Overpressure Generation and Distribution in Compressional Tectonic Setting: Basin Modeling Approach

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Abstract

Overpressure related drilling complications has restricted the exploration activities in Agartala Dome to shallow reservoirs of Upper and Middle Bhubans. Abnormally high pressure has been encountered in Lower Bhuban Formation and none of the drilled wells have reached their target depth within this formation. Uncertainty lies in ascertaining the main cause behind over pressure generation and effective pore pressure prediction methodology. In the present study the focus has been laid on identifying the causatives behind overpressure generation and then to generate a pore pressure volume to delineate the overpressure distribution in the study area. Among various methodologies, Bowers method has proved to be the most effective methodology to predict pore pressure as the area has witnessed unloading activity confirmed through sonic-density cross-plots. Compressive tectonics concurrent with the deposition of Bhubans has emerged as the main cause of unloading. 3D pore pressure volume is generated through a unique basin modeling approach where five geological control parameters and lithologically determined compaction laws are used to produce synthetic porosity, permeability and pore pressure curves. Advanced inversion scheme is then applied to obtain a minimum misfit between the synthetic and the real data. The predictive reliability of the model is determined by a blind testing procedure.

Introduction

Abnormal pore pressure regimes in the form of overpressure occur globally in a wide range of geological conditions and there are many instances where they are invariably associated with hydrocarbon occurrences. Recent development in pore pressure studies have confirmed that the studies of these overpressure occurrences play an essential role not only in hydrocarbon exploitation but also in hydrocarbon exploration (Law, B.E., and Spencer C.W., 1998).

Exploratory drilling in the last thirty years has thrown some insight into hydrocarbon habitat and pressure system across various structures in Tripura Fold Belt. The present study is restricted to Agartala Dome area (Fig.1) which is one of the prolific hydrocarbon bearing structure within Tripura Fold belt. Though commercially viable gas pools have been discovered in Upper and Middle Bhuban Formations within the structure, efforts for assessing deeper prospects remained unsuccessful because of the occurrence of overpressure within Lower Bhuban Formation. Most of the deep wells have to be abandoned prematurely as overpressure associated problems like occasional stuck ups (differential or other reasons) of drill pipes, lost circulation, pressure kicks etc, were encountered. Inadequate insight to the depth of occurrence, magnitude, causal mechanisms and prediction methodology of overpressure system are some of the major reasons of failure and successive setbacks. These failures constrained the exploratory endeavors to shallow reservoirs within hydrostatic and upper part of the transition pressure regime.

Careful and accurate pore pressure prediction i.e knowledge of the occurrence of overpressure and pressure-depth relationship in the area is therefore, holds key to defining the smooth drilling operations, well completion methods and reservoir evaluation of deeper prospects in Agartala Dome. A major component of the present study will focus first on identifying the causatives behind overpressure generation and then to generate a pore pressure volume to delineate the overpressure distribution in the study area.

