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New Method for Overburden Modeling to Improve Geopressures Calculations

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Abstract

This paper showing that using rock-density measurement from well-logs affect the calculation of overburden stress because "environmental effects" caused by borehole conditions, overpressures, gas content, high mud filtrates, formation fluid saturation and rock mineralogy. Those effects influence the rock-density measurements and consequently both the overburden stress and geopressures computations; furthermore, the lack of rock-density well-logs in the first drilling stages also affect the overburden stress determinations. However, we consider that the most important bias-effect in the overburden stress calculation is that the overburden must be determined exclusively using the rock-density due to normal compaction of sediments. Hence, we are proposing a new method and model to compute the overburden stress that utilize a power law approach to reproduce rock density values instead to use log-density measurements. The new method is based on the theory of consolidation of clays described by Terzagui and Peck in 1948 which considers that rock-porosity reduction because of compaction when sediments burial increases. This rock-porosity reduction or rock-density increment can be modeled by a power law approach and use its results to calculate overburden instead rock-density measurements from well-logs. Here, we describe how establish the normal compaction trend for rock-density and its integration into overburden equation. This modified overburden model is showed and some examples are presented to permit readers to use the method with their own data. The examples compare the overburden stress calculated with new method against those using rock-density measurements from well-logs. The results show better overburden estimations using the power law model and how the use of rock-density readings from well-logs impact in the geopressures results because mislead of the overburden stress. The results allow to conclude that the overburden stress must be calculated using rock-density due to normal compaction of sediments and avoid the use of density-log readings that are influenced by "borehole environmental effects".

Introduction

Knowledge of the overburden gradient is of prime importance when evaluating geopressures and stresses because this miscalculation unchain a domino effect into the geomechanical model. We are arguing that the uses of wireline log density data to determine overburden stress lead to errors since the density-log readings may be affected by overpressures, hole rugosity, gas content, borehole washouts and high mud filtrates among others phenomena that we have called "borehole environmental effects".

Additionally, Bell (1996) and Zoback (2007) among others, argue how the lack of density log data in the first drilling stages also affects the overburden stress results and propose the use of extrapolations methods to calculate the rock-density to the surface or seafloor.

As an example, McNeal et al. (2017) developed a study in Alaska where well density-logs readings were used directly without taking into account the "borehole environmental effects" that we are describing. Our asseveration is based on the behavior of overburden gradient of two Mexican wells that we calculate using wireline density-logs (figure 1) against McNeal's results (figure 2).

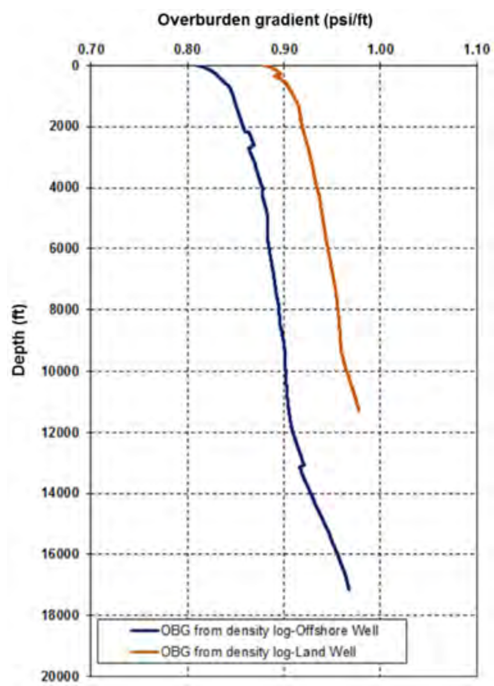

Figure 1—Overburden gradient influenced by the "borehole environmental effects " of density log readings in two Mexican wells

