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Loss of Circulation:

Causes and Consequences in Geopressured Systems

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Abstract

Drilling in the clastic over pressured sediments, mainly sand and shale, is subject to the compaction disequilibrium phenomenon. This phenomenon is the main catalyst for subsurface geopressure compartmentalization due to sediments stratifications and subsurface structural setting. As a result, geopressure transgression and regression take place in the open borehole section. Keeping the Mud Weight (Equivalent Circulating Density) in balance with the transgressive and regressive formation pressure is a challenge.

Strong pressure transgression can push the formation pressure envelopes to the fracture limit. Increasing the Mud Weight (MW) to overcome this excess pressure can cause loss of circulation (LOC). Pressure transgression can be detected ahead of the drill bit from seismic velocity, mud logs and LWD measurements.

Strong pressure regression can cause a substantial LOC in sand beds. As a result, it creates thick mud cake on the sand face which leads to drilling hurdles such as hole bridging, torque and drag. Contrary to transgression, regression is hard to predict during operation, therefore causing more drilling abandonment and side tracks.

Salt interface in several of the sub salt prospects is characterized by a sharp drop in pore pressure. Therefore, loss of circulation is common during penetration of the zone between the base of salt and the underlying sediments. Side tracks and drilling bypasses drastically increased the drilling costs of several wild cats in the frontier deep water subsalt plays.

Case histories of several Gulf of Mexico wildcats exhibited causes of LOC due to geopressure compartmentalization, especially in HPHT and sub salt environments:

- Use of overbalance MW exceeds the drilling tolerance window (FP-PP)
- Drilling the interface between salt and sediments in the sub salt prospects without advance watchfulness.
- Application of MW profile template of a well drilled on the crest of a structure to a down dip offset well.
- Drilling a wet zone using the same pressure profile of pay section.

Subsurface geopressure risk assessments, prior to drilling, can point to zones of instability along the proposed well trajectory in advance.

Introduction

Loss of Circulation occurs for several reasons. Some of these are related to the drilling process, such as bad shoe and incompetent cement job. Others are due to naturally fractured formations in hard rocks and limestone. Stratified clastic sediments (sand,mud,shale,silt) where the majority of oil and gas exploration takes place, are the subject of this paper.

Lost circulation from a hydraulic stand point, means the mud column equivalent circulation density (ECD) pressure exceeds the clastic sediment formation pressure. Permeable (sands and coarse silt) formations are good catalysts to vacate mud from the annulus, under these circumstances. In the case where the ECD exceeds the fracture pressure in the low permeable beds (shale and clay stone), LOC can take place. Therefore, the optimum mud weight (Fig. 1) to be used should stay in the drilling tolerance window (fracture pressure – pore pressure).

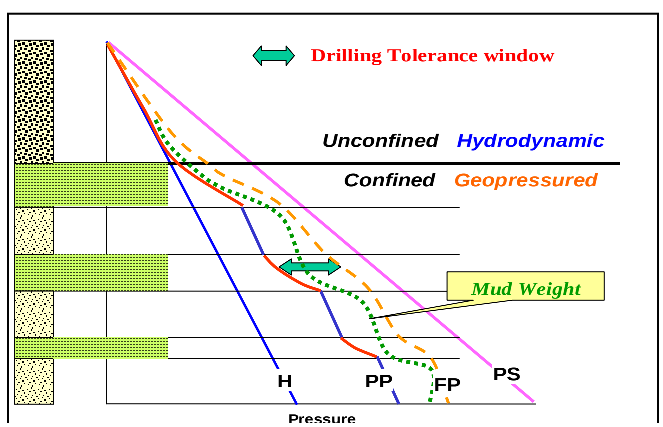

Figure 1: Pressure plot shows the drilling tolerance window

This paper sheds light on the geological settings that cause the substantial changes in pore pressure subsurface profile that leads to LOC and the costly consequences to the drilling operation.

Geopressure Transgression and Regression:
Deposit of additional sediments in a structurally relaxed (extensional) basin leads to an increase of the principal stress (Terzaghi, K. 1943) and consequently results in a higher transgressive pore pressure profile. This transgressive pressure (PT) profile is usually represented by a cascade path, as long as the basin subsidence accommodates the volume of sediment input with the absence of structural failure (Fig. 2).

