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Before Drilling Pore Pressure Prediction Modeling and Pitfalls

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Abstract

Predictions of pore pressure using interval seismic velocity (Vi) before drilling and sonic slowness (Δt) while drilling are vital for the entire drilling program appraisal. The subsurface geological progress, from deposition, to compaction, to entrapment, greatly impacts the pore pressure partitions. In fluvial and deltaic marine environment, velocity as a porosity index, drifts as a consequence of these partitions. The current known velocity – pore pressure transformation models are lacking this relationship, especially in the so called normally pressured section.

The supposition that the section above the top of geopressure is normally pressured can lead to an unrealistic pressure profile. It also can have a domino effect on drilling challenges such as shallow water flow and the flow-kill-loss of circulation cycles. It is controversial to consider the shallow section as normally pressured and at the same time extract a compaction trend to be used for the deeper over-pressure section. Moreover, it leads to a misfit between the predicted and the real time measured values in the over-pressured formations.

The purpose of this study is to establish the seismic velocity – pore pressure modeling alliance above the top of geopressure and consequently apply the correct algorithm's calculation in the deeper over-pressured section. This new approach reduces the challenges due to the shallow water flow (SWF), setting casing and mud programs at the appropriate depths and reduces the risk of kicks and loss of circulation before drilling. Moreover, it reduces the pore pressure calculation uncertainty and the risk of incorrect calibration during drilling.

Introduction

Most of the pore pressure prediction methods are based on the supposition of the presence of two sections (Figure1), namely: normally pressured (hydrostatic) and abnormally pressured (over-pressured) below the top seal (Fertl, 1976). Correlations of numerous actual pressure profiles worldwide, especially in the Gulf of Mexico, show the general likelihood of the existence of four subsurface partitions (Shaker, 2014 and 2015). The so-called normally pressured section can be divided into two zones i.e., free flow hydrostatic (A) and hydrodynamic (B) and the so-called abnormal pressure can also be divided into two zones i.e., transition (C) and geopressured (D). This is in concordance with Terzaghi and Peck's (1948) three stages model, where zones A, B and D are equivalent to their model stages C, B, and A respectively. The herein suggested zone C represents the top disk of their model. This finding is substantiated by appraising the clastic depositional environment coupled with thorough observation of a wide range of well logs, seismic interval velocities and their subsurface pore pressure partitions (Figures 1).

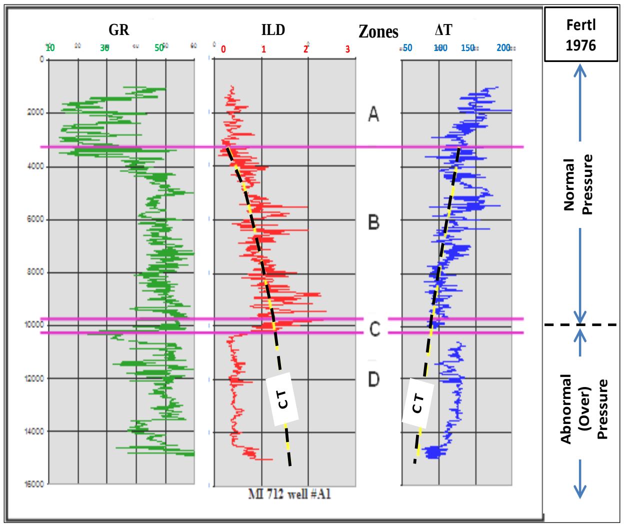

Figure 1 The impact of the four subsurface pressure zones (A, B, C and D) on the resistivity and sonic logs. Compaction trend (CT) represents the extrapolated petrophysical values as if retention of fluids does not take place.

Each of the previously mentioned four zones show a unique velocity trend associated with porosity – density behavior during subsidence at depth. Overburden load, aqua-thermal, diagenesis, clay mineral transformations, and hydrocarbon generation are the source of in-situ pressure and they are a function of depth. Compaction is associated with high energy sediment load and burial that take place during sea low-stand. Conversely, during high stand and maximum flooding events, fine clastic (especially shale) spreads widely in the deep seated basin and forms a regional seal. The youngest upper seal is usually referred to as the top of the geopressure (TOG). Throughout the geological time, sequence of stratigraphic units goes through the compaction and burial processes (Figure2). The compaction trend (CT) of the upper sequence, which is still undergoing the compaction process (i.e. zone B), is used for pore pressure prediction for the entire geopressured subsurface section (Figures 1 and 2).