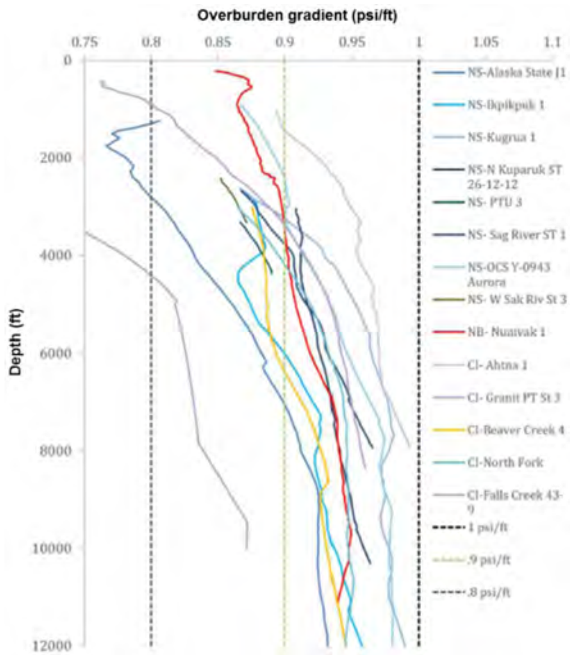

Figure 2—Overburden gradient of several Alaska wells (after McNeal et al., 2017)

Although "borehole environmental effects" have a hard impact in the overburden stress computation as we showed in last figures, we consider that the most important bias-effect in the overburden results is that the overburden stress must be determined exclusively using the rock-density due to normal compaction of sediments. Figure 3 shows the bulk density graph built by Eaton (1969) from several normally compacted wells in the Gulf Coast, USA and figure 4 presents his overburden stress results in the same area. If we compare the overburden gradients of figures 1 and 2 against figure 4 we can notice the influence of the use of raw wireline-density-log data compared to those taken from normal compacted rocks.

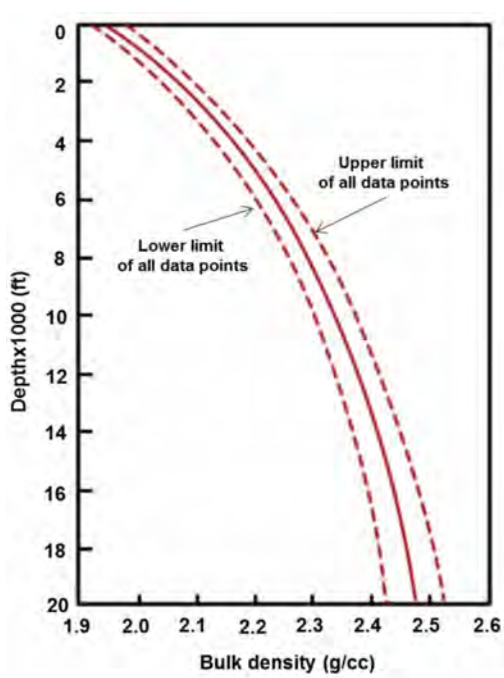

Figure 3—Bulk density from normally compacted formations in the Gulf Coast (After Eaton, 1969).

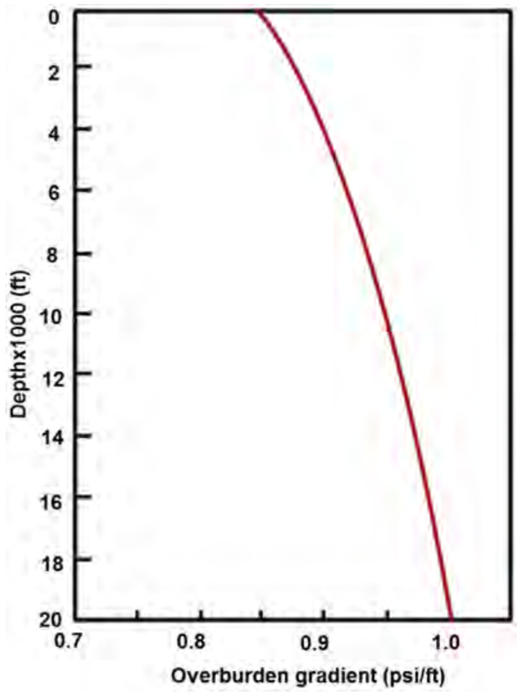

Figure 4—Overburden gradient calculated from normally compacted formations in the Gulf Coast (After Eaton, 1969).