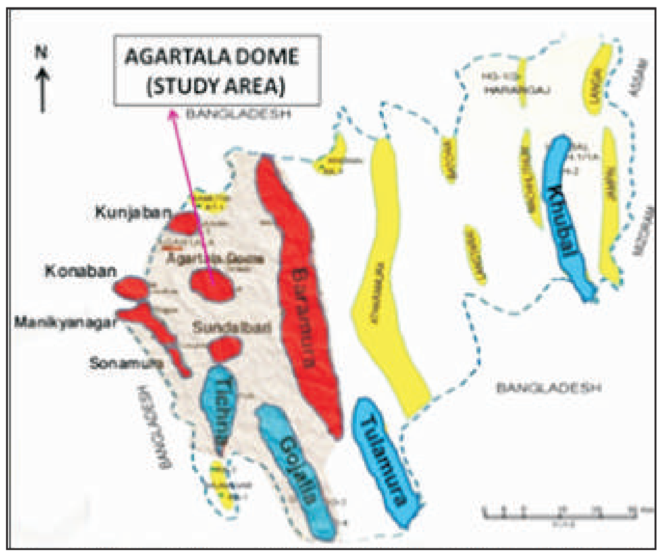

Fig. 1: Various structures across Tripura Fold Belt

Tectonic Framework and Sedimentation

In order to understand the paleo-tectonics and geology of Agartala Dome area we have to view the Tripura Fold Belt representing the frontal fold-belt of Assam and Assam Arakan Basin from the regional perspective. The dynamic nature of the basin is controlled by the interaction of three plates, namely, the Indian, Tibetan (Eurasian) and Burma Plates. The intensity and pattern of plate-to-plate interaction varied with time, affecting the basin architecture and sedimentation (Alam M., et al, 2002). The region is characterized by a series of sub-parallel, elongated, arcuate, doubly plunging, tightly folded asymmetrical anticlines arranged en-echelon and separated by wide, flat and more or less symmetrical open synclines. These folds are trending NNW-SSE to N-S direction with slight convexity towards west. The intensity of folding increases from west to east. Agartala Dome is a gentle oval shaped concealed structure located in the western part of Tripura fold belt. The present structural configuration indicates polyphase deformation with structural styles grading from those associated with basement-involved compressive block-faulting to detached thrust-fold assemblages and are characteristics of areas close to convergent plate boundaries (Ganguly S., 1983).

This fold belt is characterized by the deposition of huge pile of sediments during the Cenozoic period and exposes different sedimentary units mainly along the narrow linear ranges formed by anticlines. The general stratigraphy of the area is well documented in various published literatures (Curiale et al., 2002; (Fig.2). Disang group of Early Eocene age represents the oldest exposed sedimentation in the fold belt. Early collision sedimentation was contemporaneous with the beginning of continental collision (Oligocene-Early Miocene), when initial uplift of the Himalayan and Indo-Burmese ranges occurred.

During this period the Barail equivalent facies as well as the Surma Group comprising Middle and Lower Bhubans were deposited. While the late collision phase (Late Miocene-Pliocene) led to the deposition of Upper Bhuban, Bokabil and Tipams. Paleontological and palynological studies in the area have indicated that Lower Bhuban to Lower Bokabil sediments were deposited in cyclic fluctuating marine to marginal marine environments in an overall deltaic setting (Biswas, 1984).

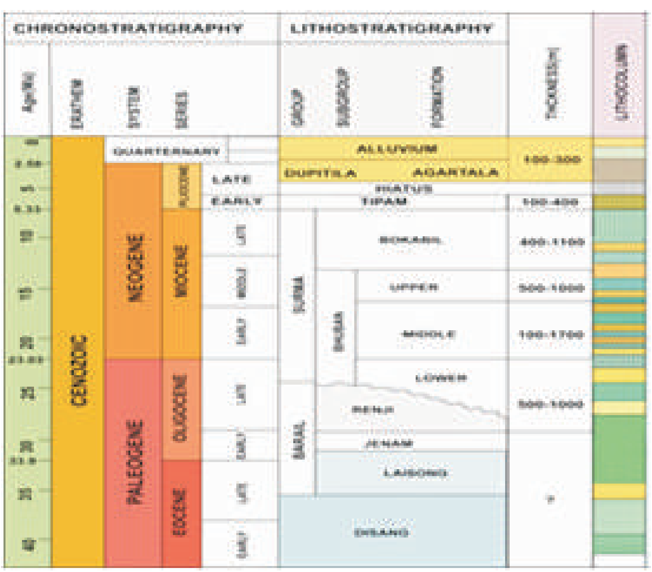

Fig. 2: Generalized stratigraphy of Tripura Fold Belt

Study Area: Challenges and Adopted Strategy

Exploration in Agartala Dome has started in mid- eighties targeting the Surma group and commercial hydrocarbon occurrences have already been established within Upper and Middle Bhuban Formations both of which falls under normal/ hydrostatic pressure regimes. However, overpressure related drilling complications constrained the exploration activity to limit itself till middle part of Middle Bhuban Formation. Some of the wells which have penetrated Lower Bhuban Formation but could not met their target depths have reported mud weight at the order of 17-18 ppg. The only silver lining during drilling is the establishment of gaseous hydrocarbon occurrences within Lower Bhuban sands. In one of the structures across Tripura a gaseous pool has been discovered within Lower Bhuban. As such, it becomes imperative to accurately predict overpressure distribution and its generating mechanisms within Lower Bhuban Formation in Agartala Dome in order to conduct successful drilling operations.

