the middle unit is composed of silty and sandy mudstone. The Bokabil formation generally consists of alternating mudstone, siltstone and fine- to medium-grained sandstones. The middle part of the Bokabil is more arenaceous and forms natural gas reservoirs in the Tripura as well as in the Bengal basin.

Theory and methodologies

The literature gives a clear idea about the pore pressure prediction by modified Eaton's method which is more promising than other pore pressure prediction methods. Pore pressure prediction by modified Eaton's method is dependent on input data and normal compaction velocity trend. For validation of pore pressure prediction, offset well pressure data are required. The pore pressure is predicted to develop a normal compaction curve with well depth and compare it with an actual compaction curve. Overpressure is calculated in terms of deviation from a normal trend. Normal compaction curve plays a critical role in determining the pore pressure prediction.

On the top of Tulamura anticline, two seismic sections at synclinal (A) and at flank (B) are taken. Both the seismic sections A and B are taken in a west–east direction. Normal (average) velocity and two-way travel time are taken as input data for various CDPs. Detail of prediction of pore pressure gradient and fracture pressure gradient process is described in Fig. 4.

Pore pressure (PP)

Modified Eaton's method

Modified Eaton's method predicts pore pressure by approximation of the effective vertical stress in terms of ratio

Fig. 2 Study area: Tulumura, Baramura and Atharamura anticlines (Jena et al. 2011)

resistivity and a ratio of sonic log velocities of observed value to normal value. For variable overburden gradient, the modified Eaton's equation is:

$$P_p = P_{ob} - (P_{ob} - P_{pNormal}) \left(\frac{V_{observed}}{V_{Normal}} \right)^3 \quad (1)$$

or

$$P_p = P_{ob} - (P_{ob} - P_{pNormal}) \left(\frac{R_{observed}}{R_{Normal}} \right)^{1.2} \quad (2)$$

Yan and Han's method

Yan and Han worked on a new model for pore pressure prediction. Yan and Han's model for pore prediction was brought up based on the stress effect modelling of laboratory core measurement. Their model requires exactly the same inputs of modified Eaton's method and should have better performance in pore pressure prediction. Then performances of pore pressure prediction by using differential pressure and effective pressure, respectively, are compared.

$$V_{observed} = V_{Normal} + 3.87 \left(e^{-1} - e^{-\frac{P_{ob}}{P_{pNormal}}} \right) \quad (3)$$

The above two methods are pretty convenient to calculate the pore pressure only by using density and P-wave velocity data. However, V_{Normal} is the necessary parameter for the two methods. When the acoustic logging curve is incomplete or fluctuates strongly, the calculated V_{Normal} is not accurate enough, which will influence the accuracy of the results predicted by these two methods.

Formulation of new method

A new method is proposed in this study by the combination of Yan and modified Eaton's method. The specialty of our new model is that it eliminates the error caused by V_{Normal} . In our model, the normal velocity is not required which was very critical to determine. Due to the elimination of normal velocity in our model, the accuracy level is increased as compared to the existing models. New method can be represented as follows:

Fig. 3 Stratigraphy and petroleum system of Tripura, Assam–Arakan basin (Akram et al. 2004)

$$\varepsilon = \mu - (\mu - 1) \left(\frac{V_{\text{observed}}}{V_{\text{observed}} - 3.87(e^{-1} - e^{-\varepsilon})} \right)^3 \quad (4)$$

where $\varepsilon = P_p/P_{p\text{Normal}}$ and $\mu = P_{ob}/P_{p\text{Normal}}$.

Fracture pressure (PF)

Fracture pressure estimation is given by Hubbert–Willis's equation:

$$\frac{P_f}{H} = \frac{P_t}{H} + \left(\frac{P_{ov}}{H} - \frac{P_p}{H} \right) \left(\frac{\gamma}{1-\gamma} \right) + \left(\frac{P_p}{H} \right) \quad (5)$$

For $\frac{P_{ov}}{H} = 1$ and $\gamma = 0.25$, Eq. 5 reduces to:

$$\frac{P_f}{H} = \frac{1}{3} \left(\frac{P_{ov}}{H} \right) + \frac{2}{3} \left(\frac{P_p}{H} \right) \quad (6)$$

Matthews and Kelly give similar Hubbert equation given by the ratio of variable horizontal stress to vertical stress given by Fig. 5.

Matthews and Kelly's equation:

$$\frac{P_f}{H} = K_i \left(\frac{P_v}{H} \right) + \left(\frac{P_p}{H} \right) \quad (7)$$

Eaton further improved Eq. (7) by familiarizing the variable overburden gradient and variable Poisson's ratio, where the ratio of lateral strain to longitudinal strain is given by Poisson's ratio. Eaton's relation for the fracture pressure is given by:

$$\frac{P_f}{H} = \frac{P_t}{H} + \left(\frac{P_{ov}}{H} - \frac{P_p}{H} \right) \left(\frac{\gamma}{1-\gamma} \right) + \left(\frac{P_p}{H} \right) \quad (8)$$

Eaton's correlation of Poisson's ratio vs depth of the Gulf Coast is given in Fig. 6. From this relation, we calculate fracture pressure using Eaton's relation.

Fracture pressure by Eaton's relation has variable overburden pressure gradient and variable Poisson's ratio.

Fracture pressure by Eaton's correlation is needed tectonic stress correction so the final fracture pressure is exact.