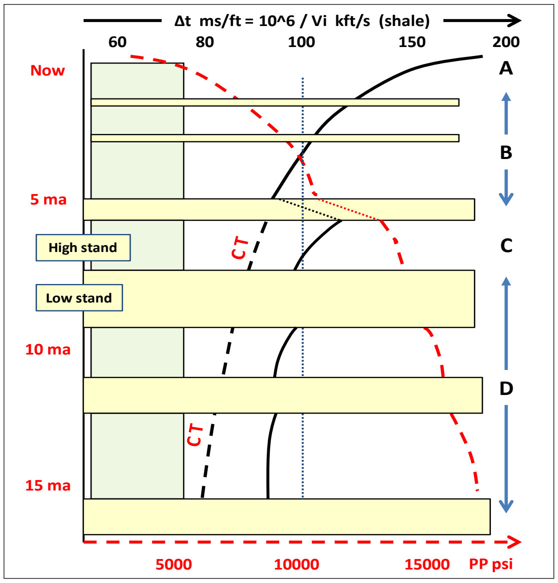

Figure 2: Cartoon shows shale velocity vs. pore pressure progress during geological time. Notice the large shift of both velocity and pore pressure at zone C.

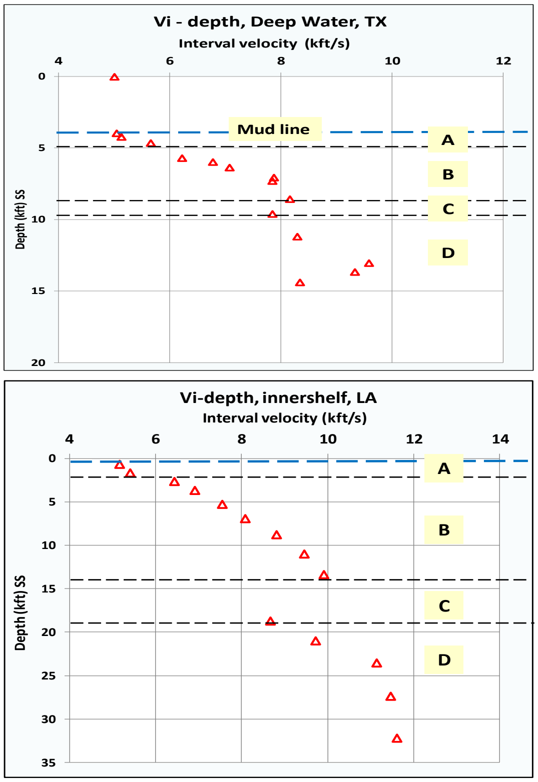

Figure 3: velocity changes vs. depth in two different geological settings showing the velocity drift due to the presence of the four subsurface pressure zones.

Velocity – pore pressure in each zone

Numerous seismic interval velocity-depth plots were studied to substantiate the validity of the four pore pressure partitions. They are from the Deepwater, outer shelf, inner shelf and onshore Gulf Coast areas (Figure 3). Formation water velocity is observed in zone A, and velocity increases exponentially in zone B, reflecting the dewatering and compaction. On the other hand, velocity reverses its slope in zone C and retains back a gradual increase associated with subtle variations in zone D due to compartmentalization (Figure 3).

Zone A: This zone in offshore is represented by un-compacted sediments with porosity ranges from 70% at the top to 40% at the bottom. Velocity responds to fluid rather than the suspended and uncoupled sediment grains and it ranges from 5000 ft/s to 5500 ft/s (Figure 3). Pore pressure gradient is a function of depth and the density of sea water (e.g. 0.465 psi/ft in GOM).

Zone B: This zone starts where the velocity shows an exponential increase with depth from ≈ 5500 ft/s at top to 8000 ft/s - 10000 ft/s at bottom (Figures 3). Older sediments exhibit faster velocity at the bottom of this zone (e.g. Miocene relative to Pleistocene). This zone was considered to be normally pressured sediments based on conventional beliefs. Measured pore pressure from several reservoirs associated with this zone shows an upward flow (i.e. hydrodynamic) as a result of compaction and the dewatering processes. Mud weight required to drill this zone ranges from 9.0 ppg to 11.5 ppg (Figure 4). That is where the shallow water flow (SWF) takes place in deepwater geological setting (Shaker, 2016).