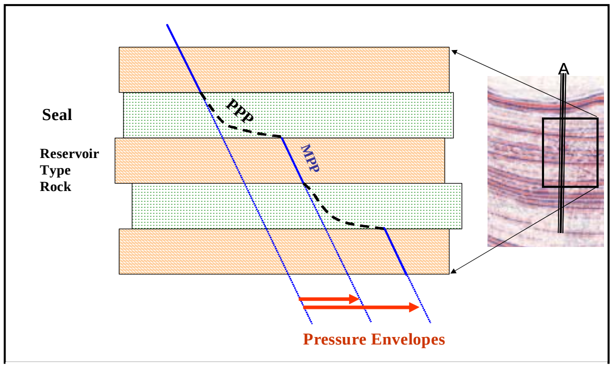

Figure 2: PP profile in a Transgressive system

Conversely, in the case of structural failure and/or when PP reaches the limit of the fracture pressure (FP), pressure regression (PR) takes place. The common regression phenomenon (Fig. 3) is usually a result of the presence of communication paths through faults and salt interfaces between the deep, highly pressured reservoir and the shallower, lesser pressured reservoir.

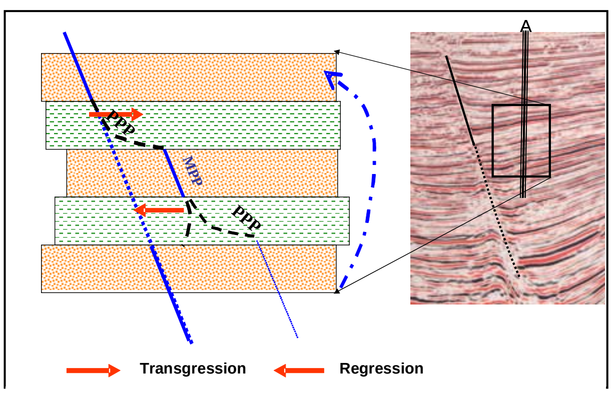

Figure 3: PP profile in a Regressive system

Fracture pressure (FP) represents the high perimeter where impermeable beds yield to hydraulic fracturing by reaching the matrix minimum stress. The difference between the FP and PP usually represents the "Drilling Tolerance Window." The drilling mud pressure ideally stays within the limit of this window. The tolerance window (FP-PP) varies in magnitude depending on the PP envelopes shift and the associated FP values. It tends to be narrow (less tolerant) in the normally pressured, shallow young deposits and the deeper, high pressure / temperature environment (Fig. 1). As a result, shallow water flow (SWF), hydraulic fracturing, loss of circulation, and flow-kill-breakdown cycles are dominant drilling problems in this narrow window. On the other hand, a wider window (more tolerant) prevails in a large portion of the geopressured (< 0.8 PG) section. This leads to relatively fewer drilling problems. Hydrocarbon accumulation favors this wider window zone.
The size and direction of the pressure envelope's shift across the interface, from the seal (shale) to the reservoir (sand), are responsible for shaping the PP and FP profile with depth. In case of a large trangressive shift, the bore hole can suffer a hard kick, especially if a hydrocarbon-bearing reservoir is encountered. Mud weight management at this interface is highly recommended. If substantial overbalanced mud weight is used to hold the well bore walls intact (stable) in the seals, a possible thick mud cake build up forms, facing the reservoir sandy beds below. A larger borehole forms facing the seals and, conversely, a tight, smaller borehole forms facing the reservoirs due to LOC.
The process of healing the LOC sometimes leads to the phenomenon of Flow – Kill- Break down. Bypass and side track is the ultimate solution to such a treatment. This increases drilling costs and might change the well bore trajectory and miss the initial objectives.

In case of pressure regression due to structural failure (mainly fault cuts) and hydraulic fracturing, PP in the reservoir drops to a lower PP envelope. A substantial LOC takes place if mud weight tracks the predicted pressure in the shale above the reservoir. This leads to thick mud cake and consequently to hole bridging, sticking pipes and excessive torque.
Most of the commercially discovered fields in the deep water of the Gulf of Mexico are characterized by large transgressive geopressure shifts (> 1000 psi). This shift takes place at the interface between the cap shale (seal) and the targeted reservoir compartment. Popeye (Green Canyon 72 # A-1), Fuji (Green Canyon 506 #1), Mickey (Mississippi Canyon 211#1), Ursa (Mississippi Canyon 809 # 1) and South Rampowell (Viosca Knoll 1001#1) fields show PT shifts usually exceeding 1000 psi.

