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Pore Pressure Prediction Before and During Drilling Applying the Four Zones Method

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Abstract

This method integrates the geological building blocks of sedimentation, dehydration to lithification and the formation water hydrodynamic forces associated with each of these phases. The current known conventional velocity – pore pressure transformation models are lacking this relationship.

In the current widely used conventional methods, it is controversial to consider the shallow section as normally pressured and at the same time extract a compaction trend from its petrophysical properties. Moreover, there is confusion about which part of the subsurface section the Effective Stress theorem should be applied to. The novelty of dividing the subsurface into four zones using this new approach reduces the risk of predicting the pore pressure before drilling and the uncertainty of its correct calibration during drilling.

This new pore pressure calculation is done separately in each zone based on the predominant formation-water dynamic. Normal hydrostatic pressure is only assigned to the loosely compacted very shallow section (A). Hydrodynamic zone B with upward formation water flow is associated with compaction and reduction of porosity due to sediments load. Petrophysical trends such as velocity, density, resistivity follows a compaction trend in this zone. As result of depositing shale seal in zone C, due to high stand sea level, fluid is prevented from permeating upward. This low permeable top seal is referred to as top of geopressure (TOG). The geopressured section of zone D below the pressure ramp in zone C follows a cascade outline where the pressure in permeable beds show linear trends and shale exhibits an exponential trend.

The petrophysical properties of the deeper shale beds below the top seal represent several passive compaction trends. Pore pressure prediction in the deep geopressured section D is derived from calculating at the same depth the disparity between the extrapolated velocity compaction trend (CT) values and the measured ones. A unique mathematical calculation is introduced here to establish the compaction trend (CT) instead of the manual graphically extrapolated so called NCT. Before drilling seismic velocity, semblance is a key for defining the four zones. Velocity – pore-pressure transformation modeling is an important aspect of the drilling cost for a proposed location. Moreover, LWD's during drilling and conventional logs post drilling are the fine-tuning tools of calibrating the pre-drilling seismic-pressure model. The calibrated model is the backbone of any predicted pore pressure in future drilling locations in the same basin.

The pore pressure prediction applying this method facilitates assigning the casing setting and mud programs at the appropriate depths before drilling. Furthermore, it reduces the non-productive time (NPT)

and challenges by assessing the subsurface formation pressure including the shallow water flow (SWF), risk of kicks and loss of circulation along the proposed bore-hole trajectory before moving rig on location.

Introduction

Pore pressure has a great impact on the economic feasibility of any subsurface exploration endeavor, ranging from hydrocarbon generation to entrapment and production. The sources of generating the subsurface formation pressure are related to increasing burial by sediment load, heat, fluid expansion and clay minerals dehydration. Fertl (1976), Magara (1976), Swarbrick et al. (2002), Tingay et al. (2009) and Velazquez-Cruz et. al. (2017) discussed numerous causes of pore pressure generation, all of which lead to an increase of in situ fluid pressure. However, fluid trapping by top regional seal (fine clastic sediment deposited by maximum flooding event) is the main driving mechanism causing the excess subsurface overpressure that creates the abnormal formation pressure ramps (Shaker 2015 a).

The distinct establishment of the four subsurface formation pressure zones (A, B, C and D) herein is to eliminate the confusion and miscalculations of using some of the current conventional methods. These different pressure zones are based on the geo-hydrodynamic relationship between the sedimentation process associated with clastic deposition load, compaction, lithification and the equivalent pore-pressure as a result of formation fluid's dynamic in each zone. These allotted four zones in this article are substantiated by evaluating a wide range of well logs, drilling histories, seismic interval velocities and their subsurface pore pressure partitions in the Gulf of Mexico (Shaker 2015 a).

Setting a standard classification for how the pore pressure developes with increasing the load (total stress) in clastic sedimentary column, Terzaghi and Peck (1948) developed a three stage model for clay compaction. Stage C represents a hydrostatic pressure gradient with a compaction equilibrium status. Stage B represents the increasing of the principal stress associated with fluid escaping from the experimental vessel. Stage A shows how overpressure is form when the fluid is retained within the vessel under increasing sediments load (i.e. compaction disequilibrium).

Leftwich and Engelder (1994) distinguished three different segments for the formation pressure profile in the Ann Mag Tertiary type fields of the Gulf of Mexico. From top to bottom they are: K1(normally pressured and normally compacted), K2 (abnormally pressured and normally compacted), and K3 (abnormally pressured and under-compacted).

An assumption was developed over the last 40 years divides the subsurface formation pressure into two major segments separated by the top of geopressure (Hottman, C.E., & Johnson, R.K., 1965, Eaton, B.E., 1975, and Fertl, W.H., 1976). This assumes a normal hydrostatic gradient above the top of geopressure (TOG) and an abnormally pressured sedimentary section below the TOG. In this study Zones A, B, D are consequently equivalent to Stages C, B and A of the Terzaghi and Peck (1948) model, whereas zone C represents the vessel's sealing disc. Zone B and D are equivalent to K1 and K2 in Leftwich and Engelder (1994).

The conventional effective stress prediction methods (e.g. Eaton, 1975; Bowers, 1994) uses the petrophysical properties (velocity and resistivity) as a porosity reduction trend in the section above the TOG (zones A and B). This trend is called the normal compaction trend (NCT). It is controversial to consider the section above TOG as normally pressured (e.g. GOM 0.465 psi/ft hydrostatic gradient) and at the same time a compaction trend (reflects dehydration and reduction of porosity) is calculated. This NCT is the leading track for the conventional calculations in the over-pressured zones below TOG. Unfortunately, after forty years, geopressure analysts still sway, break and use graphical lines to establish the NCT. "Eaton (1975) stated in his conclusion that the methods used to establish normal trends vary as much as the number of people who do it". In this four zones method, a unique algorithm has been established to calculate the Compaction Trend at a specific proposed well location.