Predicting the pressure in this zone is not an easy task especially in wildcat areas. However, a feasible formation pressure (FFP) vs. Vi is introduced in this work. Offset measured pressure and mud weight data is required to establish this empirical relationship. Calculating the pore pressure in this zone can be summarized in three phases (Figure 4): 1- Establish the velocity trend from seismic Vi and offset sonic logs. The extracted Dix's Vi from the Rms velocity was correlated to some of the sonic Δt's of offset wells and they show a very noticeable agreement (Figure 4a). 2- Create empirical depth – feasible formation pressure (FFP) relationship which can be established from the offset mud weight data (Figure 4b). 3- Build up Vi – FFP relationship that can be used in a specific basin (Figure 4c). Figure 4 exhibits the velocity (from seismic and sonic logs) – feasible pore pressure relationship of offshore shelf area in East Texas (High Island area) and West Louisiana (West and East Cameron areas). Estimating the pore pressure of zone B from interval velocity measurements in this area (Figure 4c) can be calculated as:

FFP in ppg mwe =

$28 - (3.9 \ln \Delta t) = 28 - [3.9 \ln (10^6/Vi)]$

Zones C and D: Zone C starts where velocity reverses direction and shows a distinctive slowness (i.e. increasing of Δt). Zone D starts where velocity shows a gradual subtle increase again. The pore pressures in these two zones are calculated using the horizontal effective stress algorithm (Eaton, 1975). Eaton's equation has been slightly modified to reflect the amended compaction trend. This trend (CT) is the extrapolated data from zone B only and not from the so-called normal compaction trend (NCT) from zones A and B (Shaker, 2015). The average Δt_{CT} was calculated and extrapolated to zone C and D at depth (Z_C / Z_D) from the exponential trend (Figure 5c) as:

$$\Delta t_{CT} = 129.57e^{-3E-05(Z_C \text{ to } - Z_D)}$$

This is a unique equation only applied to this depth-V_i pair at this CMP seismic gather. Predicting the pore pressure is reliant on the disparity between the extrapolated velocity data from zone B (Δt_{CT}) and the equivalent values from the actual measured velocity ($\Delta$to) at depth in zones C and D (Figure 5a).

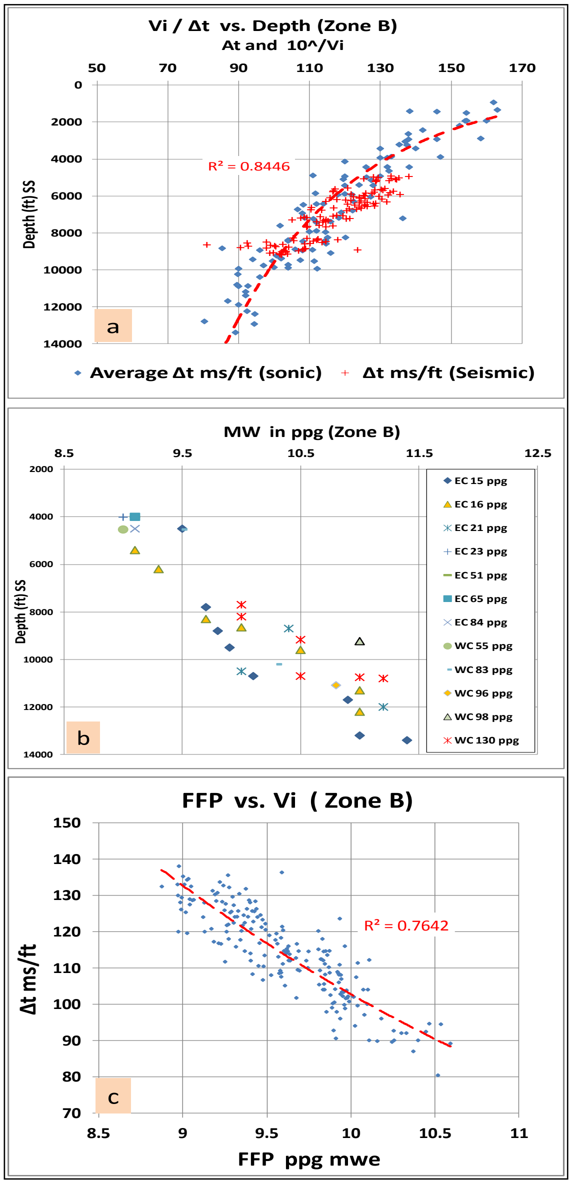

Figure 4: The three steps of calculating the pore pressure (FFP) in zone B from seismic Vi and the drilling mud weight of offset wells.