West Cameron Block 96, Well #1:

This well (OCS-G-15055 #1) was completed as dry and abandoned (D&A) by Kerr McGee in April 1998. A substantial increase in MW from 10.8# (5897 psi) to 16# (9226 psi) was applied to cap the PP increase in the process of penetrating the transition zone (Fig. 4) between the normally and abnormally geopressured systems, subsequently, the pore pressure shows a transgression envelope at 11,200 feet and MW was increased to16.7# (11900 psi). Using both velocity and resistivity to predict PP, a geopressure regression at 12,500 feet was noticed. At that depth, pressure breach was most likely a result of the presence of a fault cut at this level. Due to the relatively overbalanced mud weight, and the proximity between the mud pressure and fracture pressures, especially deeper than 14,000 feet, several drilling obstacles occurred.

Borehole size was enlarged facing the shale beds and conversely, it was very tight in several sections facing the sand beds due to excessive LOC. This led to several borehole bridges with high torque on the drill pipes and high tension spots on the wire line tools. The well was P&A.

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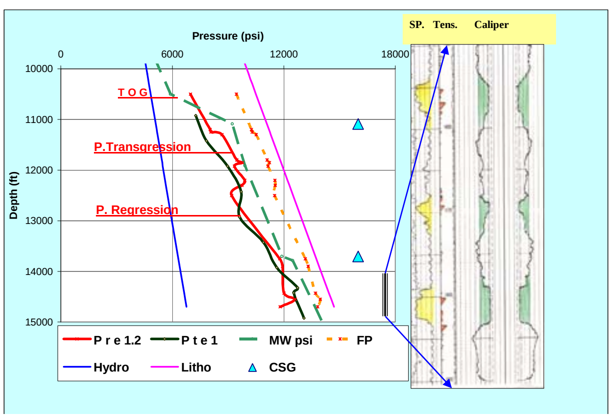

Figure 4: Drilling challenges in WC 96 #1

East Break 645 #1

This is a good example that exhibits the Flow - Kill - Breakdown phenomenon (Fig. 5) in the deep geopressured system rather than the shallow water flow case. The mud weight of 11.4 ppg was in balance with the top shale section where the background gas was minimal from 9700 to 10220 feet (mud log). The pore pressure prediction plots from the seismic velocity shows this relationship where the MW is ± 0.5 ppg over the predicted pore pressure in this section.

The nearest well with known pore pressure measurement in the same section is KMG 689#1 (±1 mile to the south). In this well, the shale above the reservoir was drilled with 11.8# mud. Penetrating the shale/sand interface the well flowed back and the mud was cut to 11.5#. Killing the flow, 12.0# MW was used and increased to 12.8 at the bottom of reservoir. Using the same MW template to drill EB 645#1 led to several trials to heal the hole and drill ahead. The Centroid effect (Shaker, S. 2004) was a factor in the Plugging and Abandonment of EB 645#1 due to the structural difference between the two prospects. Frequent circulation loss can be the result of geopressure compartmentalization and/or mechanical failure.