Tectonic stress correction is given by:

$$P_t = (P_{ov} - P_p) * \text{horizontal stress ratio} \quad (9)$$

so that the final equation is known as the modified Eaton's equation for fracture pressure relation:

FLOW CHART

Fig. 4 Pore pressure prediction and fracture pressure prediction

Fig. 5 Matrix stress coefficients of Matthews and Kelly (Matthews 1967)

$$\frac{P_f}{H} = \frac{P_t}{H} + \left(\frac{P_{ov}}{H} - \frac{P_p}{H} \right) \left(\frac{\gamma}{1 - \gamma} \right) + \left(\frac{P_p}{H} \right) \quad (10)$$

Mud weight selection

Median line principle is used for the selection of appropriate mud weight so that no formation fluid loss and no formation damage accrued with maintaining hydrostatic pressure for all depths. In the median line, principle mud weight is the average pressure of pore pressure and fracture pressure. Mud weight should be selected with an additional 0.3 ppg as the swab pressure, 0.3 ppg as the surge pressure and 0.2 ppg as a safety factor.

Target depth selection and casing shoe depth selection

Alam (1989) showed that the sediments are mainly Middle Miocene to Holocene in age and include up to 10,000 m of

coarse to fine clastic (Siwalik group) that are derived directly from the Himalayan uplift and are essential of fluvial molasses characteristics. The north margin of this fore deep is strongly folded and faulted.

From the stratigraphy (Fig. 3), it is found that Middle Bhuvan encountered around 3000 m to the 6000 m depth. Though the Middle Bhuvan is exposed on the Tulumura anticline, it is decided to select the target depth 5600 m as the pore pressure accelerates to the higher magnitude at these depths which may be due to the hydrocarbon presence. Besides, the Lower Bhuvan strata penetrated in the deepest well in Rokhia have good source rating, capable of generating gas and condensate.

Also, it is better to design an exploratory well for deeper depths not only to explore hydrocarbons but also to obtain a safe casing policy. So, the target depth for the well on the top of the anticline is selected as 18500 ft (approximately 5630 m).

After target depth selection, casing shoe depth and the number of casings are selected by the bottom-to-top approach from drilling operation manual for Oil and Natural Gas Corporation (Dehradun 2002). Mud weight is also

selected based on the above median line principle by using surge, swab and safety margin. First, shoe depth is selected for production casing at the target depth (Gabolde and Nguyen 2006).

Any wells will not be drilled with a single type of casing. Selecting casing seats for pressure control purposes starts with knowing geological conditions such as formation pressures and fracture gradients. This information is generally available within an acceptable degree of accuracy.

The second casing is selected as intermediate casing; it is between the shallowest possible depth for intermediate casing and the deepest possible setting depth for the intermediate casing.

Surface casing avoids underground blowouts to choose a depth that can competently withstand the pressures of reasonable kick conditions. First, calculate equivalent mud weight at the depth of interest and draw a graph with depth which cuts the fracture pressure at a particular depth as selected as the surface casing.

Hole geometry selection

The hole geometry selection is based on several commonly used hole geometry programs. From expected drilling condition and based on bit and casing size availability, drilling industry selects geometry programs (Gabolde and Nguyen 2006).

Collapse pressure

From the Schlumberger, oilfield glossary collapsed pressure is the pressure at which a tube, or vessel, will terribly deform as a result of differential pressure acting from outside to the inside of the vessel or tube.

The conventional approach is used for calculating collapse pressure. As shown in Eq. (11) external pressure is equal to casing annulus pressure and back up pressure is equal to zero (empty casing). Here, 1.125 is a factor of safety.

$$\text{Collapse pressure} = 1.125 * (\text{external pressure} - \text{back up pressure}) \quad (11)$$

Burst pressure

Burst pressure is the theoretical internal pressure exerted on well casing walls. From conventional approaches for calculating burst pressure, internal pressure is due to the gas kick from the next phase. Here, 1.1 is the factor of safety.

$$\text{Burst pressure} = 1.1 * (\text{external pressure} - \text{back up pressure}) \quad (12)$$

Tension load

The tensile load is due to the weight of the casing which is maximum at the top and minimum at the bottom without considering buoyancy force in a conventional approach. With considering buoyancy force, tensile load at the top and compressive load at the bottom are:

$$\text{Tensile load} = 1.8 * \text{length of the casing pipe} * \text{nominal weight} \quad (13)$$

Kick tolerance calculation

Kick tolerance calculation indicates the maximum kick volume that can be circulated at the time of drilling without fracturing the previous casing shoe at the maximum drill pipe shut-in pressure (DPSIP), and additional mud weight is required to counter the kick. Kick tolerance curve is shown in terms of plotting the kick volume v/s depth or drilling pipe depth or kick volume v/s maximum DPSIP.

$$(V) = (Ca) * (H_{\max}) \quad (14)$$

Table 1 Predicted pore pressure gradient and RFT pressures gradient at Tulumura

Well name	Overpressure starts at (m)	Number of CDP match with RFT (flank)	Number of CDP match with RFT (synclinal)
Agartala Dome (Ad-6)	2500	1	2
Ambasa N Trend	3200	4	2
Kathalchari Trend	2130	3	1
Kubal	1800	—	3
Masimpur—3	2500	3	1
Rokhia Structure—Ro1	2300	4	4
Tichna Structure—Ti1	2400	1	4
Ad—4 Trend	3000	1	1

$$Ca(\text{bbl/ft}) = \frac{(\text{hole size(in)}^2 - \text{drill pipe size(in)}^2)}{1029.4} \quad (15)$$

$$H_{\max} = \frac{(P_{fg} - M_w) * \text{TVD} - (P_{pg} - M_w) * \text{TVD}}{(M_w - \rho_k)} \quad (16)$$

where V is the influx volume at the shoe, Ca is the capacity of the open hole annulus, $H_{\max}$ is the maximum height of a gas bubble, M_w is the mud weight, ρ_k is the influx density = 1.9 ppg, TVD is the true vertical depth, P_{fg} is the fracture pressure gradient at the current casing shoe, P_{pg} is the pore pressure gradient at the next target depth.

Influx volume at the bottom is calculated by Boyles's law from calculated influx volume at the shoe:

$$V_1 = V_{\text{shoe}} \times \frac{P_{P,\text{shoe}}}{P_p} \quad (17)$$

Result and discussions

Pore pressure prediction

Seismic data were used as an input for pore pressure prediction. Overburden pressure that starts at 1240 m in section A (syncline) and 2300 m in section B (anticline) on Tulumura is shown in Table 1.