Modeling before and calibration while drilling

Subsurface pore pressure prediction from interval velocity before drilling should be done individually in the aforementioned four zones. This will avert the confusion of applying the effective stress theorem in the zones above the top of geopressure (i.e. in zones A and B) and also use the right compaction trend to estimate the pressure in zones C and D. Figure 6a shows the before drilling predicted pore pressure using the new four zones method. On the other hand, Figure 6b displays the discrepancy between the pressure predictions using the so called NCT and using the new trend of the actual compaction trend (CT) from zone B only.

Logging while drilling (LWD) of sonic slowness (Δt) and measuring while drilling (MWD) of well records is widely used to calibrate the before drilling prediction pressure model (Figure 7). Adjusting the before drilling seismic prediction model's exponent in real time (RT) is one of the common practices at the rig location or via high speed connection to the exploration/operation office. The calibrated exponent (e.g. 3 in Texas inner shelf) will be used for any future pressure prediction in the same basin. Measured pore pressures, static mud weight (ESD), equivalent circulation density (ECD), shut in pressure (SIP) are frequent calibration points. Drilling events such as kicks, connection gas measurements and loss of circulations are also good reference spots between the before and while drilling transformation models (Figure 7).

Discussion and conclusions

Interval primary velocity Vi in shale is the optimum technique to predict pressure before drilling. Bell, 2002 recommended the methods for estimation and calibration of CMP gathers of velocity from seismic for pore pressure prediction.

Defining the four subsurface partitions from Dix or tomographic velocities coupled with sequence stratigraphy is an important procedure for pore pressure prediction before drilling. Zone A is an extension of the pore pressure at the mud line. Zone B, where velocity shows an exponential increase, bears hydrodynamic pressure ranges from ≈ 9.0 ppg mwe (pound per gallon mud weight equivalent) at the top to ≈ 11.0 ppg mwe at the bottom. Velocity follows this compaction / dewatering progression and gradually increases from ≈ 5500 ft/s at the top to ≈ 8000 - 10000 ft/s – at the base contingent on sediment's age. In this study, a velocity – pore pressure relationship is established. Moreover, the slope and extent of the velocity in zone B (Δt_{CT}) to the deeper section is calculated and used to estimate the deeper geopressured zones.

Zone C and D is where the fluid is entrapped in the deeper sedimentary section (stage A of Terzaghi and Peck, 1948 model) and the effective stress theorem is applicable. Pore pressure bears an excess pressure (over-pressured) greater than the pressure at the base of zone B. At the transition zone, coinciding with the top of geopressure, velocity takes a reverse turn. The velocity retreats and extent are dependent on the top seal thickness and its age. It is noticed that older sediments (inner and outer shelf) show a stronger pressure ramp than younger sediments (deepwater Plio-Pleistocene).

Pore pressure ramps can range between 100's psi and 5000 psi contingent on the competence of the top seal.

The geopressured zone D is characterized by several compartments contingent on the numbers of high stand system tracts when paleo-seals were formed. Shale velocity show subtle changes in this zone. This is due to the fact that the deep sediments already went through the compaction process which is currently taking place at zone B (Figure 2).

The geopressure partition can be foreseen during the prospect generation phase by assessing the corrected interval velocity. This will help appraise the trapping integrity and the drilling challenges which are very important elements of the prospect's economic feasibility.

Recommendations

- The stratigraphic column above the TOG (zone C) is not hydrostatically pressured. The top unconsolidated section (zone A) is only hydrostatically pressured.
- Compaction trend concurs with the dehydration process which starts where velocity increases exponentially. Therefore, draw a compaction trend includes the whole section above TOG (zones A and B) can leads to erroneous pore pressure prediction calculations.
- The hydrodynamic fluid flow of zone B can cause the SWF.
- Penetrating the section that shows velocity reversal (Zone C) should be done cautiously to avoid hard kicks in sand and excessive bore-hole caving in shale.
- Effective stress theorem (e.g. Eaton's method) is only valid below the TOG where sediments and fluid share the brunt of the vertical stress under confining compartments (zones C and D).
- Calibration the Pre-drilling model in RT from LWD should be done with sanitized data set from the sand's Δt measurements.