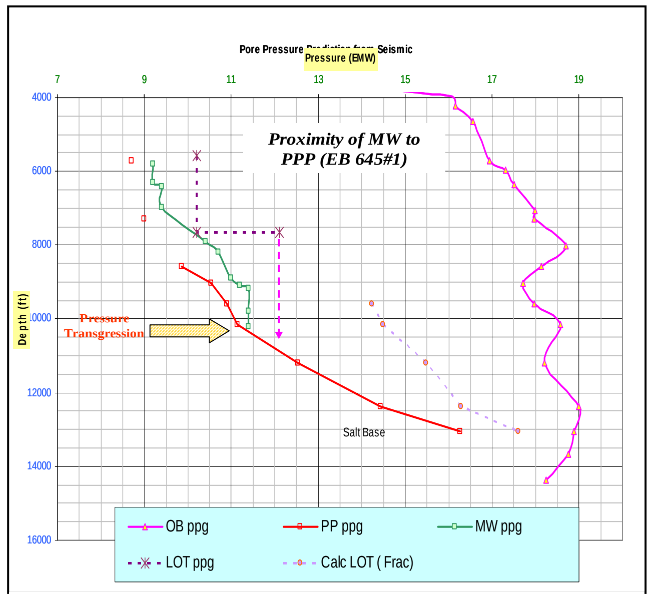

Figure 5: PP plot of EB 645#1 shows the cause of Flow-Kill-Breakdown phenomenon

Salt Toes and Fold Belts

The new deeper exploration fairway is associated with the creeping salt toe at the Sigsbee Escarpment (Chowdhuerry, A. and Lopaz-Mora, S. 2004). As a result, the lateral stress has generated compressional fold/fault structural plays in the Wilcox (equivalent sediment) below the salt. The fault plane in this structural setting usually yields high sealing capacity. Perdido, Walker Ridge and the Mississippi fold belts are the new, exciting and promising exploration plays needed to rejuvenate domestic energy needs. Based on the released data from these frontier wells, a geopressure model (Fig. 6) has been proposed and might explain some of the trapping mechanism and drilling challenges facing the industry (Shaker,S. and Smith, M. 2002).

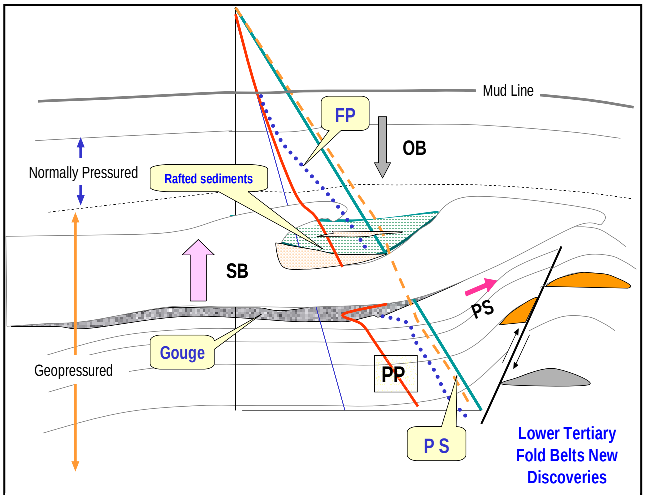

Figure 6: Geopressure model of the salt toe at the Sigsbee Escarpment

In addition to the salt buoyancy effect, on the sediment below and above the salt, rafted sediment blocks embedded in the salt mass and gouges (furrows filled with transported and crumbled sediments) at the base of the salt impact the subsurface geopressure profile. If these older rafted blocks are cased with impermeable layers, PP will show a high gradient. In the case of plowing the older sediment underneath the salt toe, the shear stress will substantially reduce the PP in this thin rubble layer underneath the moving salt (Fig.6). Sub salt gouges represent a drilling difficulty and hazard in frontier exploration plays. In addition, the salt buoyancy will accelerate and decelerate pore pressure above and below the salt respectively.

Atlantis Field

Atlantis field represents an exploration success of testing a prospect below the salt toe. This probably will not be the general case in the frontier lower Tertiary fairway where the targeted traps are located down-dip from the tip of the toe.

The geopressure plot of the discovery well #1 ST#2 in Green Canyon Block 699 (Fig.7) exhibits the relationship between the principal stress, overburden and fracture pressure. Note, the fracture pressure is in the proximity of the calculated overburden above the salt, whereas principal stress far exceeds the overburden and fracture pressure in the sub-salt. This leads to a wide window of retention capacity and the presence of a thick column of oil especially between 17800' and 18500'.

On the other hand, the reduction of PS in the sub-salt section led to a moderate PG of +/- 0.61 psi/ft at depth +/- 18400' (MDT measurements). This can be attributed to the thick salt layer above (+/- 7000') and the water depth of the mud line (-4495'). Mud weight was increased to 10.5 ppg and an extra casing point was set in the middle of the salt due to the presence of rafted sediments within the salt body. Moreover, the possible presence of the interface salt-sediment gouge, causing a sharp drop in the PP, was responsible for sidetracking the original hole and multiple drilled bypasses.