Another notion that we are discussing is the impact of adding water column pressure to the overburden stress calculation in offshore wells. The idea behind this, it's a belief that water column creates a "pre-stress" that needs to be considered but we will show to do that affect fallaciously the magnitude of overburden stress

Overburden Model

Overburden stress at a given depth is the stress exerted by the weight of the overlying sediments; therefore, it may be determined by means of bulk density of rocks by the following equation (Fertl, 1976; Mouchet and Mitchell, 1989; Bourgoyne, 1991; Bell, 1996; Zoback, 2007; McNeal et al., 2017):

$$S = \int_0^Z \rho_r g dZ \tag{1}$$

Solving Eq. (1) we have Eq. (2):

$$S = \sum_{i=1}^{n} \rho_{ri} g [Z_i - Z_{i-1}] \tag{2}$$

Where:
S_v = Overburden stress
ρ_{ri} = Bulk density of rock at depth i
g = Acceleration of gravity
Z_i = Depth i
Z_{i-1} = Depth before depth i

The bulk densities of rock (ρ_r) that we must use in Eq. (2) are those ones due to normal mechanical compaction of sediments with depth and we need to avoid using raw wireline-density-log data because of the "borehole environmental effects" that we have described. Figure 5 present an overburden gradient of an offshore Mexican well calculated with Eq. (2) and using raw density-log data. We are comparing the results against Eaton (1969) Gulf Coast model and the shaded area represents the differences between overburden gradients with normal compacted rock-density data (Eaton paper) contrary to rock-density data with "borehole environmental effects". In figure 6, we can observe that mud weight profile exceed the fracture gradient (red shaded). This mistake occurs due to bias in overburden stress originate for "borehole environmental effects" in rock-density-log data.

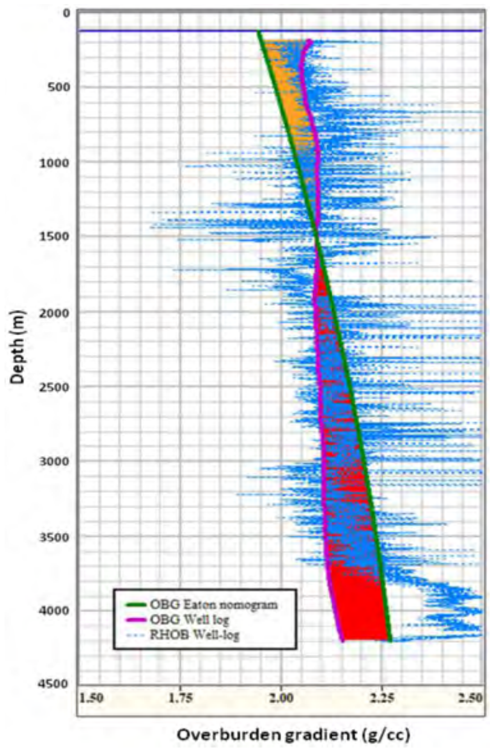

Figure 5—Overburden gradient calculated with eq. 2 and using raw wireline-density-log data.