The modified Vertical Effective Stress by Bowers (1994) exhibit a lack of cohesion by displaying a four pound per gallon difference between the predicted PP and actual MW used to drill a specific well in GOM, whereas Eaton's (1975) Horizontal Effective Stress method is successfully used to predict over-pressure worldwide.

The Geological building blocks of formation pressure

Formation pressure build up requires the presence of porous rock matrix that is saturated with mobile formation fluid and is subjected to increasing stress with depth. Based on the geological setting and the formation water dynamics, the four zones are denoted as: Normal Hydrostatic (A), Hydrodynamic (B), Transition (C) and Geopressured (D) from top to bottom. Zone A represents the very shallow zone where sediments are unpacked and pressure is related to sea water density. Zone B begins where formation fluid starts expulsion to the shallower section under the sediments load. Exponential reduction (Ethy, 1930) of porosity (i.e. compaction) associated with sediments dehydration with increasing depth. At the top of zone C fluid up-flow ceased due to the presence of low permeability lithology. The formation below the fluid retention depth (Velazquez-Cruz et. al., 2017) represent the sealed over pressured vessel in the Terzaghi and Peck model. The low permeability regional seal causes the shift from hydrodynamic pressured zone (B) to an over-pressured section(D) below.

The pressure profile in the geopressured zone (D) is impacted by the passive geological history of the basin such as high stand (shale) and low stand (sandy facies). This cascade profile shows a linear trend in reservoirs and exponential trend in shale (Shaker 2017).

Lithology:

Sand beds are built up of quartz, feldspars, orthoclase .etc. grains of different shapes ranging from angular to perfect spheres. The grain to grain contacts allow open pore throat that lead to a hydrostatic linear pressure gradient (PG). Measured pressure (MP) in clean sand reservoirs follows linear trend. RFT's and MDT's from sand and sandstone beds in the GOM always show linear trends with a slope reflects the formation water salinity.

Shale beds are mainly made of clay minerals (montmorillonite, illite .etc) which are subject to diagenesis and chemical alterations under high pressure and temperature. The shale platelets have the capability of permanently entrap a portion of the fluid that acts as a fluid cushion surrounding the shale platelets (bounded water). Pore pressure in shale mimics the exponential porosity reduction trend described by Ethy's (1930). This compressibility of the entrapped water in the shale beds leads to pressure inflation. The bounded and interstitial water's pressure acts against matrix grains in the pore spaces and reduces the principal stress to a lesser value known as the effective stress (ES). Figure 1 is a schematic representation shows water dynamic during the process of sedimentation, reduction of porosity associated with increasing the pore pressure with depth and the reduction of principal stress (OB) due to fluid entrapment by the clogging the pore throats below TOG. Water saturation associated with the subsurface porosity profile impact velocity, resistivity and density measurements.

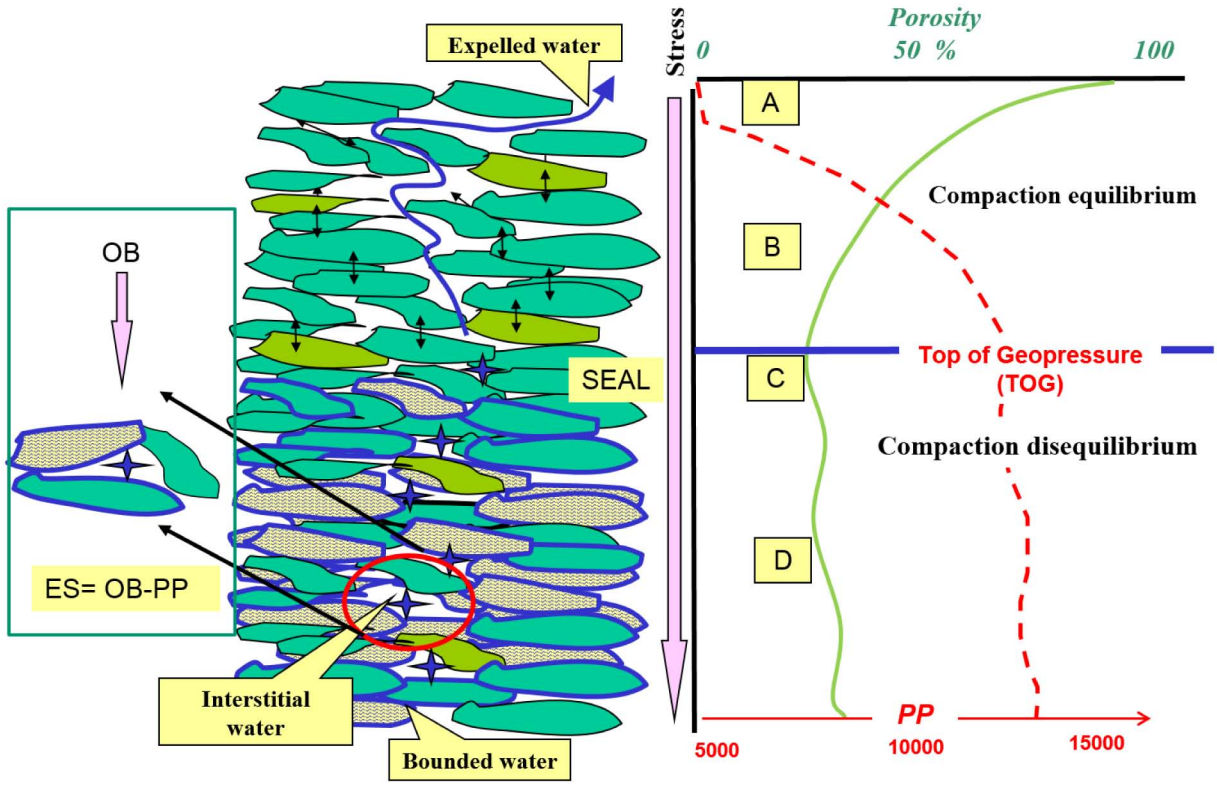

Figure 1—schematic representation shows water dynamic during the process of sedimentation, reduction of porosity associated with increasing the pore pressure. A simple explanation of the effective stress theorem on the left.

