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# Integrated Pore Pressure Prediction for Successful Drilling of a HP Deep Exploration Well, North-East India

**Rajeev Ranjan Kumar*, Rahul Talreja* & Ankit Kakrania***
**Sumit Roy****

***PTS, Schlumberger, Mumbai, India, **ONGC, India***
*Email: Rajeev_iit2@yahoo.co.in*

## Abstract

Rock mechanics has played a pivotal part in finalizing drilling programs in deep-exploration fields of North East India. Wellbore stability analysis (WBS) is conducted to validate calculated pore pressure, stress and rock properties against drilling observations, caliper and images acquired. Casing plan and mud weight design needs be consistent with WBS in order to avoid extra cost and delay in drilling. Present paper gives an insight to the role of Geomechanics in successful drilling of a vertical well (HP Gas field).Extensive geological tectonics has resulted in complex structures and high pressure zones in the range of 2.0-2.10 SG at the depth of 3000m. Look-ahead pore pressure model using monte-carlo simulation (uncertainty model) and surface seismic velocity was used to recommend safe mud weight for successful drilling of the deepest exploration well in that area. Deterministic models like Eaton, Bowers and Miller's Methods were used to validate the estimated Pore Pressure Profile. Later on, actual formation pressure measurements were acquired, which matched closely with prediction. There was clear ramp from 1.20 SG to 2.0 SG within 200m with top of overpressure zone clearly marked below the thick shale layer. Proper hole cleaning practices and RSS* were utilized to drill faster with smoother borehole. A discussion of results for optimized drilling has been provided.

## Introduction

Overpressures in the subsurface pose major problems for safety and cost-effective well design. Furthermore, geopressures impact prospect and play appraisal and economics in a number of ways. Normal pressure is pore fluid pressure that equals the hydrostatic pressure of a column of formation water extending to the surface. Overpressure is pore fluid pressure greater than normal pressure. Pore pressure has overburden stress as it upper limit. The phenomenon of overpressure in sedimentary basins has been attributed to a wide range of mechanisms that can be related to the following processes: increase in stress applied to a compressible rock, fluid expansion within a restricted pore space, fluid movement, buoyancy, digenesis, and osmosis (Osborne and Swarbrick, 1997). The ability for each of these mechanisms to generate pressures above hydrostatic pressure depends on the rock and fluid properties of the sedimentary rocks and their rate of change under the normal range of basin conditions. The magnitude of overpressure varies from basin to basin. Present-day pressure distribution can be interpreted from direct measurement in permeable units (e.g., MDT, XPT, DST pressures). The pressures in low-permeability lithology cannot be measured directly but can be inferred from indirect measurements. In the absence of offset well data seismic, velocities are the only available pre-drill tools to estimate the formation pressures. Pore pressure prediction in geologically challenging areas such as anticlines and fold thrust faults combined with possibility of abnormal pressures elevates this prediction to a high level of uncertainty (Swarbrick *et al*., 2010)

Overpressure detection is based on the theory that pore pressure affects compaction-dependent geophysical properties such as density, resistivity, and sonic velocity. Shale is the preferred lithology for pore pressure interpretation because they are more responsive to overpressure. Most of the techniques are linked to porosity and assume that the porosity is controlled by the maximum effective stress the sediment has experienced. However, process like fluid expansion is accounted using velocity vs. effective stress method as proposed by Bowers, 1995.

Porosity and density are *bulk properties*, while sonic velocity and resistivity are *transport properties (Bowers et al. 2002).* Bulk properties only depend on net pore volume, while transport properties are sensitive to pore sizes, shapes, and interconnectivity of pores. A combination of relatively large, high aspect ratio *storage pores are* linked together by a network of lower aspect ratio *connecting pores*, where transport properties are controlled by the connecting pores. Storage pores can undergo primarily inelastic volume losses with the more flexible connecting pores capable of elastic rebound. Hence, during unloading or reduction in effective stress cause connecting pores to increase in width without significant change in storage pore sizes. As connecting pores widen, flow path sizes are increased for conducting electrical current, and the number of intergranular contacts are reduced for transmitting sound. The final effect is on transport properties than bulk properties which suggest that an indicator of in-situ rebound (unloading) is a depth interval in which sonic velocity and resistivity data appear anomalously low in comparison to bulk density measurements.