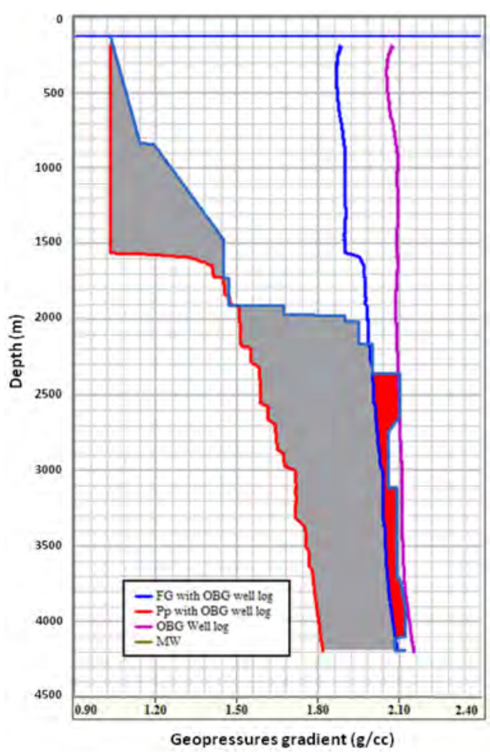

Figure 6—Geopressures estimated with overburden gradients computed in figure 5.

Overburden Model for Offshore Wells

In offshore areas, the Eq. (1) need to be corrected to consider water column (Bourgoyne, 1991; Zoback, 2007):

$$S_v = \int_0^{z_w} \rho_w g dZ + \int_{Z_w}^{Z} \rho_r g dZ \tag{3}$$

Solving eq. 3 we have eq. 4:

$$S_v = \rho_w g Z_w + \sum_{i=1}^{n} \rho_{ri} g [Z_i - Z_{i-1}] \tag{4}$$

Where:

ρ_w = Water density

Z_w = Water depth

Figure 7 presents a rock-density-log affected by overpressures, the overburden stress behavior using Eaton (1969) model for Gulf Coast, and overburden stress of Mexican offshore well calculated with Eq. (4). We can see how the "borehole environmental effect" influence the calculation of overburden stress, however, the addition of water column pressure creates a severe bias effect in the magnitude of overburden gradient (red shaded of figure 7). Also, we calculated the geopressures using overburden gradient affected by water column and density data with "borehole environmental effect", figure 8 shows the same bias effect as in figure 6 but increased by water column. We can observe that mud weight profile exceeds the fracture gradient (orange shaded) and overburden gradient (red shaded).

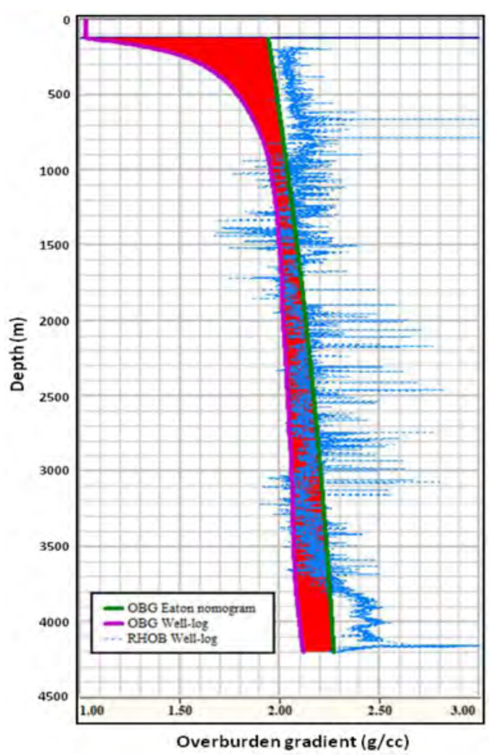

Figure 7—Overburden gradient calculated with Eq. 4, using raw wireline-density-log data and considering water column.

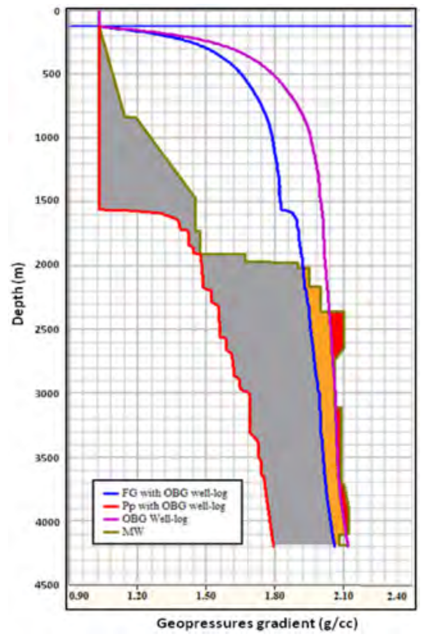

Figure 8—Geopressures estimated with overburden gradient of figure 7.