Sequence Stratigraphy:

The deposition system in a sedimentary basin is controlled by the interaction of the eustatic rise and fall (sea level changes) and the continental environment sediments source. Low stand system tract is dominated by course reservoir type sediments whereas, high stand system is dominated by fine clastic seal type (shale) deposits (Van Wagoner J.C. et.al., 1990). The repeated sea level rise and fall, associated with different depositional system, during the course of geological time, create a sedimentary column of alternating lithologies. The older sediment subsides under the newer sequence's load and preserves the passive compaction characteristics (Figure 2).

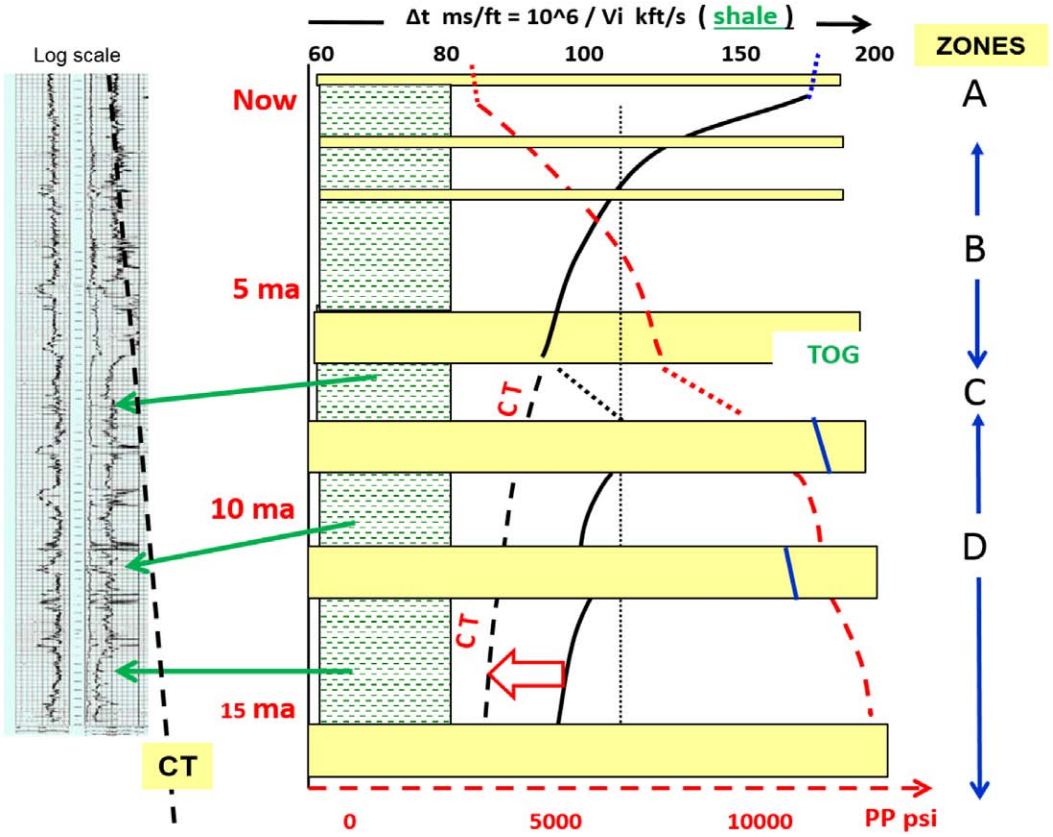

Figure 2—Cartoon shows a 15 million years several clastic sequences. High stand is shale (green) and low stand is sandy facies (yellow). Compaction trend is active in the young 5 ma sequence. CT (dashed) represents the extrapolation of the compaction to zone C and D. Note the reverse of velocity slope and the pressure surge at the ramp C. The red arrow expresses the Δt c – Δt o in shale beds.

During the last five million years of the sea stand (e.g. Plio-Pleistocene) sediments compaction remain in process until the future next sea high stand occurs. This is when the next younger top seal will form and where the compaction trend (CT) is calculated. Deeper in the subsurface section the sand and shale beds represent cyclical high and low stand throughout the geological history of the basin (Figure 2). The difference between the petrophysical properties (velocity, resistivity, density etc.) of the extrapolated youngest sediment's compaction trend (Δt ct) and the preserved (Δt o) in the older geopressured system (zones C and D) mimics the effective stress profile. The derived effective stress formula from velocity or resistivity (e.g. Δt o - Δt ct) is used as a numerator in the pore pressure prediction algorithms (Eaton 1975).

Before Drilling

Defining the four zones from seismic

The primary seismic velocity (V_p) is the first petrophysical property that can be used to predict the depth to the previously-mentioned four zones. Quality control and processing of the compressional seismic velocity are required for the purpose of pore pressure prediction (PPP). Converting the time-velocity pairs to depth-velocity pairs is the first objective on this PPP workflow and needs to be calibrated against check-shot, velocity survey and/or sonic logs from offset wells. Porosity, water saturation and dynamic control to a great extent the petrophysical properties of each zone.

Zone A is represented by high porosity uncompacted sediments with porosity ranges from 70 to 40%. Therefore, interval velocity (Vi) is in proximity of water's velocity and ranges from 5000 to 5500 ft/sec. Pressure gradient in this shallow zone (200 to 2000 ft thick) is a function of sea water density (e.g. 0.465 psi/ft in GOM).