Tripura has 400 billion metres3 reserves of natural gas, out of which 16 billion metres3 is recoverable (Directorate of Economics and Statistics). Well-X was drilled to explore the potential resources of Surma Group (Miocene) consisting mainly of (a) argillaceous Middle Bhuban Formation (3000m), (b) arenaceous Upper Bhuban Formation (1100 m) and (c) argillaceous Bokabili Formation (1000 m).Tripura fold belt is a part of Neogene Surma Basin (Assam-Arakan Basin). It is a shallow marine to deltaic environment. Middle Bhuban formation is characterized by abnormal pore pressure as observed by past drilling events like kick, well flow and tight hole etc. in the area. The mechanism of overpressures in Middle Bhuban formation appears to be due to both due to compaction disequilibrium and Repressurization i.e. Type-I and Type-II both. Undercompacted shales in this zone are probably recharged with fluid due to active plate-tectonic movements in North East. In the deeper parts of the basin, where the sediments are likely to be over matured, hydrocarbon generation / oil to gas cracking is expected to provide an additional pressuring mechanism. The top of gas-bearing overpressured reservoirs cuts across structural and stratigraphic boundaries, thereby demonstrating the diminished role of structure and stratigraphy. This paper reviews different mechanisms for overpressure and presents case studies on pore pressure analysis from North East India onshore.

## Overpressure mechanisms

Normally pressured formations are able to maintain hydraulic communication with the surface during burial. Consequently, their pore fluid can easily be squeezed out to accommodate compaction, and their pore pressure follows the hydrostatic pressure curve for formation water. Effective stresses in normally pressured environments continually increase with depth. On velocity vs. effective vertical stress plot, normal pressure points lie on the virgin curve as seen *Figure 1*.The causes of overpressure can be divided into four general categories: undercompaction (compaction disequilibrium), fluid expansion (aqua thermal expansion; hydrocarbon generation and gas cracking; mineral transformations), lateral transfer, and tectonic loading. The conditions that produce normal pressure and the four types of overpressure are described below.

### (a) *Undercompaction*

With increase in overburden pressure during loading, there can be incomplete dewatering with part of the weight of the load being added to the pore-fluid pressure. This mechanism is commonly termed “disequilibrium compaction,” and the physical manifestation in the bulk rock is excess pore pressure and a higher porosity relative to the normally pressured and fully compacted rock at the same depth. The onset of overpressure is controlled by the loading rate and the porosity and permeability evolution of the sediment during burial. For an impermeable seal and an incompressible pore fluid, pore pressure would increase at the same rate as the overburden stress once sealing occurred. However, undercompaction will not drive pore pressure toward the overburden stress curve. This also means that undercompaction cannot cause effective stress reductions as seen in *Figure 1*.

### *(b) Fluid expansion*

Overpressure can be generated by fluid expansion in low permeability rocks, where pore fluid volume increases with lesser change in porosity and at a rate that do not permit effective dissipation of fluid. Different causes of fluid expansion can be clay dehydration, smectite-illite transformation, maturation of source rocks to oil and gas, gas cracking, aquathermal pressuring and mineral precipitation/cementation reactions. Increasing temperature during burial causes both rocks and fluids to expand. The volume expansion of rock is approximately one order of magnitude smaller for rock than for water and therefore can be ignored. The fluid volume change due to aquathermal expansion is 1.65% for an increase in temperature of 40 degC (Osborne and Swarbrick, 1998). Volume changes occur when kerogen transforms to oil and gas and when oil cracks to gas. The volume change depends on the kerogen source and the density and volume of the petroleum products generated during maturation. This leads to reduction of effective stress with less change in sonic compressional velocity (*Figure 1*).

### *(d) Lateral transfer*

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It can occur along dipping sand enclosed in shale. The sand transmits pore fluid and pore pressure from deeper shale up dip (Yardley and Swarbrick, 2000). Lateral transfer can generate crustal pore pressures high enough to fracture overlying shale seals, especially when there are long gas column. Sometimes this can be caused by charging along faults.

*(e) Tectonic loading*

Trapped pore fluid squeezed by tectonically driven lateral stresses induces overpressure in the same way that undercompaction does. However, unlike undercompaction, tectonic loading is capable of generating high overpressure (Yasser and Addis, 2002). This also means that tectonic loading can cause vertical effective stress to decrease, but in tectonic environments, compaction is no longer controlled by vertical effective stress alone.