New Method

To avoid the "borehole environmental effects" in wireline density log readings, a modification to rock density in Eq. (1) is proposed. We are changing the measures of rock density with well-logs by a power law equation that describes the behavior of rock density compacted normally with depth as follows:

$$\rho_r = \rho_o + kZ_i^c \quad (5)$$

Using the new model is necessary extrapolating the density-log data at surface as show in figure 9. In our Mexican offshore well as example, we observed a typical value equal to 1.95 g/cc for density at mud line. Figure 10 contrast rock-density calculated with new method against wireline density-log data, we notice an important bias due to "borehole environmental effects" beginning at 900 m.

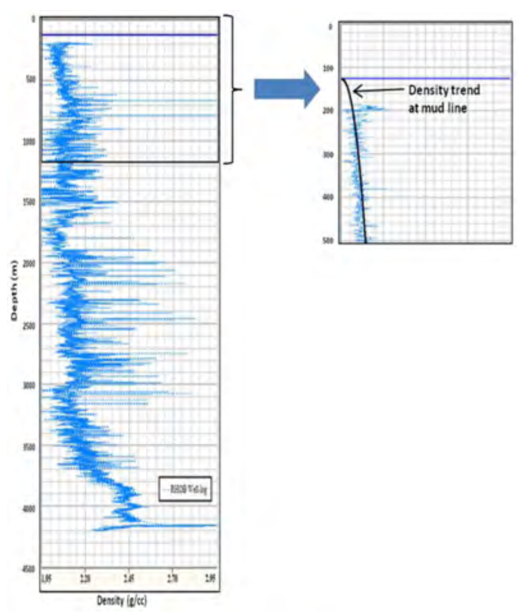

Figure 9—Density extrapolation at mud line.

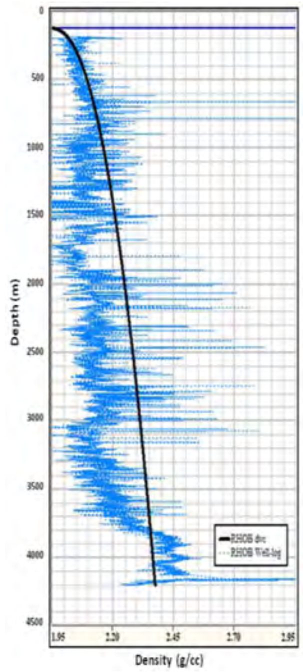

Figure 10—Density calculated with Eq. 5

Substituting Eq. (5) into Eq. (1), we obtained an overburden stress model which can be expressed with following expression:

$$S_v = \int_0^Z 0.145 \cdot \left(\rho_o + kZ_i^c\right) \cdot g \cdot dZ \quad (6)$$

Now, if we integrate the Eq. (6) to obtain a new model that we can use to compute the overburden stress as follows.

$$S_v = 0.145 \cdot \left(\rho_o \cdot g \cdot Z_i + \frac{k \cdot g}{c+1} \cdot Z_i^{c+1}\right) \quad (7)$$

Where:
S_v = Overburden stress, (psi)
ρ_0 = Bulk density at surface or mudline, (g/cc)
c = Normal compaction behavior index (varies from 0.3 to 0.6)
k = Declination parameter (0.01)
g = Acceleration of gravity (9.81 m/s^2)
Z_i = Depth i below surface or mud line, (m)

The Eq. (7) considers that rock bulk density vary normally with compaction of the sediments as depth increases. This correction avoids the "borehole environmental effects" of density log readings as observed in figures 11 and 12. Also, the overburden calculation

Figure 11—Overburden gradient calculated with Eaton (1969) model and Eq. 7.