Zone B starts where velocity shows an exponential increase (reduction in porosity) from 5500 ft/sec at the top to 8000 – 10000 ft/sec at base (Figure 3). This zone was considered to be normally pressured sediments based on the conventional beliefs. Measured formation pressure from this zone shows a hydrodynamic flow as a result of the dewatering process. Mud weight required to drill this zone ranges from 9.0 ppg to 11.5 ppg. Shallow water flow (SWF) events take place during penetrating this zone where formation water in the process of ejecting out of the sedimentary system (Shaker 2016).

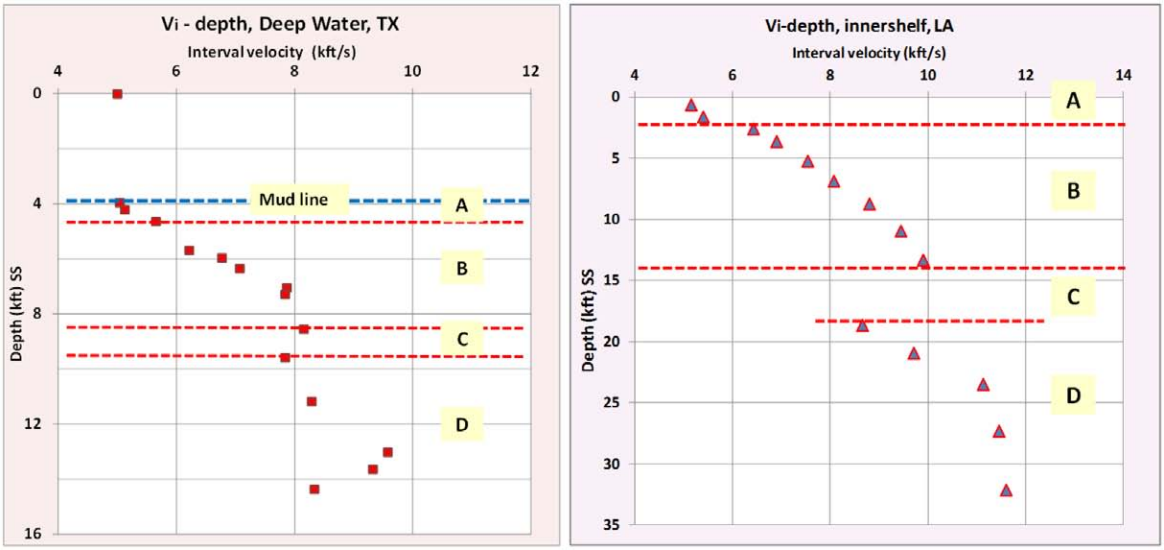

Figure 3—Exhibts two velocity (Vi) – depth profiles in deep-water and innershelf. Velocity gradient in older innershelf is greater than deepwater one. Moreover, velocity reversal is stronger in older sediments than younger deepwater one. This is due to compaction maturation with time.

A distinct velocity reversal drift (negative slope) take place at the top of Zone C and retains the same negative slope until it reaches the top of zone D when it goes back to the positive exponential trend (Figure 3). Velocity in zone D meanders, following the lithology of the geopressured compartmentalized of the deeper section. The geological history and the eustatic sea level dictate the cyclical number of the velocity drift in zone D (Figure 2). This also leads to creating the successive subsurface geopressure compartmentalization. Figure 3 shows examples of velocity pairs from deep-water (young sediments), and inner-shelf (older sediments). Velocity in older sediments is higher at the base of B and the velocity reversal section at C is stronger. This because older sediments compaction is more mature than younger one.

Pore Pressure Prediction (PPP) calculation from Seismic:

Zone A: The normal hydrostatic pressure gradient derived from the weight of the water column in this zone reaches depth of 1 to 2 km in the GOM (Rubey and Hubbert, 1959). Pressure gradient (PG) in this zone of the Gulf of Mexico is 0.465 psi/ft (10.52 MPa/km) based on water density is 1.06 g/cc. Therefore, pressure at depth z1 is:

$$Pz = PG*z \quad (1)$$

Where

Pz = pressure at depth z

PG = pressure gradient of 0.465 psi/ft

psi/ft = pound square inch per foot length.

MPa/km = mega pascal per kilometer

Zone B: Dehydration process plays an essential role in calculating the formation pressure in this zone. The formation water up flow (hydrodynamic) creates a differential pressure from the bottom to the top follow

the Darcy's flow law. Using the effective stress theorem in this upward hydrodynamic condition is not valid because it mimics Stage B of Terzaghi and Peck (1948). The method of establishing the relationship between the acoustic velocity and the formation pressure in this hydrodynamic dehydration zone was established by Shaker (2015 b). A new algorithmic relationship between feasible formation pressure (FFP) vs. interval velocity (Vi) of offshore East Texas and West Louisiana shelf area is as follow:

$$\begin{aligned} \text{FFP in ppg mwe} &= 28 - (3.9 \ln \Delta t) \\ &= 28 - [3.9 \ln (10\text{^}6/Vi)] \end{aligned} \quad (2)$$

Where

ppg mwe =pound per gallon mud weight equivalent

Δt =acoustic impedance

Vi =interval velocity

This method's and workflow can apply in almost every clastic sediment worldwide where dehydration (compaction) is undergoing process (Figure 4). However, this equation (2) is uniquely tailored to the offshore shelf area of west Louisiana.