Acknowledgements

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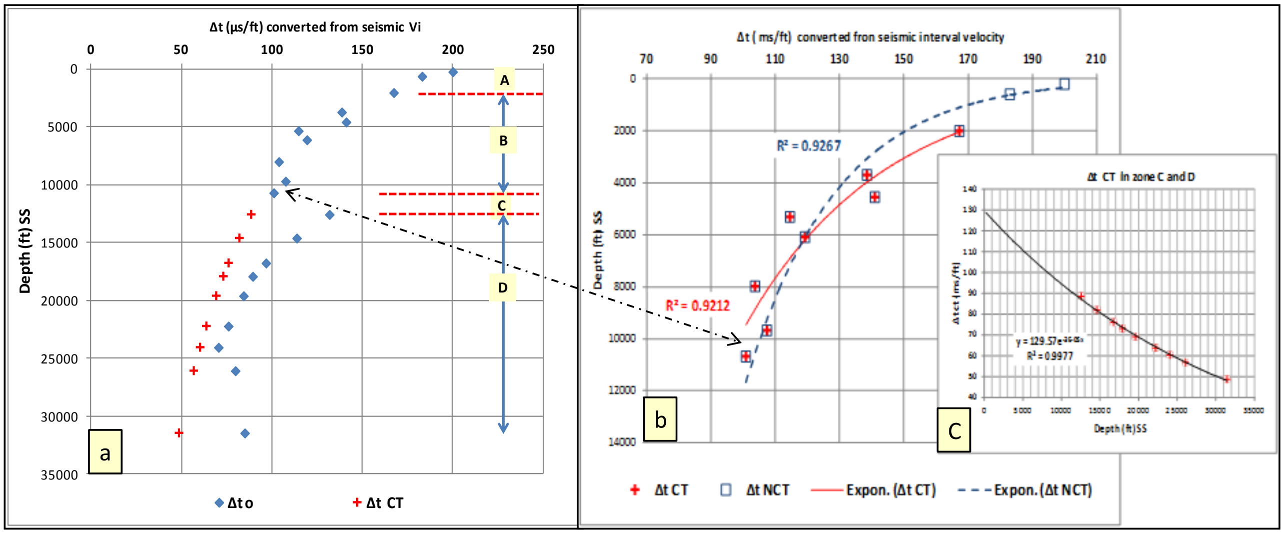

Figure 5: 5a) Estimating the four zones on Δt (converted from Vi) - Depth pair. 5b) Graph exhibits the discrepancy between calculating the compaction trend (CT) from zone B only (Δt_{CT}) and from zones A and B combined (Δt_{NCT}). 5c) Insert shows CT calculation in zones C and D.