Pore pressure (PP) predicted by new method indicates results up to the basement rock (i.e. up to 6000 m depth).

Basement rock is normally metamorphic or igneous below sedimentary basins and sedimentary rock formation. It is significant to select target depth is up to sedimentary formation because basement does not have a pore. In Tulumura anticline, we focused up to depth of 6000 m, as the sedimentary rock is encountered up to that depth. In this study, $V_{\text{rms}} = V_{\text{avg}}$ is the first equation assumed for pore pressure prediction. This assumption is valid only for shallow depth (6000 m).

All CDPs for flank and synclinal sections are used as input data to calculate pore pressure by new method and modified Eaton's equation. Predicted pore pressure at different CDPs is compared with existing offset well repeat formation tester (RFT) pressure data for validation. Totally, 14 RFT pressure data from offset wells are considered for comparison with predicted pore pressure from seismic data. Out of 14 offset wells, 8 of them have overpressure.

Overpressure starts for Rokhia structure at the depth of 2300 m. Here, red colour indicates the RFT pressure gradient with respect to depth. Blue colour indicates a pore pressure gradient by modified Eaton's equation, and green colour indicates a pore pressure gradient by the new method. Pore pressure gradient predicted by new method and modified Eaton's equation is matched by the RFT pressure gradient data. Overpressure gradient is constant nearly 8.13 ppg up to the normal depth. After the normal depth, 2300 m for Rokhia structure pore pressure gradually increased 19.5 ppg up to the depth of 6000 m. Comparatively, it has been observed that pore pressure gradient trend predicted by new method is better matched with RFT pressure gradient on

Fig. 6 Variable Poisson's ratio with depth as proposed by Eaton (1969)

Rokhia structure than pore pressure gradient predicted by modified Eaton's method.

In Fig. 7, details of comparisons of pore pressure gradient predicted by new method and modified Eaton's method along with RFT pressure gradients of offset wells with respect to the depth are displayed for Tichna structure. Overpressure starts in Tichna structure from the depth 2400 m to the depth of 6000 m. Pore pressure predicted by the new method and modified Eaton's method is 8.13 ppg up to the normal depth of 2400 m. Here, an excellent match between the RFT pressure gradient with pore pressure gradient by a new method and modified Eaton's method is observed for Tichna structure.

The above two comparisons on the top of Tulamura anticline show that pore pressure gradient predicted by the new method is excellently matched with RFT offset well data. It signifies that our new method is working properly for the prediction of pore pressure from seismic velocity on the top of Tulamura anticline, Tripura. The details of comparisons of the pore pressure gradient (PPG) by new method and modified Eaton's method for different CDPs along with RFT pressure gradient data are displayed in Table 1.

Well design based on new method

To design a safe and economical well on the top of Tulamura anticline, Tripura, a set of seismic profiles with seismic velocity data and two-way travel time are implemented in this research work. Details of methodology and theory are discussed in methodology section. The CDPs of both

syncline and flank sections are considered as input data to design a safe well on Tulamura. The main parameters for that purpose are discussed in detail in the following subsections.

Pore pressure prediction

Table 2 displays the calculated density, overburden pressure, overburden pressure gradient, pore pressure and pore pressure gradient. The overburden pressure gradient is increased up to the shallow depth and then becomes constant about 20 to 21 ppg for all depths. Normal hydrostatic pressure gradient becomes constant 8.13 ppg for all the depths, and pore pressure gradient predicted by new method is constant up to the normal compaction depth (8000 ft) and then suddenly increased due to the possible hydrocarbon accumulation and high formation pressure due to Lower Bhuvan formation above the depth of 8000 ft. The details of pore pressure regime are shown in Fig. 8.

Fracture pressure prediction

The fracture pressure estimated using pore pressure as input values is given in Table 3. The fracture pressure is showing the lowest by Hubbert's equations apart from all equations; fracture pressure estimated by Eaton's and modified Eaton's methods gives more readable value because of the variable Poisson ratio. Complex regions like the Tulamura where normal faults are frequent than horizontal stress ratio are not homogeneous; Eaton's equation works well with variable stress ratio. Tulamura structure is an anticline which has undergone folding and stress

Table 2 Pore pressure prediction by a new method

Time (msec)	RMS velocity (m/s)	Interval velocity (m/s)	DEPTH (ft)	Density (g/cc)	Overburden pressure (kg/cm ²)	Overburden pressure gradient (ppg)	Pore pressure by new method (kg/cm ²)	Pore pressure gradient by new method (ppg)
36	1829	0.00	108.01	—	3.29	8.35	—	—
149	1900	1922.07	464.40	2.10	26.13	15.41	14.21	8.38
312	2060	2196.08	1054.33	2.19	65.45	17.00	32.25	8.38
433	2285	2782.45	1623.04	2.33	105.84	17.85	49.65	8.38
876	2594	2863.99	3727.60	2.35	256.37	18.83	114.02	8.38
1068	2730	3279.70	4782.87	2.42	334.34	19.14	146.30	8.38
1273	2885	3585.72	6024.61	2.47	427.92	19.45	184.28	8.38
1561	3080	3824.63	7886.94	2.51	570.23	19.80	241.25	8.38
1712	3205	4288.78	9000.92	2.57	657.33	20.00	415.09	12.63
2163	3502	4452.59	12,425.90	2.58	927.07	20.43	738.40	16.27
2410	3573	4143.09	14,125.54	2.55	1059.08	20.53	910.79	17.65
2974	3668	4048.91	17,894.74	2.54	1350.47	20.66	1221.94	18.70
3517	3757	4211.22	21,675.47	2.56	1645.05	20.78	1512.03	19.10
4044	3816	4188.52	25,314.80	2.55	1928.31	20.86	1786.31	19.32
4959	3899	4246.45	31,717.75	2.56	2428.02	20.96	2259.25	19.50

Fig. 7 RFT and predicted pore pressure by new method and modified Eaton's method. (Rokhia structure—RO1)

anisotropy so tectonic stress correction is required. Therefore, using variable Poisson's ratio, Eaton and modified Eaton's equations give the best result after tectonic correction. For a geologically complex region like Tulumura, modified Eaton's method is more suitable. The comparative fracture pressures estimated by various methods on Tulumura are shown in Table 3.