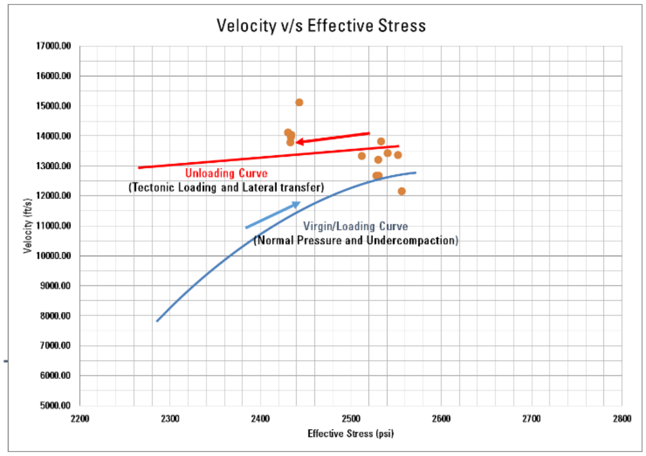

**Figure 1- Crossplot between velocity and effective vertical stress to identify the overpressure mechanisms.**

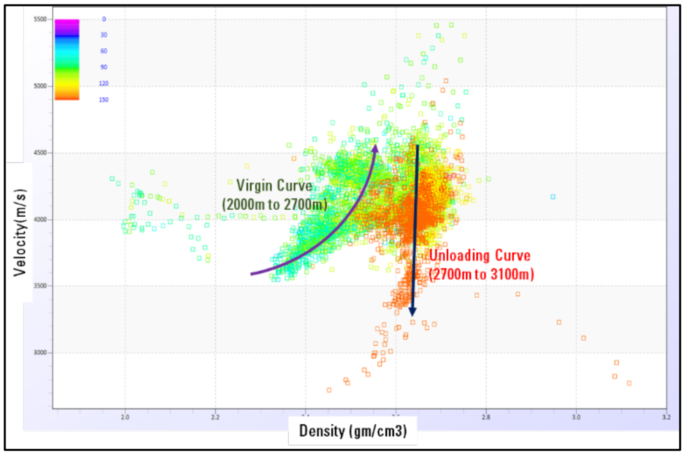

**Figure 2- Crossplot between velocity and density to identify the overpressure mechanisms.**

Areas of thrusting and folding typically contain overpressured rocks, and the magnitude of overpressure in these regions relates to both the amount of stress and strain in the rocks and their physical properties. North-East of India is tectonically active and folded belt is even under E-W stress field even to present day. It is one of main reasons for overpressure region in Middle Bhubhan formation. Crossplot between Velocity v/s Effective stress in Figure 1 and Velocity v/s density in Figure 2 validates the existence of unloading behavior of Middle Bhuban formation. Some of the porosity loss or velocity gain is because of inelastic behavior of rock. As a result sonic velocity will not decrease with the decrease in effective stress and it will fall on unloading curve.

## North-East onshore: Overpressure detection using well logs

An appropriate knowledge of formation pressure is required for safe well design and avoids drilling risks. Usually pore pressure is estimated using compaction dependent petrophysical measurements like sonic compressional slowness (velocity), density, resistivity, porosity etc. Normal pressure sonic trend is demarcated with decreasing sonic compressional slowness in shale with depth due to compaction in same depositional unit. In over-pressurized formations, sonic compressional slowness in shale will show a deviation from their normal compaction trend and remain same or increase with depth (Figure 3). All these estimated pore pressure values need to be calibrated using actual measured formation values using *MDT*, XPT** and well test in reservoir zones. Abnormal pressures are very much evident in this area as suggested by past drilling history. Two main reasons for their occurrence i.e. compaction disequilibrium, tectonic activity and uplift appear to be the major causes of over pressure generation aided by clay transformation and aqua thermal phenomena in the sediments in north eastern India. (Bhagwan *et al*, 1998).