Building a pore pressure model entails integration of data from various sources like geophysics, geology and drilling in order to accurately describe the formations in terms of formation pressure. Fourteen deepest wells from the study area (including five wells which have penetrated Lower Bhuban Formation viz. Well- A1, A2, A3, A4 and A5) with varying availability of required dataset for pore pressure prediction and its calibration have been selected to carry out 1D and 3D pore pressure modeling. Pore pressure prediction is the ability to create numerical formulas that mimic the subsurface pressure profile. Most methods of predicting pore pressure are based on Terzaghi`s effective stress principle, which implies that elastic wave velocities are a function of the effective stress tensor. The effective stress tensor is the difference between the total stress tensor and the pore pressure. From Terzaghi`s work, the total stress equation is written as:

$$S = \sigma + P$$

where, S= total stress, σ = effective stress and P = pore pressure.

In the present study, multiple methods have been used to calculate the geopressure from algorithm-based methods (Eaton, 1975; Bowers, 1994). These pore pressure prediction methods uses shale properties derived from well log data such as resistivity and sonic log data and uses compaction trend. For the calibration of predicted pore pressure, recorded pressure in the well, like MDT/RFT/DST data, SBHP data recorded during production testing and actual mud weight data have been incorporated. In absence of recorded pressure data, well complications like kicks, self flow, gas cut, tight pull, tool stuck, held up etc have also been incorporated since they indirectly offer a check on overestimation of pore pressure.

1D Pore Pressure Prediction

Eaton's method is one of the most commonly used techniques for pore pressure prediction (PPP). Based on Eaton's resistivity (Fig. 3A) and Eaton's sonic methods (Fig 3B) 1D pore pressure curves are generated at all the fourteen

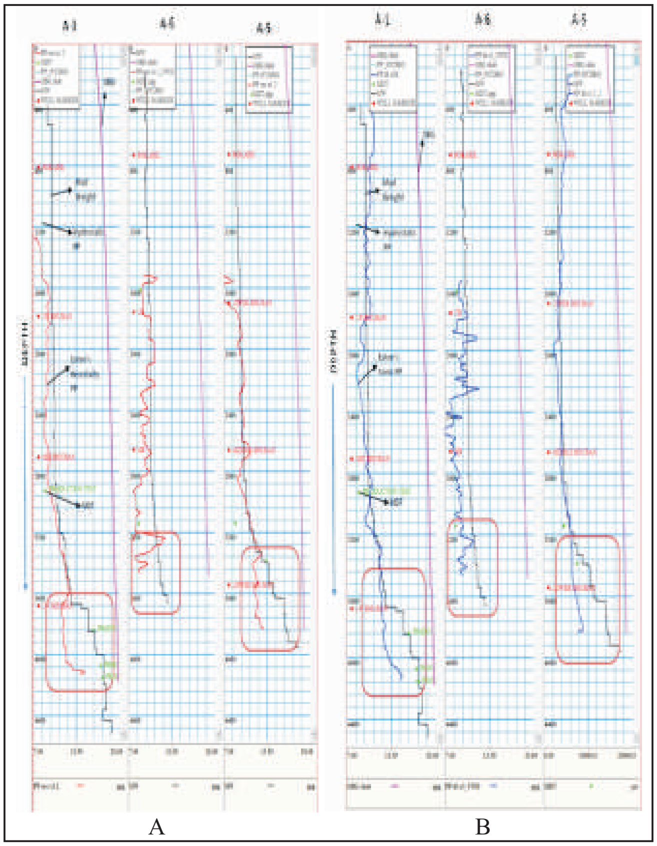

Fig. 3: Eaton's Resistivity (A) and Sonic (B) based Pore Pressure Prediction at wells- A1, A-6 and A-5

wells and have been tried to calibrate with recorded pressure data and/or well events. The prediction showed a fair match within Upper and Middle Bhuban Formations, however it under-predicted pore pressure within Lower Bhuban Formation. This method produces a good prediction where disequilibrium compaction is the main overpressure generating mechanism, however, the major drawback of this method is that it underestimates the overpressure effect of secondary overpressure mechanisms. One of the effective ways of identifying overpressure generation mechanism is by using velocity vs. density cross-plotting (Hoesni, M.J., et al, 2007). Fluid expansion (secondary overpressure mechanism) involves dehydration reactions like Smectite to Illite transformation which releases water. However, the release of bound water into sediment pores is minor in terms of generating overpressure (Swarbrick, and Osborne 1998). Maturation of hydrocarbons, particularly in the case of gas generation can lead to rapid volume expansion, reducing effective stress and increasing pore pressure.

In all the deepest wells (5 wells) in the study area, velocity (ft/sec) vs density (g/cc) crossplot (Fig.4) has shown that majority of the data points fall in the disequilibrium compaction zone however, a distinct unloading limb can also be seen. When these unloading zone data points were calibrated with depth, they corresponded to bottom part of Middle Bhuban Formation and below i.e till drilled depth within Lower Bhuban.