All units are taken on FPS (foot–pound–second) measurement system for simplicity to design a well and selection of casing effortlessly. Table 2 indicates the fracture pressure in psi with respect to depth on the top of Tulumura anticline. Calculated fracture pressure by modified Eaton's equation, Eaton's equation, Hubbert and Willis's equation and Matthews and Kelly's equation is shown in Table 2 and Fig. 9. All calculations are based on the pore pressure predicted by the new method.

Pressure gradient (ppg) v/s depth (ft) is given in Fig. 9 and Fig. 10 shows all fracture pressure gradient behaviours with respect to depth. Here, black colour indicated pore

pressure gradient by new method, fracture pressure gradient by Hubbert and Willis's equation (blue) lowest compare to all fracture pressure gradients because constant Poisson's ratio (0.25) is used. Fracture pressure gradient by Matthews and Kelly's equation (red) is very high at higher depth due to the use of matrix stress coefficient (0.33). Fracture pressure gradient by Eaton's equation (green) is given better result but required tectonic correction. Fracture pressure gradient by modified Eaton's method is given by purple colour. Continuous line indicates fracture pressure gradient estimated using pore pressure predicted by new method, and dotted line indicates fracture pressure gradient estimated by using pore pressure predicted by modified Eaton's method. This graph further plays an important role to estimate mud weight selection and casing selection.

Table 3 Fracture pressure on the Tulumura anticline using pore pressure by the proposed new equation

DEPTH (ft)	Overburden pressure Pob (psi)	Pore pressure PP (psi)	Fracture pressure by Hubbert and Willis PFH (psi)	Fracture pressure by Matthews and Kelly PFM (psi)	Fracture pressure by Eaton's equation PFE (psi)	Fracture pressure by Modified Eaton PFME (psi)
108.01	46.87	—	—	—	—	—
464.40	372.10	201.53	258.87	326.28	270.63	326.68
1054.33	931.86	457.54	616.73	769.78	654.74	810.73
1623.04	1506.85	704.34	973.51	1209.12	1046.41	1310.41
3727.60	3650.09	1617.63	2298.95	2840.08	2562.54	3231.36
4782.87	4760.12	2075.58	2975.35	3669.67	3374.63	4258.09
6024.61	6092.59	2614.45	3780.03	4654.61	4373.84	5518.56
7886.94	8118.66	3422.63	4996.08	6141.02	5948.37	7494.04
9000.92	9358.83	4889.54	7059.54	9029.50	7825.05	8963.20
12,425.90	13,199.24	10,285.84	11,408.40	14,912.73	12,150.67	13,037.13
14,125.54	15,078.66	13,356.73	13,671.22	17,993.72	14,307.76	15,004.44
17,894.74	19,227.43	18,462.25	18,007.40	23,806.53	18,653.12	19,257.03
21,675.47	23,421.52	23,031.38	22,158.95	29,334.83	22,912.33	23,537.30
25,314.80	27,454.46	27,280.97	26,106.58	34,584.13	26,985.85	27,653.05
31,717.75	34,569.03	34,526.52	32,967.17	43,689.26	34,135.84	34,928.76

Optimal drilling mud weight selection

It is very critical to decide proper mud weight for safe well drilling. Mud weight should be varying with depth at drilling time. For maintaining hydrostatic pressure at a time of drilling, mud weight selection is the main decision variable. Hydrostatic pressure must be maintained between pore pressures and fracture pressure for safe drilling. Optimum mud weight is selected using the median line principle and shown in Fig. 11. In the depth v/s mud weight graph, red line indicates mud weight in ppg calculated by using the median line principle. A green colour line indicates mud weight estimated by considering surge and swab with the median line principle. Tulumura is a high pressure and temperature formation at a deep depth. Mud weight up to the normal pressure depth upto (8000 ft) should be 11 ppg to 14 ppg, but for abnormal pressure, at depth from 8000 ft to 20,000 ft the required mud weight is from 14 to 20 ppg as shown in Table 4.

Burst pressure, collapse pressure and casing seat selection

A single type of casing is not used for the whole depth of well. Casing shoe depth, number of casing string, casing dimension and material are decided by casing policy selection from pore pressure gradient and fracture pressure gradient. For casing depth selection, pore pressure, fracture pressure and optimal mud weight are required. In the process of casing seat selection, shoe is set where the next formation is drilled out without fracturing casing shoe. From graphical plotting of pore pressure gradient, fracture pressure gradient

against depth. This procedure is implemented bottom to top. In this paper, casing depth selection is shown in Table 5. First, 100 ft is considered as conductor casing. Casing depth up to 6050 ft, 15,500 ft and 18,500 ft is considered for a surface, intermediate and production casing, respectively, by the method of setting depth selection as described in theory and methodology by using pore pressure predicted by a new method.

After casing depth determination, casing dimension, nominal weight and grade are selected from calculating collapse pressure, burst pressure and tension load for each casing. For load calculation, conventional approach is used for all casings. In the conventional approach, the minimum desired safety factor for collapse 1.125, burst 1.10 and tension 1.80 is considered.