## Geological Setting

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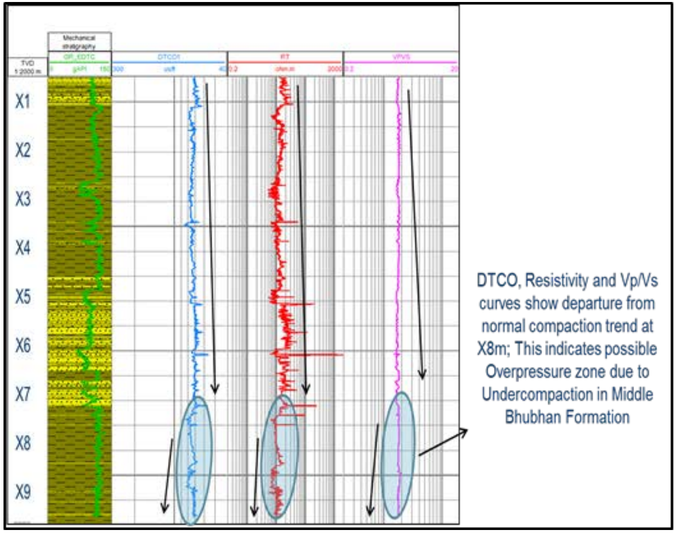
The area forms the major part of the Neogene Surma basin to the west of the Arakan Yoma subduction-collision zone, which represents the northward extension of the Sumatra-Java trench—the eastern margin of the Indian plate. The basinal sediments are folded into long arcuate belt in a series of linear narrow anticlines and synclines forming a unique foreland fold belt in the Indian sub-continent. The entire sedimentary column of the area is constituted of sandstone, siltstone, shale, mudstone, sand rock, silt and rare pockets of shell-limestone, which is divided into four major stratigraphic units based mostly on lithologic characteristics. Sequentially they are, (1) Barail (Oligocene; 3000 m) sandstone and shale, (2) Surma Group (Miocene) consisting mainly of (a) arenaceous Lower Bhuban Formation (+ 9000m, (b) argillaceous Middle Bhuban Formation (3000m), (c) arenaceous Upper
Bhuban Formation (1100 m) and (d) argillaceous Bokabili Formation (1000 m), overlain by (3) Tipam Group (Pliocene; +1300 m) consisting of feldspathic sand with fossil wood and minor silt. (Nandy *et al*, 1983).

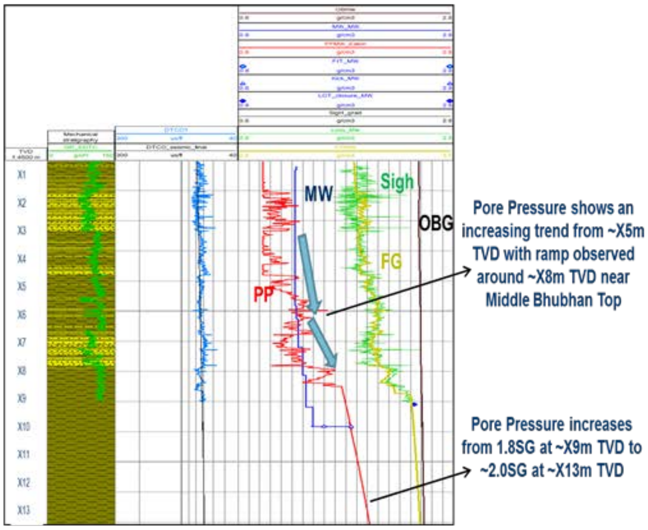
*Case Study*

Well-X was to be drilled to explore the potential resources of Surma Group (Miocene) mainly Middle Bhuban formation (3000m).This was the deepest exploration well in Tripura and there was no previous experience of pore pressure and MW for the upcoming section. Original 8.5” section of this well before sidetrack was drilled till ~X10 where kick was encountered while drilling with mud weight of 1.43SG. Later on MW of 1.85SG was used to control the well and gas cut. However their tool got stuck and it was decided to perform sidetrack from X1m and perform 8.5” section TD at X9m. Geomechanics study was done in order to provide MW for further drilling of 6” section to reach well target depth of X12m in Middle Bhuban. Based on seismic interval velocity, pore pressure has been estimated (Figure 4 and 5) for 6” section using calibration as mud weight used to control of kick. MW recommended was 0.03SG to 0.05SG higher than pore pressure. It was advised to increase the MW in steps from 1.85SG at X9m to 2.1SG till X12m



DTCO, Resistivity and Vp/Vs curves show departure from normal compaction trend at X8m; This indicates possible Overpressure zone due to Undercompaction in Middle Bhubhan Formation

**Figure 3- Departure of compressional slowness, resistivity and compressional to shear slowness ratio from normal compaction trend due to overpressure**



Pore Pressure shows an increasing trend from ~X5m TVD with ramp observed around ~X8m TVD near Middle Bhubhan Top