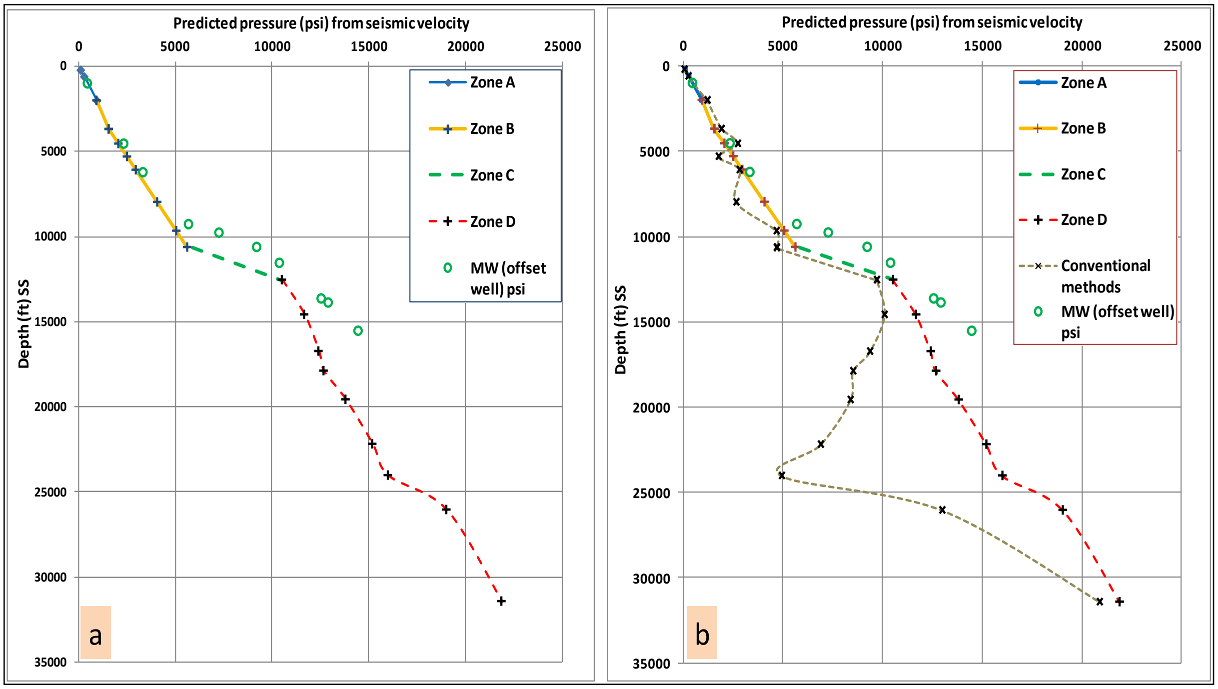

Figure 6: 6a) before drilling seismic – pore pressure transformation model. MW of offset well was used to customize the exponent for zones C and D pressure prediction. Vi picks are questionable at depth greater than 25000 ft. 6b) shows correlation between the conventional method (black dashed curve) using NCT and the new four zones method. Using conventional method shows erroneous calculations of under-pressured formation from 5,000 ft to 10,000ft and strong pressure regression deeper than 18,000 ft.

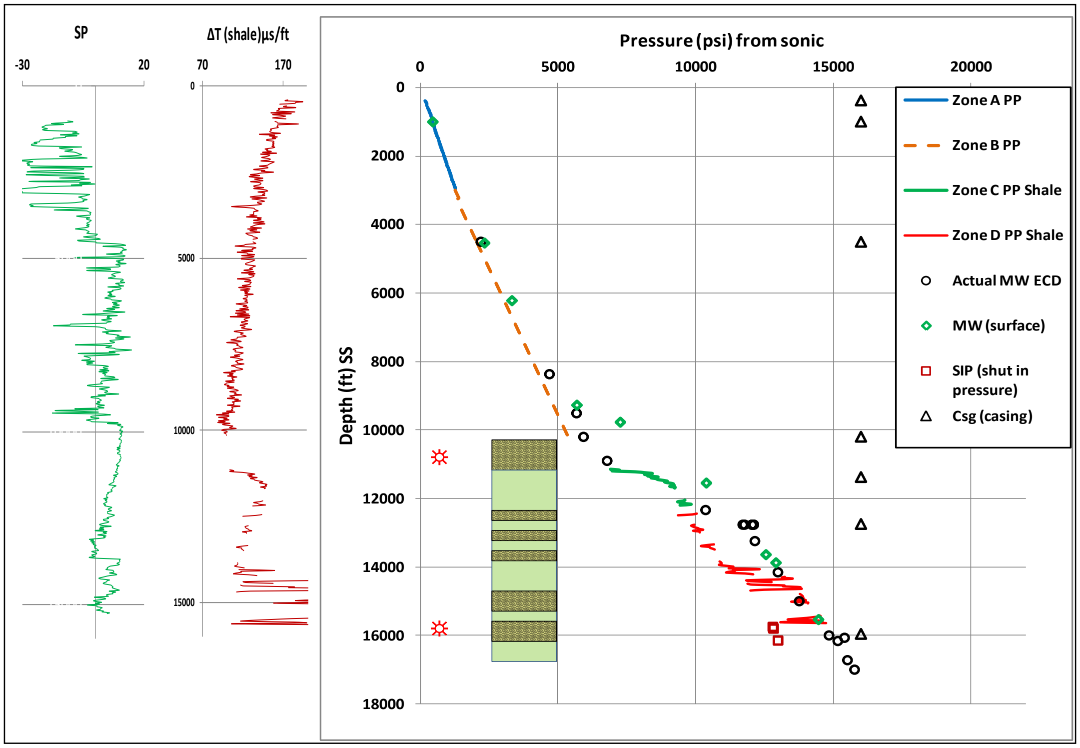

Figure 7: LWD and MWD for pore pressure model calibration. Note Δt was sanitized and represents shale beds only. The SIP's were taken in sand formations. Moreover, three casing seats were needed to penetrate the transition zone (C) between the bottom of zone B and the top of zone D. ECD was noticeably higher than MW at the mud pit during drilling this transition zone. The well reached TD of 17,000 ft with few challenges at zone C and discovered two gas pay zones.