Casing pipe property is given in Table 5. Here, we used four casings: conductor casing, surface casing, intermediate casing and production casing. Available standard casing property from petroleum handbook data book by Adams and Charrier (1985) is selected based on casing diameter, collapse resistance and burst resistance. Tension resistance is also considered for selection parameter in this research work. Casing collapsed pressure (psi), burst pressure (psi) and casing type with respect to depth are given in Table 6.

Casing grade is selected for conductor casing up to depth of 100–150 ft and recommended with grade (K-55, 94.0 lbm/ft), surface casing up to depth of 6050 ft with casing grade (Q-125, 92.50 lbm/ft) as shown in Fig. 12. Intermediate casing 6050 ft to 15,500 ft with casing grade (V-150, 70.30 lbm/ft) in Fig. 13, and two types of production casings for the depth 0 ft to 11,500 ft with casing grade (P-110, 38.0

Fig. 8 RFT and predicted pore pressures by new method and modified Eaton's method. (Tichna structure TI-1)

lbm/ft) and for 11,500 ft to 18,500 ft is grade (V-150, 42.70 lbm/ft) shown in Fig. 14.

Figures 12, 13 and 14 indicate casing grade selection by considering collapse and burst pressure for the surface casing, intermediate casing and production casing. Green colour indicates recommended collapse pressure in psi, red colour indicates internal burst pressure in psi, yellow colour indicates backup burst pressure in psi, and maroon colour indicates recommended resultant burst pressure in psi for casing grade selection. Blue and purple colours indicate selected casing grade for respective casing diameter.

Kick tolerance calculation

The curve shown in the drill pipe depth v/s kick volume (Fig. 15) is called a kick tolerance graph. A point above and

left the side of a line is the safe zone. The point below and right side of the line is the blowout zone. The combination of drill pipe shut-in pressure and kick size gives kick tolerance in bbl. Table 7 gives the details of kick tolerance values for the top of Tulamura anticline.

For drilling up to depth 100 ft to 6050 ft, no surface casing is required; only conductor casing is necessary. Therefore, kick volume 750 bbl is required to control at the depth 100 ft and up to 10 bbl at 6050 ft. After drilled up to 6050 ft, it is advisable to install surface casing before further drilling. After conductor casing, kick volume is controlled up to 254 bbl at 6050 ft and up to 60 bbl at 12,500 ft. After drilled up to 12,500 ft, it is advisable to install intermediate casing. Finally, drilling up to target depth 18,500 ft. After drilled up to the 18,500 ft, two-step production casing install is (P-110,

Fig. 9 Fracture pressure gradient calculated using pore pressure predicted by new method

38.0 lbm/ft) for 0–11,500 ft and (V-150, 42.70 lbm/ft) for 11,500–18,500 ft.

Determination of cement slurry volume for cementing

Cement slurry volume is calculated as described in theory section. The details of volume required for all casings are shown in Table 8. Firstly, the annular capacity of the casing and an open hole in (bbl/ft) is calculated, and then, cement slurry volume for all casings is estimated. Cement slurry volume required for conductor casing is 26.28 bbl, for production casing is 748.52 bbl, for intermediate casing is 527.14 bbl and for production casing is 1283.39 bbl. Total cement slurry volume required for the cementing operation is 2585.86 bbl.

Well design base on modified Eaton's method

Pore pressure prediction

Pore pressure prediction by modified Eaton's method required compaction trend line for velocity ratio of normal velocity to observe velocity. The normal compaction trend line is given by the equation $x = -0.000155y + 2.215$. Here, x indicates $\log(\Delta t)$ and y indicates formation depth as shown in Fig. 16.

Table 9 indicates the calculated density, overburden pressure, overburden pressure gradient, pore pressure and pore pressure gradient. An overburden pressure gradient is increased up to the shallow depth and then becomes constant about 20 to 21 ppg for all depths. Normal hydrostatic pressure gradient becomes constant 8.13 ppg for all the depths, and pore pressure gradient by using new method is constant up to the normal compaction depth (8000 ft) and

Fig. 10 Pore pressure gradient by the new method

then suddenly increased due to the hydrocarbon possibility and high formation pressure due to Lower Bhuban formation above the depth of 8000 ft. The details of pore pressure regime are shown in Figs. 16, 17.

Fracture pressure prediction

All fracture pressures are calculated by using predicted pore pressure by modified Eaton's method as input parameters.

The details of values are displayed in Table 10. In this research work, the fracture pressure calculated by Hubbert's equations is observed at the lowest values; fracture pressure estimated by Eaton and modified Eaton's equations gives more readable value because of the variable Poisson ratio (Fig. 18). Complex basins like the Tulumura structure where normal faults are frequent than horizontal stress ratio are not homogeneous; Eaton's equation works well with variable stress ratio. Tulumura structure is anticline which has

Table 4 Optimum mud weight by median line principle on the top of the Tulumura anticline

Depth (ft)	Overburden pressure gradient (ppg)	Pore pressure gradient by new method (ppg)	Fracture pressure gradient by modified Eaton (ppg)	Mud pressure gradient (ppg) median line	Mud pressure gradient (ppg) surge and swab
108.01	8.35	—	—	—	—
464.40	15.41	8.38	13.52753	11.89175	12.49175
1054.33	17.00	8.38	14.78755	12.68599	13.28599
1623.04	17.85	8.38	15.52654	13.11459	13.71459
3727.60	18.83	8.38	16.67064	13.60299	14.20299
4782.87	19.14	8.38	17.12075	13.75718	14.35718
6024.61	19.45	8.38	17.61542	13.91142	14.51142
7886.94	19.80	8.38	18.27276	14.08542	14.68542
9000.92	20.00	12.63	19.15018	16.31107	16.91107
12425.90	20.43	16.27	20.17674	18.34895	18.94895
14125.54	20.53	17.65	20.42732	19.09127	19.69127
17,894.74	20.66	18.70	20.69477	19.67962	20.27962
21,675.47	20.78	19.10	20.88261	19.93975	20.53975
25,314.80	20.86	19.32	21.00705	20.08824	20.68824
31,717.75	20.96	19.50	21.17763	20.23111	20.83111