Pore Pressure increases from 1.8SG at ~X9m TVD to ~2.0SG at ~X13m TVD

**Figure 4- Pre-drill pore pressure profile for 6” section of Well-X**

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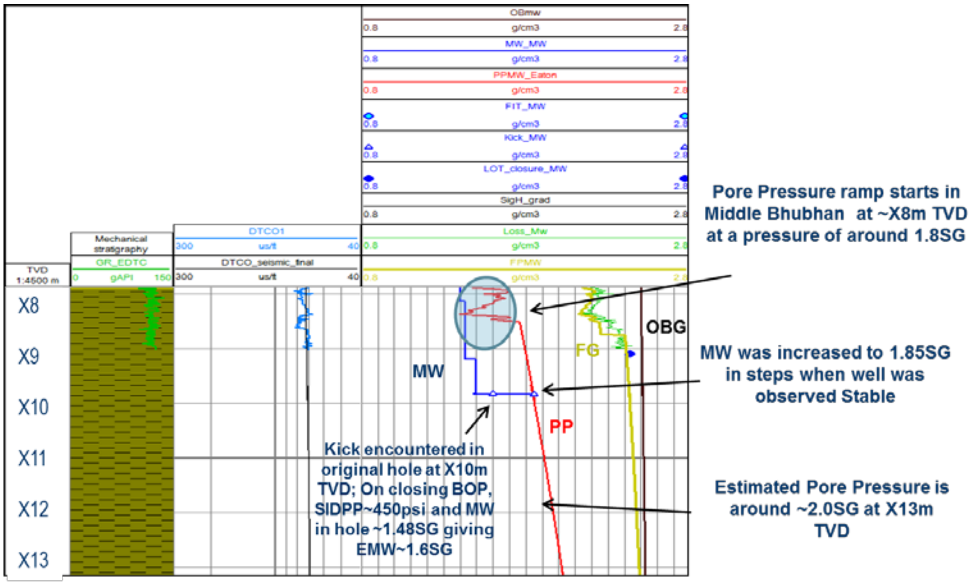

Pore Pressure ramp starts in Middle Bhubhan at ~X8m TVD at a pressure of around 1.8SG

MW was increased to 1.85SG in steps when well was observed Stable

Kick encountered in original hole at X10m TVD; On closing BOP, SIDPP~450psi and MW in hole ~1.48SG giving EMW~1.6SG

Estimated Pore Pressure is around ~2.0SG at X13m TVD

**Figure 5- Estimated pore pressure profile for well-X**

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## Post-drill Validation

Well was successfully drilled without much difficulty. They faced only one incidence of gas influx at X11m where lower (1.91SG) than recommended mud weight was being used. Later on 1.95SG was used to control gas cut and well was TD with 2.00SG.Comparison was made between the pore pressure with *XPT** values recorded. It can be seen in Figure 6 that the recommended pore pressure and MW is in close agreement with *XPT** values