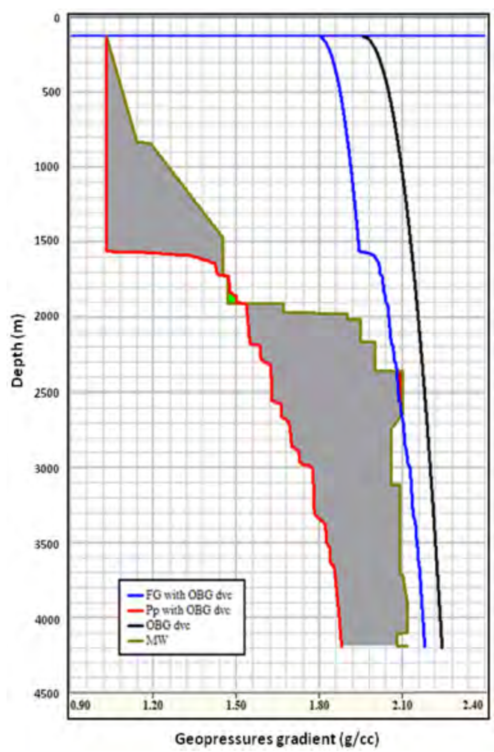

Figure 12—Geopressures estimated with overburden gradient computed with Eq. 7

Other Overburden Models

Table 1 list several overburden models developed for specific regions worldwide. Most of them are function of depth below mud line and take into account the water column.

Table 1—Overburden gradient models published for different authors

Author	Overburden Model	Region
Eaton (1969)	$OBG = 1.9447 + 1.17\cdot10^{-4}\cdot D - 9\cdot10^{-9}\cdot D^2$	Texas Gulf Coast
Bell (1969)	$OBG = OBG_0 + 2.64\cdot10^{-5}\cdot D - 1.97\cdot10^{-9}\cdot D^2 + 6.60\cdot10^{-14}\cdot D^3 - 5.97\cdot10^{-19}\cdot D^4$	Texas Gulf Coast
Gardner (1974)	$OBG = \frac{\rho_w\cdot WD + \left(0.23\cdot\left(\frac{304878.05}{\Delta t}\right)^{0.25}\cdot 0.43353\right)\cdot D}{TVD}$	
Bellotti and Giacca (1978)	$OBG = \frac{\rho_w\cdot WD + \left(\left(2.75 - 2.11\cdot\frac{\Delta t - 53}{\Delta t + 200}\right)\cdot 0.43353\right)\cdot D}{TVD}$	Gulf Coast and Santa Barbara Channel
Aadnoy and Larsen (1987)	$OBG = \left(19.48 - 1.17910^{-3}\cdot\frac{D}{3.2808} + 8.56\cdot10^{-7}\cdot\left(\frac{D}{3.2808}\right)^2 - 10.06\cdot10^{-11}\cdot\left(\frac{D}{3.2808}\right)^3\right)\cdot(0.442)$	Statfjord Field
Simmons and Rau (1988)	$OBG = EXP\left[\frac{(\ln(Deff) - 6.206593)^2}{84.36084}\right]\cdot 0.8511934$	Gulf of Mexico
Zamora (1989)	$OBG = (8.5\cdot WD + (C_3 + C_4\cdot A)\cdot D_x{}^{+1})\cdot 0.052$	
Traugott (1997)	$OBG = \left(\frac{8.5\cdot WD + \left(16.3 + \left(\frac{D}{3125}\right)^{0.6}\right)\cdot D}{TVD}\right)\cdot 0.052$	Gulf of Mexico
Barker and Wood (1998)	$OBG = \left(\frac{(8.55\cdot WD + 5.3\cdot D^{1.1356})}{TVD}\right)\cdot 0.052$	Gulf of Mexico

Figure 13 contrast the results of overburden models listed in Table 1 against our model proposed in Eq. (7). In all models, we have used the same data of a Mexican offshore well.