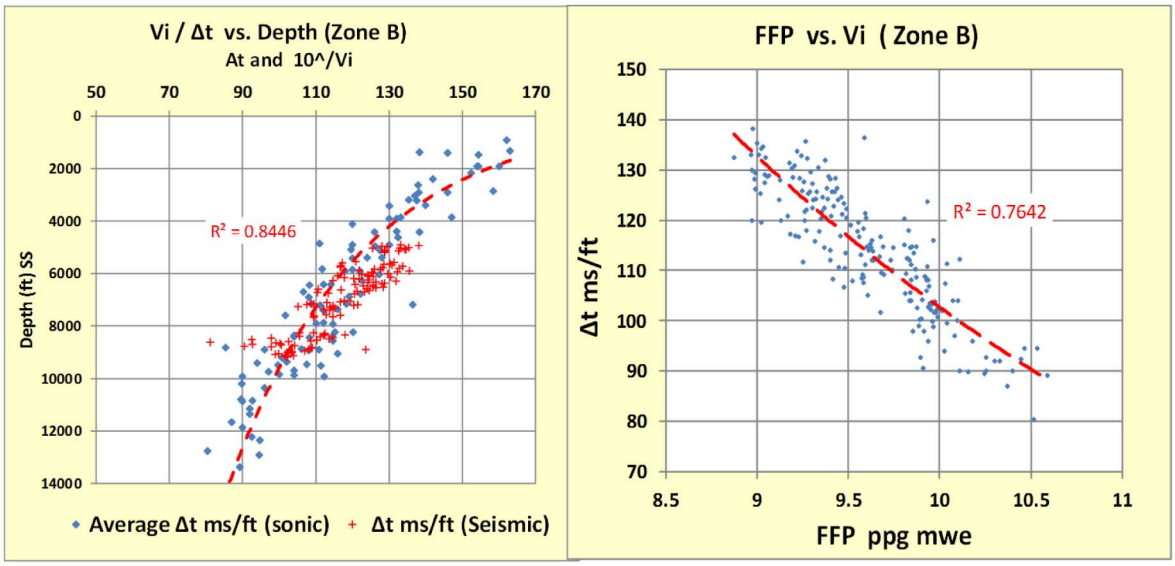

Figure 4—The workflow of establishing the algorithm in equation #2 from seismic velocity, sonic and drilling mud. The right panel shows the feasible formation pressure (FFP) vs. Δt (from seismic or sonic) at any depth in zone B.

Calculating the Compaction Trend (CT):

The compaction trend (CT) is the average calculated petrophysical data increment with increasing depth. The extrapolated deeper values of this trend below the top of geopressure is used to calculate the difference between the measured actual Δt (i.e. Δto) and the velocity slowness (Δt ct) as if the compaction in zone B has held in zones C and D. Therefore, the effective stress is calculated using CT extracted from zone B only and not from the so-called normal compaction trend (NCT) from zones A and B. The average Δtct was calculated and extrapolated to zone C and D at depth (ZC / ZD) from the exponential trend (Shaker 2015 b) as:

$$\Delta t \text{ ct} = 129.57e \text{ -3E-05 (ZC to - ZD)} \quad (3)$$

This is a unique equation only applied to this depth-Vi pair at this Common Midpoint Point (CMP) seismic gather. Predicting the pore pressure is contingent on the disparity between the deeper extrapolated velocity data values (Δtct) from zone B and actual measured velocity values (Δto) at equivalent depth in zones C and D (Figure 5).

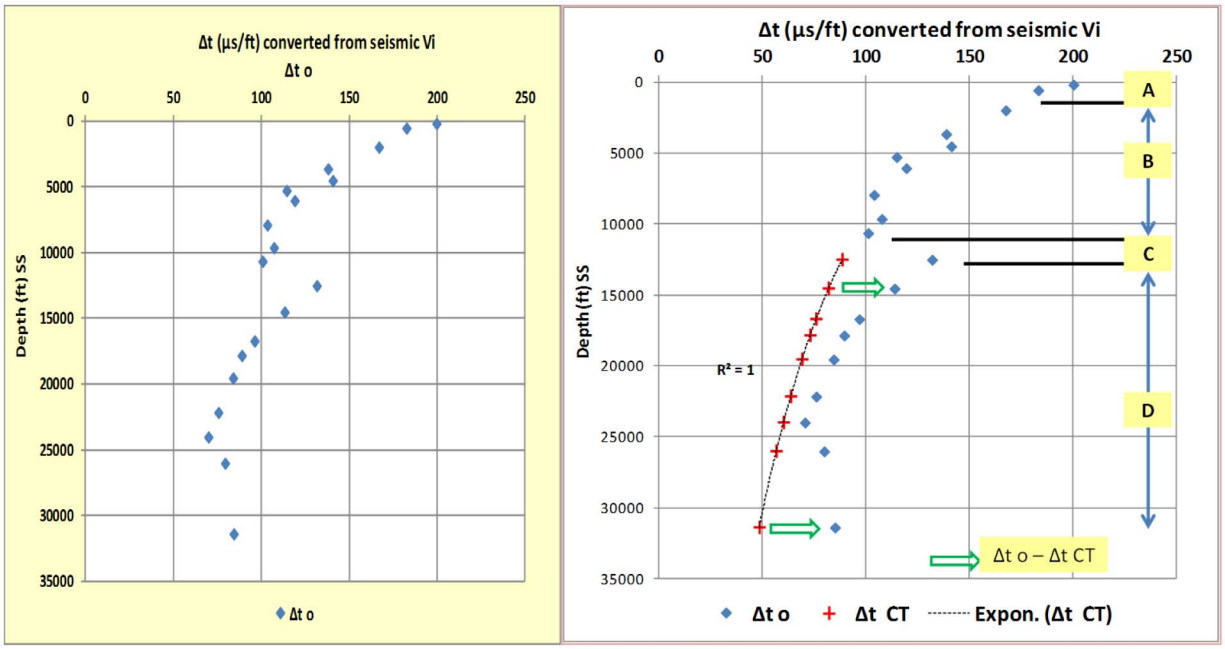

Figure 5—The Δt extracted from Vi-depth pair(left). The same Δt – depth pair with the assigned four zones on the right panel. Note the Δt CT extrapolated data (red cross markers) deeper to C and D to calculate the Δt o – Δt CT.