Table 5 Casing properties

Casing diameter (inch)	Nominal weight (lbm/ft)	Grade	Wall thickness (inch)	Pipe body yield strength 1000 lbf	Joint strength 1000 lbf	Collapse resistance psi	Blast resistance psi
20"	94.00	K-55	0.438	1480	955	520	2110
13 3/8"	92.50	Q-125	0.672	3352	1690	5950	10,990
9 5/8"	70.30	V-150	0.734	3075	2185	18,800	16,680
7"	38.00	P-110	0.540	1205	1087	15,140	14,850
7"	42.70	V-150	0.625	1875	1514	24,390	23,440

Table 6 Calculated collapse pressure and burst pressure at casing shoe depth

Depth (ft)	Open hole diameter (inch)	Casing diameter (inch)	Type of casing	Collapse pressure (psi)	Burst pressure (psi)
100	26"	20"	Conductor	–	11,809.39
6050	17 1/2"	13 3/8"	Surface	4593.16	9223.05
15,500	12 1/4"	9 5/8"	Intermediate	16,039.4	5708.74
18,500	9 1/2"	7"	Production	18,181.8	4558.91

Fig. 11 Optimum mud weight on the top of the Tulumura anticline

Fig. 12 Surface casing selection **Fig. 13** Intermediate casing selection

Fig. 14 Production casing selection **Table 7** Kick tolerance parameter calculation

Depth (ft)	Casing size (in)	GPF at shoe (ppg)	GPP at shoe (ppg)	Mud weight (ppg)	Height of a gas bubble (ft)	Borehole diameter (in)	Open hole annulus capacity (bbl/ft)	The volume of influx at casing shoe (bbl)
100	20"	13.5	8.38	12.4	–	26"	0.6140	–
6050	13 3/8"	17.4	8.38	14.5	2947.30	17 1/2"	0.2548	750.97
15,500	9 5/8"	20.4	18.00	19.7	2466.01	12 1/4"	0.1031	254.24
18,500	7"	20.8	18.60	20.4	2386.48	9 1/2"	0.0450	107.46

undergone folding and stress anisotropy so tectonic stress correction which is required is given by modified Eaton's equation. For using variable Poisson's ratio, Eaton and modified Eaton's give the best result after tectonic correction. For a geologically complex region like Tulumura, modified Eaton's equation is more suitable. The comparative fracture pressures on Tulumura are shown in Table 10.

Optimal drilling mud weight selection

It is very critical to decide proper mud weight for safe well drilling. The hydrostatic pressure of drilling mud must be maintained between pore pressures and fracture pressure for safe drilling. Optimum mud weight is selected using the median line principle and shown in Fig. 19. In the depth v/s mud weight graph, red line indicates mud weight in ppg estimated by the median line principle. A green colour line indicates mud weight by considering surge and swab with the median line principle. Tulumura structure has high pressure

and temperature formation at a deep depth. Mud weight up to the normal pressure formation depth at 8000 ft the mud weight should be in the range 11–15 ppg, but for abnormal pressure, depth from 8000 ft to 20,000 ft the required mud weight is in the range of 15–21 ppg as shown in Table 11.

Burst pressure, collapse pressure and casing seat selection

Consider 0.3 ppg trip margin, 0.3 ppg surge pressure gradient and 0.2 ppg safety factor to select all surfaces, conductors, intermediate and production casings. In this paper, casing depth selection is shown in Table 13. First, 100 ft is considered a conductor casing. Casing depth up to 6050 ft, 13,500 ft, and 18,500 ft is considered for surface, intermediate and production casing, respectively.

The conventional approach is used for the load calculation with the minimum desired safety factor for collapse 1.125, burst 1.10 and tension 1.80. Casing pipe property is given in Table 12. Here four types of casings: conductor

Fig. 15 Kick tolerance (bbl) versus depth (m) on the top of Tulamura anticline

Table 8 Cement slurry volume calculation for the cementing

Type of casing	Open hole diameter (inch)	Casing diameter (inch)	Casing shoe depth (ft)	Annular capacity between open hole and casing (bbl/ft)	Cement slurry volume required for cementing (bbl)
Conductor	26"	20"	100	0.2681	26.81
Surface	17 1/2"	13 3/8"	6050	0.1237	748.52
Intermediate	12 1/4"	9 5/8"	15,500	0.0557	527.14
Production	9 1/2"	7"	18,500	0.0400	1283.39
				Total	2585.86

casing, surface casing, intermediate casing and production casing are used to prevent blowout during the drilling process.

Casing collapsed pressure (psi) and burst pressure (psi) with casing type with respect to depth are given in Table 13 required to design the casing pipe.

Fig. 16 Normal compaction trend line for CDP 4 syncline **Table 9** Pore pressure prediction by modified Eaton's method

Time (ms)	RMS velocity (m/s)	Interval velocity (m/s)	Depth (ft)	Density (g/cc)	overburden pressure (kg/cm ²)	Overburden pressure gradient (ppg)	pore pressure by Eaton (kg/cm ²)	pore pressure gradient by Eaton (ppg)
36	1829	0	108.01	—	3.29	8.35	—	—
149	1900	1922.07	464.4	2.1	26.13	15.41	14.16	8.35
312	2060	2196.08	1054.33	2.19	65.45	17	32.14	8.35
433	2285	2782.45	1623.04	2.33	105.84	17.85	49.47	8.35
876	2594	2863.99	3727.6	2.35	256.37	18.83	113.62	8.35
1068	2730	3279.7	4782.87	2.42	334.34	19.14	145.78	8.35
1273	2885	3585.72	6024.61	2.47	427.92	19.45	183.63	8.35
1561	3080	3824.63	7886.94	2.51	570.23	19.8	240.39	8.35
1712	3205	4288.78	9000.92	2.57	657.33	20	343.43	10.45
2163	3502	4452.59	12,425.9	2.58	927.07	20.43	722.44	15.92
2410	3573	4143.09	14,125.54	2.55	1059.08	20.53	938.13	18.18
2974	3668	4048.91	17,894.74	2.54	1350.47	20.66	1296.73	19.84
3517	3757	4211.22	21,675.47	2.56	1645.05	20.78	1617.65	20.43
4044	3816	4188.52	25,314.8	2.55	1928.31	20.86	1916.13	20.72
4959	3899	4246.45	31,717.75	2.56	2428.02	20.96	2425.03	20.93

Kick tolerance

The kick tolerance curve is shown in Fig. 20. A point above and left the side of a line is the safe zone. The point below and right side of the line is the blowout zone calculation of kick v/s are shown in Table 14.