The presence of several wet sandy rich sections below the pay zone, which started at 18500' to TD (19500' TVD) and concurred with an increase of MW to 12.4 ppg (overbalanced), led to thick mud cake, stuck pipes, plug back and side track. BP is planning to put Atlantis field on line the next year. The projected daily production is estimated to be 250 Mbblod and 180 MMcfgd.

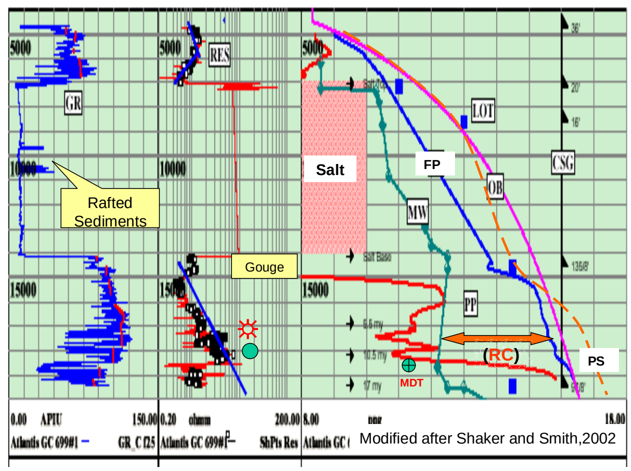

Figure 7: PP plot of GC 699#1 shows the large drop in PP below the salt

Jack Prospect

The Jack prospect is a part of the emerging Wilcox-equivalent salt toe belt at the Sigsbee Escarpment in the Deep Water of the Gulf of Mexico. It is located in the Walker Ridge (WR) Blocks 758, 759, and 678. Applying the same geopressured model designed for the salt toe (fig.6) can explain the drilling hurdles of WR 759 #1 ST 00BP00 (OCS-G-17016), which jacked up the drilling cost to over one hundred million dollars. These challenges were:

- Lost return at the base of the salt (at depth 19653').
- Pump LCM sweep of 13.5#
- inability to stop losses
- Side track had to be performed
- Set Casing at 13507' at the salt mass, possibly due to presence of rafted block sediment

Conclusions

Geopressure compartmentalization is a double edged sword. It is the main catalyst for hydrocarbon entrapments, and yet it causes PP shift which creates drilling problems. Most of the troubles spots commence at the interface zones between the seals and reservoir type rocks. Pressure transgression and regression take place at the interface zone due to the geological setting and state of stresses in the basin.

In the transgressive zone, a larger hole can be developed in the seal and a smaller one facing the reservoir due to LOC. The overbalanced mud results in loss of mud and a relatively thick mud cake. This leads to sticking pipes, borehole bridging, high torque and erroneous logging measurements.

Drilling the regressive zones, with overbalanced mud, usually leads to LOC and creates a bore hole bridging (tight), sticking pipes and excessive torques facing reservoirs.

Pre-drilling pore - fracture pressure prediction is essential to dependable wildcat drilling prognoses. During drilling, it is important to administer the MW program, especially the ECD, to keep the bore-hole stable in the shale zones and free of bridges facing the sand zones.

Sub-salt prospects represent a serious challenge especially in the Deep Water frontier areas around the World. The salt-sediment interface zone needs to be modeled and thoroughly probed before the drill bit strikes it.

On site drilling surprises can be minimized in advance by forecasting depth to top of geopressure (TOG), pressure gradient changes in shale beds with depth, pressure envelopes shift (transgression-regression) in sand beds, fracture matrix coefficient, and expected hydrocarbon density and height. Therefore, pore pressure prediction using pre-stacked velocities, in addition to geopressure basin modeling from the offset wells are vital for pre-spud well planning. It is essential to use all the geological building blocks to estimate the pressure differential between the seals and reservoirs expressed in PSI and PPG MWE.

Nomenclature

H =Hydrostatic pressure
PP=Pore pressure
FP=Fracture pressure
PS=Principal stress
OB=Overburden
SB=Salt buoyancy
RC=Retention capacity
PPP=Predicted pore pressure
MPP=Measured pore pressure
PPG MWE=Pound per gallon mud weight equivalent

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