The widely used conventional effective stress prediction methods are usually categorized into two groups, 'horizontal' and 'vertical' methods. They are mostly dependent on the departure of the measured velocity, resistivity and density values (Vo, Ro and ρo) from the equivalent extrapolated normal compaction trend (NCT) values. The NCT petrophysical trend from the section above the TOG (zones A and B) causes numerous misfits and undervalue pressure estimates. Figure 6 shows the slope difference between the trend extracted from the actual compaction B zone and the trend covers zones A and B (NCT).

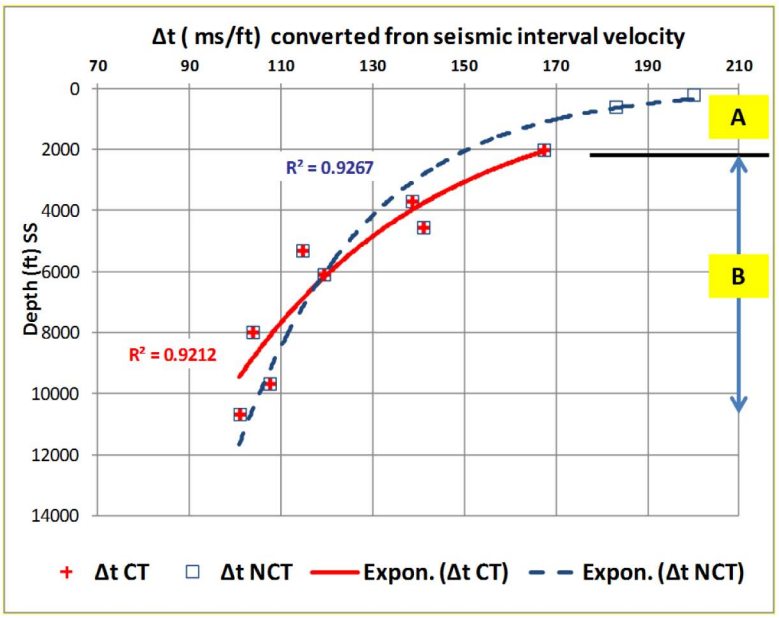

Figure 6—shows the disparity between creating a Compaction Trend (CT) from the actual dewatering B zone (red) and the Normal Compaction Trend NCT from zones A and B (dashed blue).

Zone C and D: The pore pressures in these two zones are calculated using the horizontal effective stress algorithm. In this article, Eaton's equation (1975) 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, since zone A is normally pressured zone (Shaker, 2015 a).

$$P/zc = S/zc - [S/zc - (P/zc)h] * (\Delta tct\ c / \Delta to\ c)\ x \quad (4)$$

$$P/zd = S/zd - [S/zd - (P/zd)h] * (\Delta tct\ d / \Delta to\ d)x \quad (5)$$

Where

P/zc = pressure gradient at depth c in zone C

S/zc = principal stress gradient at depth c in zone C

(P/zc)h = formation water hydrostatic gradient at c depth

Δtct c = acoustic impedance (Δt) of the compaction trend (CT) at c depth

Δto c = actual measured (observed) Δto at c depth.

x = exponent.

The same applies to zone D.

Figure 7 (left panel), shows the pressure – depth (P-D) plot generated by using this four zones method. The interval velocity (Vi) was conditioned, processed and extracted from a seismic gather at the well's proposed location. On the same figure (right panel) a correlation between using this method and using the old conventional method by extracting the NCT from A and B and or using the effective stress in the whole well-bore. Breaking and swaying NCT became a norm calibration practice among analysts for the purpose of matching and calibrating the calculated model to the actual pressure data.