Determine cement slurry volume for cementing

The volume required for all types of casings is shown in Table 15. First, calculate the annular capacity of the casing and an open hole in (bbl/ft) and then find out cement slurry

volume for all casings as given in Table 15. Cement slurry volume for conductor casing is 26.81 bbl, production casing is 748.52 bbl, intermediate casing is 414.95 bbl and for production casing is 1279.64 bbl. Total cement slurry volume required for the cementing operation is 2470.00 bbl.

Fig. 17 Pore pressure by modified Eaton's method

Fig. 18 Fracture pressure gradient

Table 10 Fracture pressure on the Tulamura anticline using pore pressure by the proposed new equation

DEPTH (Ft)	Overburden pressure (Psi)	Pore pressure by modified Eaton (Psi)	Fracture pressure by Hubbert and Willis (Psi)	Fracture pressure by Matthews and Kelly (Psi)	Fracture pressure by Eaton's equation (Psi)	Fracture pressure by modified Eaton (Psi)
8.01	46.87	—	—	—	—	—
464.40	372.10	258.39	258.87	325.57	270.20	326.25
1054.33	931.86	615.65	616.73	768.16	653.79	809.78
1623.04	1506.85	971.84	973.51	1206.62	1044.97	1308.97
3727.60	3650.09	2295.12	2298.95	2834.33	2559.46	3228.27
4782.87	4760.12	2970.43	2975.35	3662.29	3370.81	4254.27
6024.61	6092.59	3773.83	3780.03	4645.31	4369.23	5513.95
7886.94	8118.66	4987.97	4996.08	6128.84	5942.73	7488.40
9000.92	9358.83	6379.31	7059.54	8009.15	7371.29	8509.44
12,425.90	13,199.24	11,256.97	11,408.40	14,685.59	12,062.00	12,948.47
14,125.54	15,078.66	13,930.70	13,671.22	18,382.95	14,449.89	15,146.57
17,894.74	19,227.43	18,717.31	18,007.40	24,871.39	18,987.30	19,591.21
21,675.47	23,421.52	23,161.43	22,158.95	30,838.56	23,316.63	23,941.60
25,314.80	27,454.46	27,338.80	26,106.58	36,432.46	27,414.25	28,081.45
31,717.75	34,569.03	34,540.69	32,967.17	46,049.53	34,561.37	35,354.29

Fig. 19 Optimum mud weight on the top of the Tulamura anticline

Table 11 Optimum mud weight by median line principle on the top of The Tulamura anticline

Depth (Ft)	Overburden pressure gradient (ppg)	Pore pressure gradient by modified Eaton (ppg)	Fracture pressure gradient by modified Eaton (ppg)	Mud pressure gradient (ppg) median line	Mud pressure gradient (ppg) surge and swab
108.01	8.35	—	—	—	—
464.40	15.41	8.35	13.5098	11.87,691	12.47,691
1054.33	17.00	8.35	14.77,016	12.67,115	13.27,115
1623.04	17.85	8.35	15.50946	13.09975	13.69975
3727.60	18.83	8.35	16.65472	13.58815	14.18815
4782.87	19.14	8.35	17.10539	13.74234	14.34234
6024.61	19.45	8.35	17.60072	13.89658	14.49658
7886.94	19.80	8.35	18.25901	14.07058	14.67058
9000.92	20.00	10.45	18.18071	15.22107	15.82107
12425.90	20.43	15.92	20.03952	18.17318	18.77318
14125.54	20.53	18.18	20.62082	19.35623	19.95623
17894.74	20.66	19.84	21.0539	20.25181	20.85181
21675.47	20.78	20.43	21.24131	20.60682	21.20682
25314.80	20.86	20.72	21.33249	20.79029	21.39029
31717.75	20.96	20.93	21.43563	20.94664	21.54664

Table 12 Casing properties

Casing diameter (inch)	Nominal weight (lb _m /ft)	Grade	Wall thickness (inch)	Pipe body yield strength 1000 lbf	Joint strength 1000 lbf	Collapse resistance psi	Blast resistance psi
20"	94.00	K-55	0.438	1480	955	520	2110
13 3/8"	92.50	Q-125	0.672	3352	1690	5950	10,990
9 5/8"	70.30	V-150	0.734	3075	2185	18,800	16,680
7"	38.00	P-110	0.540	1205	1087	15,140	14,850
7"	42.70	V-150	0.625	1875	1514	24,390	23,440

Table 13 Calculated collapse pressure and burst pressure at casing shoe depth

Depth (ft)	Open hole diameter (inch)	Casing diameter (inch)	Type of casing	Collapse pressure (psi)	Burst pressure (psi)
100	26"	20"	Conductor	—	11,809.39
6050	17 1/2"	13 3/8"	Surface	4593.16	9223.05
13,500	12 1/4"	9 5/8"	Intermediate	13,616.96	6451.91
18,500	9 1/2"	7"	Production	18,181.8	4558.91