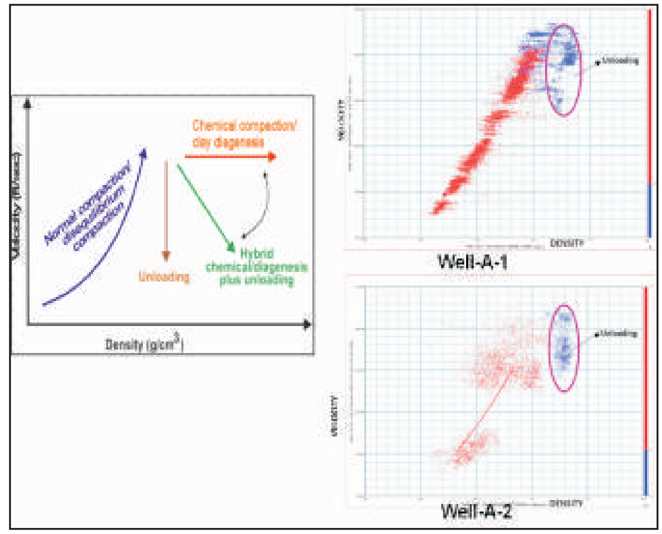

Fig. 4: Velocity (ft/sec) vs Density (g/cc) crossplot at wells A-1 and A-2, showing distinct unloading limb

Results from SEM and XRD studies on core samples taken from Upper, Middle and Lower Bhuban Formations across many wells in western Tripura indicate dominance of Kaolinite followed by Illite and Chlorite in the samples (KDMIPE, 2012). Therefore, the role of clay diagenesis in overpressure generation is highly speculative but not ruled out. Luo and Vasseur (1996), and Osborne and Swarbrick (1997) have suggested that a significant amount of excess fluid pressure can be generated through hydrocarbon generation only when the TOC content in a source rockis very high. However, Bhuban Formations possess poor to fair quality source potential for hydrocarbon generation (Farhaduzzaman, M., et al, 2013) which may not contribute significantly to overpressure.

The role of tectonics is analogous to that of strata overburden, which causes mudrock compaction and a decrease in porosity and permeability, resulting in retardation of fluid expulsion and overpressure generation (Luo, X., et al, 2007). Tripura fold belt has witnessed major episodes of tectonic compressions especially post-Oligocene, congruous with the deposition of Bhubans in the area. As such, the combined effect of tectonic stress and overburden on sediment compaction can cause a much greater porosity and permeability reduction than the overburden alone and, as a result, abnormally high overpressure can generate at deeper levels. In the present study this may be the main overpressure generation mechanism within Middle and Lower Bhuban.

Such type of complex overpressure systems where the unloading phenomenon depends on more than one type of overpressure generation mechanisms it becomes imperative to include a pore pressure prediction method that accounts for unloading phenomenon. Using Bowers (1992) method, which defines a relationship between velocity and change in effective stress, 1D pore pressure is carried out again in deeper wells. The prediction showed a good calibration with the recorded pressure within Lower Bhuban Formation (Fig.5).