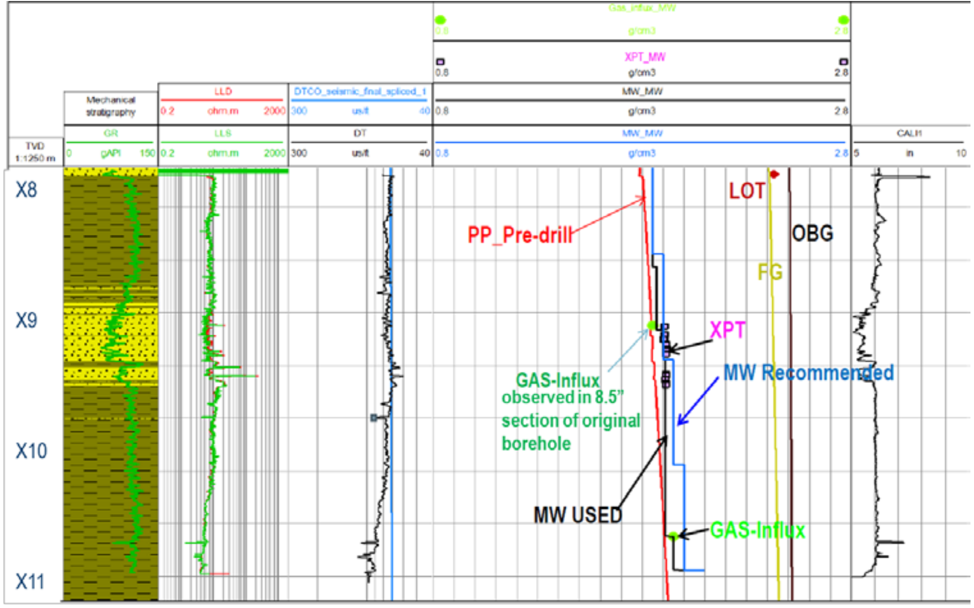
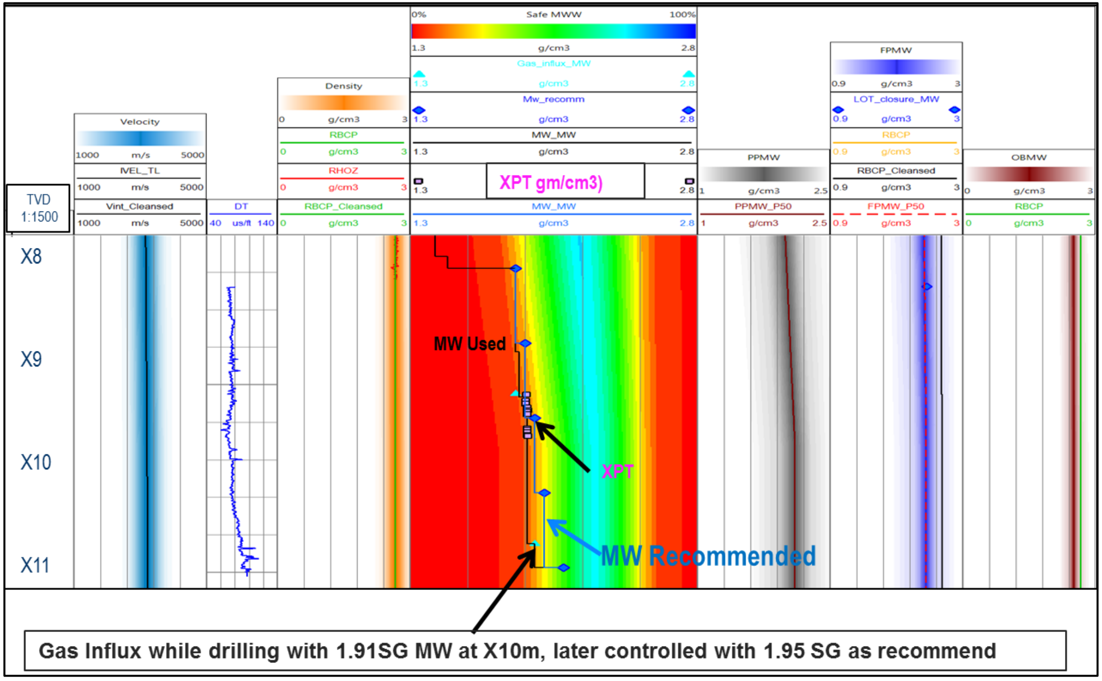


Figure 6.-Comparison of Pre-Drill Pore Pressure Model with XPT values

## Pore Pressure Uncertainty Model

The pore pressure uncertainty model allows to conduct pore pressure and fracture gradient predictions through a proprietary probabilistic approach (Malinverno *et al*, 2004) that honors the uncertainty in both, input data and parameters for the transforms (models) used to compute pore pressure and fracture gradient. This PPUncertainty process helps to design, evaluate, and monitor wells by computing the safe mud weight window. By computing the probability distribution for pore pressure and fracture gradients, and displaying the probabilistic safe mud weight window, helps to evaluate drilling hazards and plan and/or act accordingly



Gas Influx while drilling with 1.91SG MW at X10m, later controlled with 1.95 SG as recommend

Figure 7- Pore Pressure uncertainty model with XPT values

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Uncertainty model was prepared for Well-X (Figure7) which shows its probabilistic safe mud weight window. The gas kick was encountered at MW of 1.91SG shown in Figure 7 during the drilling of 6” section. It could had been avoided if recommended MW of 1.95SG was used.

## Conclusions

Accurate pore pressure prediction is one of the key factors for safe drilling of wells and casing design. Past experience from wells drilled in that area shows the existence of overpressure in Middle Bhuban formation. Exposure of this formation escalates the possibility of overpressure at shallower depths which may result into blowouts if proper planning is not done. There are two key over pressure mechanisms acting in this region which are compaction disequilibrium and tectonic loading. Overpressure in the formations above X8m is due to undercompaction and below X8m is due to tectonic loading. The pore pressure profile for the 6” section was prepared using seismic interval velocity and calibrated using observed drilling events like gas kick. Formation pressure ranges observed from 1.80SG to 2.02SG. Mud weight was recommended for further drilling to reach well target depth of X12m in middle Bhuban. They were able to successfully drill 6” section avoiding much difficulty by following the recommended mud weight. Estimated pore pressure was also compared with *XPT** values measured after drilling of this section. They are in close agreement with pressure data with a maximum deviation of 250psi.

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