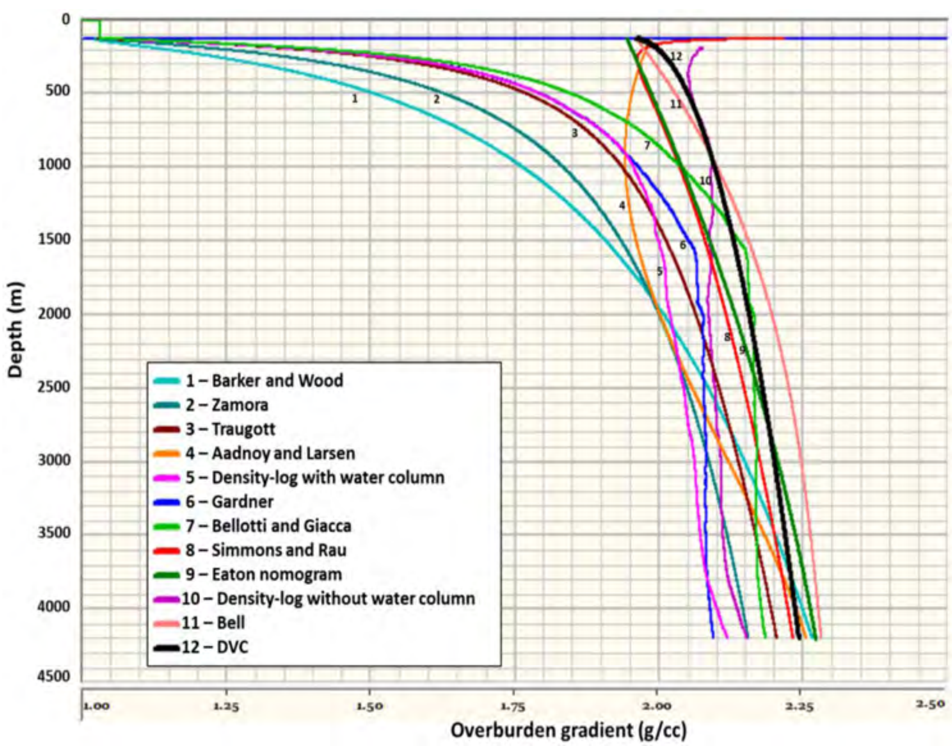

Figure 13—Contrast of our model (OBG dvc) with respect to the models listed in table 1.

The polynomial models and exponential models as a function of depth below surface or mudline reproduce overburden gradient properly (Eaton, 1969; Bell, 1969; Simmons and Rau, 1988). However in the other ones models, we can see the "borehole environmental effects" caused by the use of raw-density-log-readings as well as the bias effect when we include the water depth. Also, the exception too is curve 12 which was calculated with the new model that we have proposed.

Conclusions

- Using raw wireline-density-log produce a bias effect in the magnitude of overburden gradient because of borehole environmental effects discussed here.
- Adding water column in overburden equations creates a severe bias effect in the magnitude of overburden gradient.
- We need to use the rock bulk density due exclusively to normal compaction of sediments to avoid the borehole environmental effects in overburden magnitudes.
- We are proposing a new model base on power law equation that describes the normal compaction trend of rock-density.

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Nomenclature

A = Zamora model parameter dependent on the geologic age of the rock
c = Normal compaction behavior index
C_3 = Zamora model Constant (8.03)
C_4 = Zamora model Constant (0.232)
D = Depth below mud-line, ft.
$Deff$ = Effective sediment penetration depth, ft
FG = Fracture gradient, g/cc
k = Declination parameter
MW = Mud Weight, g/cc
OBG = Overburden gradient, psi/ft
OBG_0 = Overburden gradient at the mudline in Bell model (Original study 0.850), psi/ft.
P_p = Pore pressure, g/cc
$RHOB$ = Bulk density, g/cc
S_v = Overburden stress, psi
TVD = True vertical depth, ft.
WD = Water Depth, ft
Z = Depth, m.
dZ = Delta depth, m.
Δt = Transit time, us/ft.
ρ_0 = Bulk density at surface or mudline, g/cc.
ρ_w = Water density, g/cc.

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