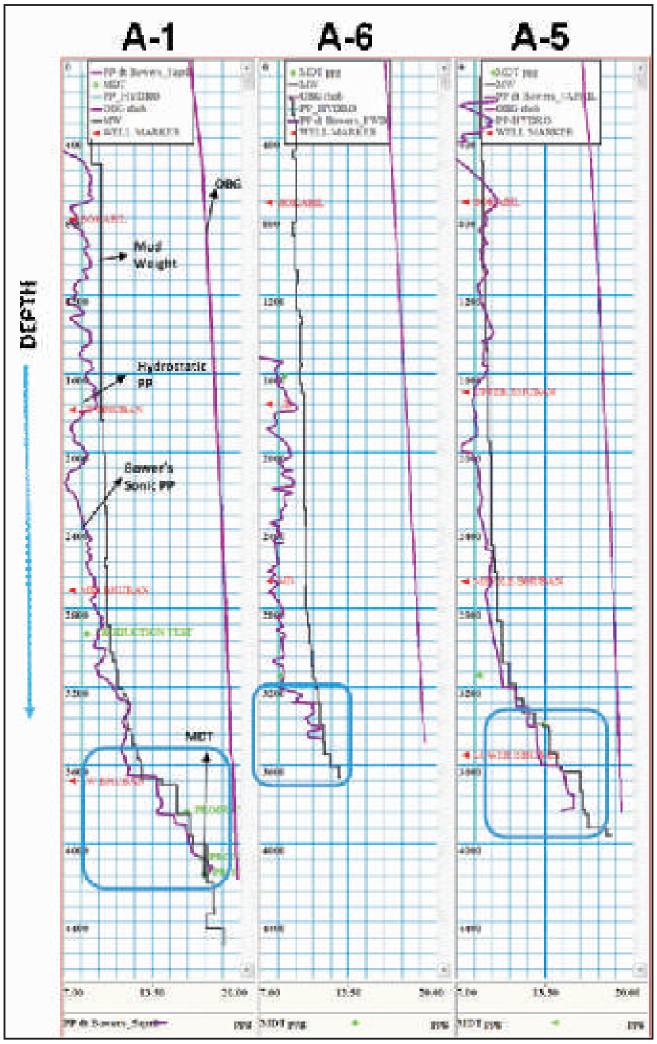

Fig. 5: Bowers Sonic method based Pore Pressure Prediction at wells- A1, A-6 and A-5

3D Pore Pressure Volume: A new approach

A unique 1.5D basin model is used for pre-drill pore pressure prediction (Madatov et al, 1996). It is similar to full basin model that is simplified for pore pressure estimation. Creation of a model is similar to the 2D basin models. In the model each stratigraphic unit contains a set of five control parameters, which are responsible for the development of the pore pressure through geological time. These parameters are initial porosity, compaction constant, effective hydrocarbon generation, specific surface area and effective lateral conduction. Each parameter is assigned some default values, however, the default values established for these parameters are initially not accurate and the best fit values is then calculated using numerical techniques. The values are modified at each control point such that three or four of the five factors have no or little variation between wells. The idea is to adjust the paramaters so as to closely relate them to the real world conditions. Each well is then modeled with respect to the control parameters and lithologically determined compaction laws to produce synthetic porosity, permeability and pore pressure curves (Fig.6).

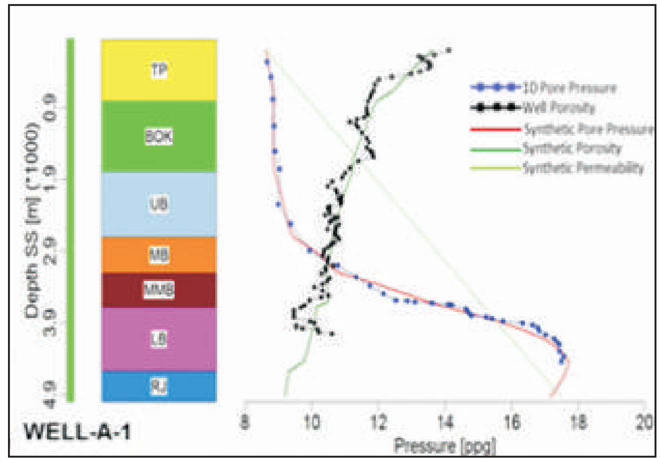

Fig. 6: Creation of synthetic Pore Pressure and Porosity curves through advanced inversion scheme

These parameters are manually adjusted through an advanced inversion scheme in order to obtain a minimum misfit between the synthetic and the real data (1D pore pressure and porosity curves) resulting in a set of calibrated control parameters. A back-stripping technique is applied to reproduce the sedimentation history of the basin with particular attention to the development of porosity and pore pressure.

The pressure evolution model also accounts for the 3D effects of lateral pressure communication phenomenon by incorporating fault framework to support the structural framework of the study area and to addresses the issues of pressure compartmentalization because of restricted lateral and vertical movement of fluids or hydrocarbon. The available reservoir data of different pay sands within different formations have been analyzed to predict the sealing and non-sealing behavior of the faults. Cross-plot between stabilized reservoir pressure and production profile for different pay sands within Upper and Middle Bhuban Formations in Agartala Dome area does not give any conclusive evidence of faults posing as pressure barrier. Thus, for the study area, faults play no role in pore pressure compartmentalization. The structure is fine tuned through creating many geological cross-sections (Fig. 7).