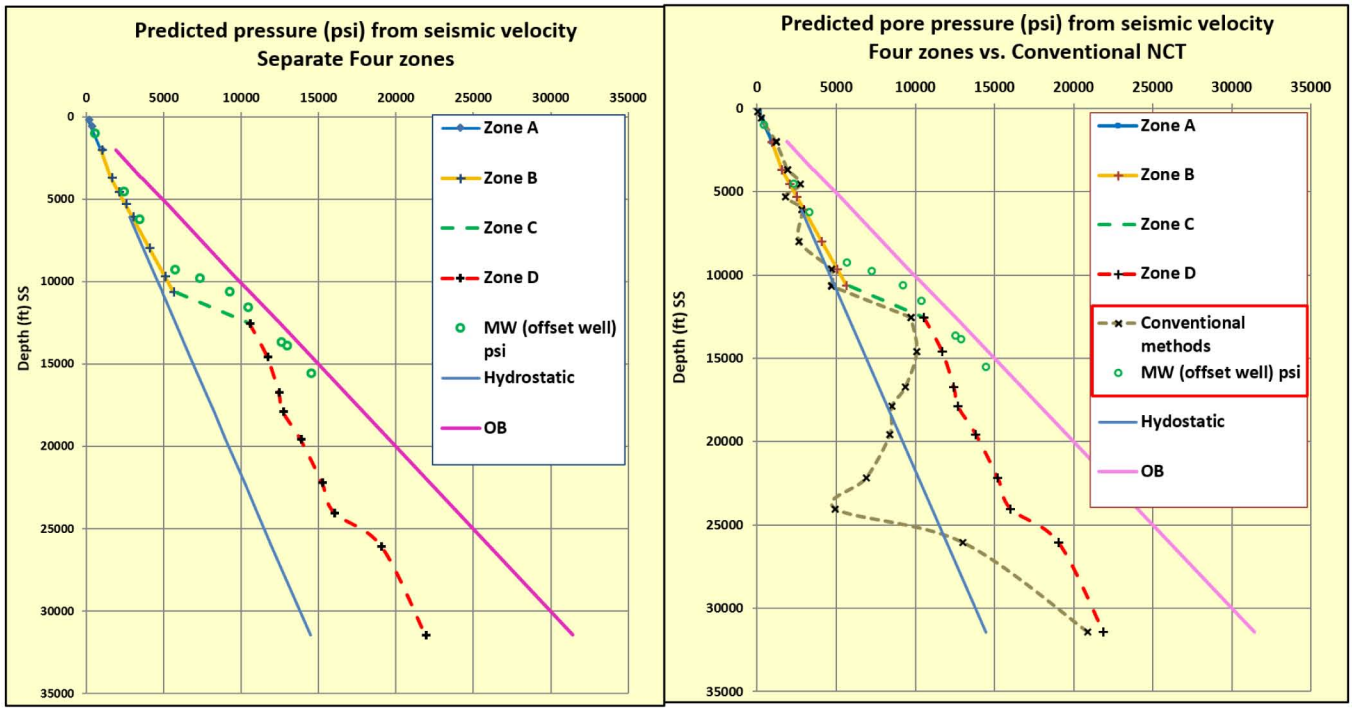

Figure 7—The left plot shows the benefits of predicting pore pressure from velocity utilizing the four zones method. On the right plot, a correlation between the prediction using the Four Zones vs. the conventional methods. Note the conventional prediction shows subnormal values above and below the pressure ramp C.

During Drilling

Formation Pressure calculation and calibration

Sonic velocity while drilling is a very valuable tool in establishing the relationship between the formation velocity slowness and the actual formation pressure in the bore-hole. The in-balance mud weight with equivalent static (ESD) and circulating mud densities (ECD) are fundamentals in calculating the pore pressure along the open hole trajectory. Mud cuts and shot-in pressure (SIP) are good pertaining drilling events in estimating the pressure differential between the formation and the mud column pressures at depth.

Some of the real time (RT) tools attached to the bottom hole assembly measure formation pressure in permeable reservoir beds. Drilling formation tester (DFT), reservoir descriptive tool (RDT), formation pressure while drilling (FPWD) are among the RT pressure gauges. They are measuring the sand pressure rather than the shale. Borehole instability (caving, cutting volume on shale shaker, pack off bore hole .etc.) is a good indication of shale pressure relative to the bore hole mud column pressure at depth.

The velocity – PP models and algorithms are designed for pp prediction and calculation in the shale. Applying the pre-drilling previously assigned equations (2,3,4 and, 5) during penetrating zones B, C and D for real time calculation is recommended. Utilizing the MWD sonic values (Δto) sheds light on the PPP divergence between the before drilling seismic prediction model and the RT calculated PP from LWD sonic log. Sonic measurement of the shale beds should be used for pressure calculations and calibrations in the geopressured zones (C and D) where effective stress is applicable. The velocity of the sand beds should be excluded from the calculation in the geopressured section (Figure 8). On the other hand, extracted and sampled Δt of sand and shale in zone B from LWD (LAS file) can be used for calculating the PP in this zone. This is because equations 2 and 3 were resolved to predicting Feasible Formation Pressure (FPP) during compaction of multiple lithologies of mainly shale and sand. Shot in pressure (SIP) is used as a gauging window for adjustment during drilling.

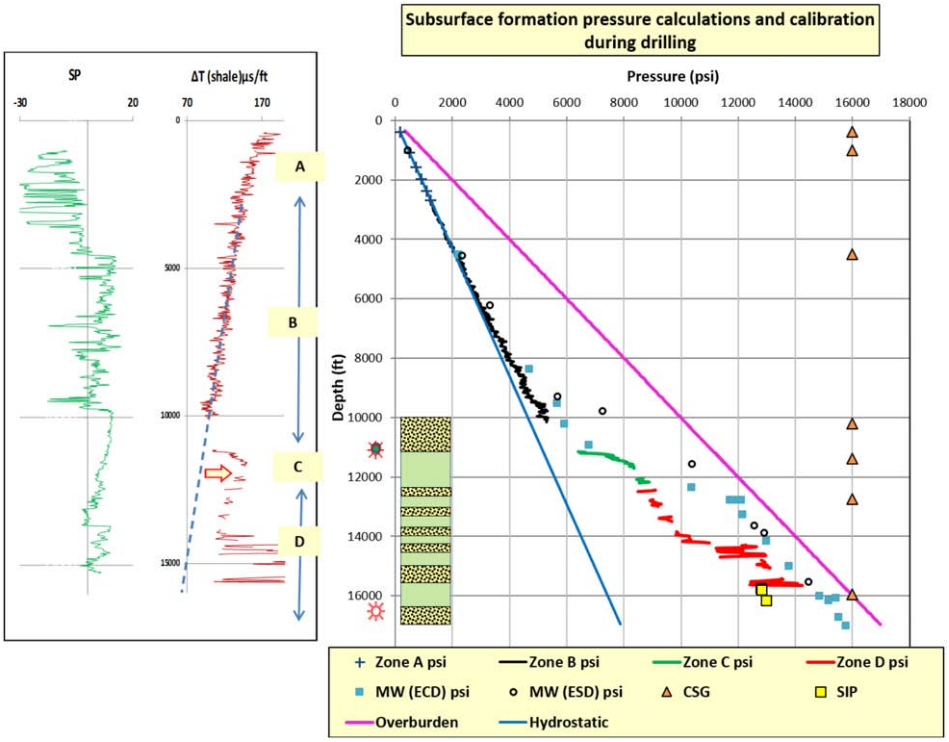

Figure 8—Formation pressure calculation during drilling using RT long space sonic log. Note that shale's Δt only was used in zones C and D. Whereas, Δt from the entire clastic B section was used for the calculation. HP-HT compartmentalized environment in C and D was responsible for setting four casing seats from 10,000'to TD.

The high pressure (HPHT) environment in geopressure deep old Oligocene sediments were exasperated by the multiple sediment's compartmentalization. This led to the need of four casing seats between 10,000 ft and TD to reach the objective reservoir (Figure 8). Several kicks and mud cuts took place in the D section. There is a noticeable disparity between the pressure in the sand vs. shale due to subsurface geological generated pressure transgression and regression (Shaker 2002).