Table 14 Kick tolerance parameter calculation

Depth (ft)	Casing size (in)	Fracture pressure gradient at shoe (ppg)	Pore pressure gradient at shoe (ppg)	Mud weight (ppg)	Borehole diameter (in)	Open hole annulus capacity (bbl/ft)	Height of a gas bubble (ft)	Influx volume at casing shoe (bbl)
100	20"	14	8.38	12	26"	0.6140	—	—
6050	13 3/8"	18	8.38	14	17 1/2"	0.2548	2947.30	750.97
13,500	9 5/8"	20.5	17	19.5	12 1/4"	0.1031	2466.01	243.54
18,500	7"	21	20	20.5	9 1/2"	0.0450	2386.48	107.463

Fig. 20 Kick tolerance (bbl) versus depth (m) on the top of Tulamura

Table 15 Cement slurry volume calculation for the cementing

Type of casing	Open hole diameter (inch)	Casing diameter (inch)	Casing shoe depth (ft)	Annular capacity between open hole and casing (bbl/ft)	Cement slurry volume required for cementing (bbl)
Conductor	26"	20"	100	0.2681	26.81
Surface	17 1/2"	13 3/8"	6050	0.1237	748.52
Intermediate	12 1/4"	9 5/8"	13,500	0.0557	414.95
Production	9 1/2"	7"	18,500	0.0400	1279.64
			Total		2470.00 bbl

Comparison between proposing well design based on the pore pressure by a new method and based on pore pressure by modified Eaton's method

Summary and conclusions

It has been observed that pore pressure predicted by the new method is excellently matched with offset well data (RFT) along with excellently matched pore pressure predicted by the modified Eaton's method.

Comparatively, it has been observed that in the new method, normal velocity data from the compaction trend are not the necessary input; thus, the error caused by normal velocity has been eliminated where in the modified Eaton's method the normal velocity may cause the error.

The new method has been successfully applied to seismic data and turned out to be reliable to repeat formation test data; it provides a new way to predict pore pressure and contributes much to the next step exploration and exploitation. The proposed new method has the potential to perform better in pore pressure prediction than modified Eaton's method.

Table 16 Comparison of proposed well design on the top of Tulumura anticline

Wall design parameter	New approach	Modified Eaton's equation
Pore pressure	Not depend on compaction trend line	Depend on normal compaction trend line
Pore pressure and RFT data	Excellent matched with RFT pressure data	Matched with RFT pressure data
Fracture pressure gradient by modified Eaton's method	The fracture pressure gradient is in both cases nearly the same because of tectonic correction Fracture pressure gradient regime shows that pore pressure based on the new method is higher than the fracture pressure gradient based on pore pressure by modified Eaton's method	
Target depth selection	Independent to pore pressure	
Casing setting depth selection	Casing setting depth which is selected by the pore pressure gradient and fracture pressure gradient for the conductor casing, surface casing and production casing setting depth is same, but intermediate casing setting depth is changed. Intermediate casing depth from 6050 ft to 15,500 ft Conductor casing—100ft Surface casing—6050 ft Intermediate casing—15,500 ft Production casing—18,500 ft	Intermediate casing depth from 6050 ft to 13,500 ft Conductor casing—100ft Surface casing—6050 ft Intermediate casing—13,500 ft Production casing—18,500 ft
Casing policy selection-	Casing policy is selected in consideration of collapse pressure, burst collapsed pressure and tension load Figs. 21 and 22 Conductor casing: k-55, 94.0 lbm/ft Surface casing 6050 ft: Q-125,92.50 Intermediate casing: New approach: 6050-15,500 ft: V-150, 70.30 lbm/ft Modified Eaton's equation: 6050-15,500 ft: V-150, 70.30 lbm/ft Production casing: (1) 0-11,500 ft: P-110, 38.0 lbm/ft (2) 11,500-18,500 ft: V-150, 42.70 lbm/ft	
Cement slurry volume calculation	Total cement slurry volume required at cementing process is 2585.86 bbl	Total cement slurry volume required at cementing process is 2470.00 bbl
Kick tolerance calculation	Based on the kick tolerance graph with depth safe zone area in the new approach is high compare design a well by considering modified Eaton's method. Which indicate casing proposed by new approach is safe then the second one shown in Figs. 15 and 20	

Fig. 21 Proposed well design by a new method

In this study, it has been observed that that pore pressure is drastically increased by the depth of 8000 ft, and abnormal formation pressure is between 8000 ft and 20,000 ft. Tulamura is a very complex geological structure with normal faults that are frequent so that Poisson's ratio may vary with depth. Fracture pressure by Eaton and modified Eaton's method gives more readable value because of

the variable Poisson ratio. Suitable mud weight by median line principle is calculated and improved via considering 0.3 ppg trip margin, 0.3 ppg surge pressure gradient and 0.2 ppg safety factor for calculation of all casing pipes.

From pore pressure gradient, fracture pressure gradient and mud weight using graphical method, four types of casing setting depth are selected: conductor casing, surface

Fig. 22 Proposed well by modified Eaton's method

casing, intermediate casing and production casing. After casing depth determination, casing dimension, nominal weight and grade are selected from calculated burst pressure, collapse pressure and tension load. For each casing, kick volume in bbl is calculated and is given by kick tolerance for safe drilling.

Finally, a comparison between proposed well design by a new approach and modified Eaton's method is given in Table 16, and the final proposed well plan is given in Figs. 21 and 22.

This study gives all the detailed flows of designing an exploratory well in the overpressure zone. The seismic survey uses only raw data for virgin area to exploration and exploitation of hydrocarbon. To drill a well in overpressure zone, the idea of pore pressure, fracture pressure, drilling mud weight required casing policy; kick tolerance graph plays an important role for driller. This study gives all guidelines for driller to eliminate the loss throw blow-out and uncertainties. This study is only based on seismic velocity data; therefore, to get more reliable pore pressure prediction and design of safe well different types of data such as density data and well log data are suggested.

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