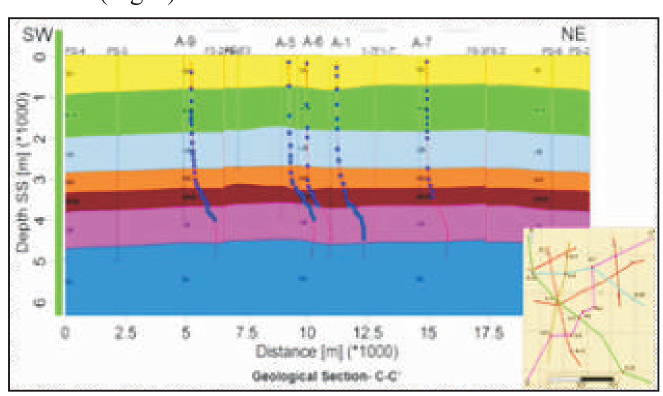

Fig. 7: Geological cross-section with synthetic pore pressure

Once the formation parameters are calibrated (showing a low range of variation) and structural framework is built, the pore pressure misfit calculation is run for the entire study area

(Fig. 8). The misfit shows a variation of pore pressure in the range of 1ppg (pounds per gallon) in the study area and it is accepted as the best misfit.

The predictive reliability of the model is determined by a blind testing procedure. In the present case one deep well A-3 has been selected for blind testing. The pore pressure output from basin modeling fairly matches with the 1D pore pressure model (Fig. 9). The model can be updated once the prediction made at some proposed location is updated in terms of pore pressure, porosity, formation top after drilling.

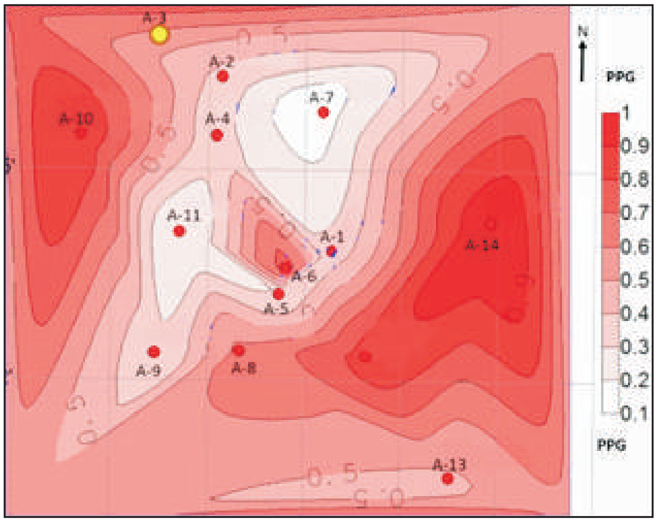

Fig. 8: Interpretation pore pressure misfit showing a variation within 1ppg range in the study area

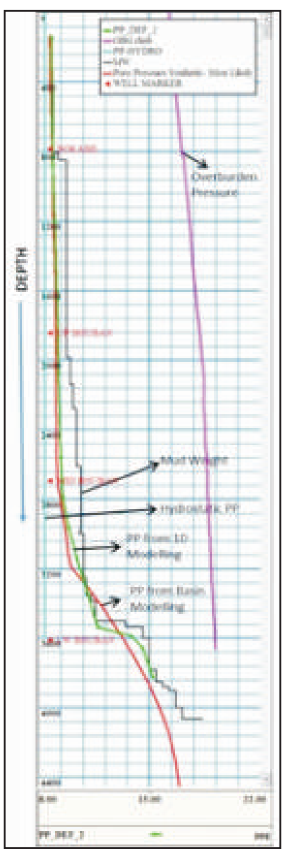

Fig. 9: Blind testing carried out at well A-3

Conclusion

A sophisticated and industry prevalent approach has been adopted for 1D and 3D pore pressure prediction and to explore the probable causes of abnormally high pore pressure. Hoesni cross plot analysis (sonic-density cross plot) reflect two trends of data concentration, indicating that along with disequilibrium compaction, unloading (Tectonics) is also a major contributor to this high pressure regime in deeper stratigraphic intervals. Of the various methods used for prediction of 1D pore pressure, Bower's method (accounts unloading phenomenon) showed a good match with the recorded pressure in the deeper stratigraphic intervals. Basin modelling based 3D pore pressure prediction incorporates five control parameters and lithologically determined compaction laws to produce synthetic porosity, permeability and pore pressure curves. It also addresses the lateral and vertical pressure compartmentalization of pore pressure. The predictive reliability of the model is determined by a blind testing procedure which fairly matches with 1D log based pore pressure prediction.

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