Transforming the Δt in real time (RT) to pressure values in the shale beds using the before drilling effective stress set of equations is preferable. A slight modification of the algorithm's exponent may be needed to calibrate the PPP calculated from the RT petrophysical properties. This amendment is due to possible discrepancy of the sonic slowness (Δt) extracted from CMP seismic gather velocity and the actual measured Δt in bore-hole. The converted Δt from seismic represents an average thick interval where acoustic reflectors exist (Figure 3). On the other hand, Δt measured from LWD long space sonic represents slowness of short intervals in specific formation.

Some of the common pitfalls in real time calculation are as follow:

- Calculate pp in sand using ES equations.
- Overlay the RFT pressure reading on the erroneously created sand predicted values from RT's Δt (Figure 9).
- Incorporate the converted RFT's in psi values to PPG.MWE to the subsurface pressure profile. This gives the impression of a pressure negative slopes with increasing depth (Shaker 2003).
- Applying the Effective Stress model above the TOG. This leads to creating under-pressure values in the shallow zones (e.g. B and A). ES theorem is applicable in relatively thick shale beds and only in the overpressure zone below the TOG (Terzaghi's stage A)

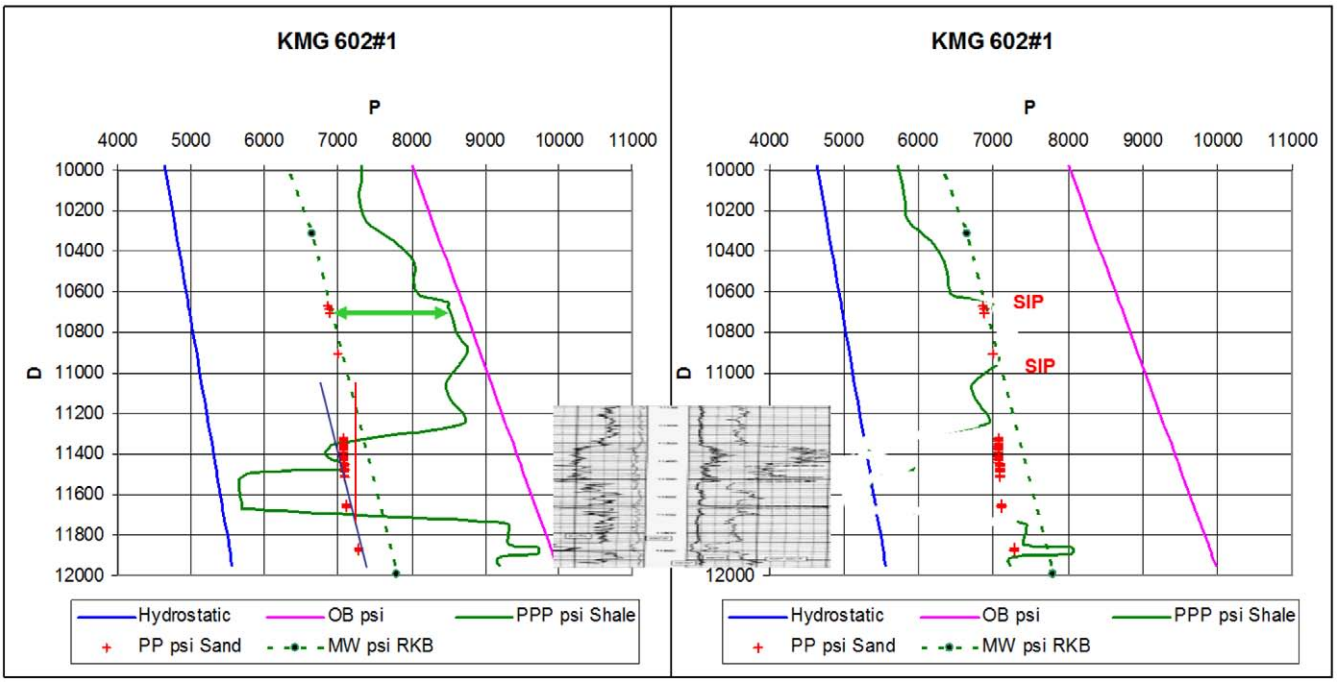

Figure 9—This figure shows one of the widely used incorrect calibration technique. It is lining up the measured por pressure (e.g.MDT) in the reservoir rock with the predicted pore pressure in sand from Δt or R (left). It is wrong, because prediction should be done in shale. Note the excessive difference between the MW psi RKB and the predicted pressure in the left panel. Calibration is more practical if using the drilling events (e.g.SIP).

Summary and Recommendations:

Establishing the subsurface formation pressure is essential for exploration risk and drilling challenges. Therefore, a comprehensive understanding of the development of pressure with depth based on the geological and fluid dynamics is crucial for success and safety. This article, in spite of the limited space, has shed light on several criteria:

- Pore pressure prediction (PPP) is before drilling from regional offset or seismic velocity. On the other hand, during and post drilling it is pore pressure calculation and calibrations and not prediction.
- The four zones partition complies with sediments deposition development with time and gravity load associated with formation water dynamics.
- Sediment goes from uncompacting (A), compacting and dehydration (B), sealing (C) and geopressured with entrapped fluids (D).
- Compaction trend should be calculated (not drawn) in zone B only.
- The effective stress theorem is only applicable below the TOG where fluid is captured under the rock load and the burden of the principal stress is shared between fluid and rock matrix.
- The assumption that the pressure in the sand is equal to the pressure in shale can be hazardous and leads to erroneous pressure estimate.
- Calibration of the during and post drilling pressure profile model can be assessed by the pressure pertaining drilling events (SIP, kicks, LOC …etc.) rather than measured pressure in reservoir sand (RFT's, MDT's …etc.).

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