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Pore pressure gradient prediction- A case study of the jubilee field

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Abstract
The estimation of pore pressure gradient is a necessary requirement to safely, economically and efficiently drill an oil and gas well. As such this project sought to predict the pore pressure gradient of the Jubilee field using Eaton's correlation and Hubbert and Willis' correlation and then further comparing with the actual pore pressure gradient from the field. This was done to know which of the methods predicts best. The Jubilee Field is the most prolific oil and gas field in Ghana among others. Four different Wells from the Jubilee were analyzed and the results obtained were used to make necessary conclusions. The results obtained showed a deviation of -50% from the normal field data (0.481) when Eaton's correlation was used. This showed that the Eaton's correlation underestimated the pore pressure gradient. Similarly, the results obtained from Hubbert's and Willis Correlation showed approximately +24% increase in the normal field pore pressure gradient. The pore pressure from the field gave a strong correlation with an error of prediction less than 2%. The Hubbert and Willis' method predicted better than the Eaton's method for this project. The mathematical correlation model for the field analysis can therefore be used to calculate the pore pressure gradients for other Wells with an error of prediction less than 2%.

Keywords: pore pressure gradient, economically and efficiently

Introduction

Over the years, petroleum has become one of the most common sources of energy in the world and this has resulted in various exploration and drilling activities in the quest for oil and gas (Amorin *et al*., 2022b) [3]. The drilling of oil and gas wells is not without a problem because of the abnormal formations encountered during drilling and cementing operations (Bruce and Bowers, 2002; Woodland *et al*., 2022) [7, 13]. Two key formation pressures that are constantly monitored are pore and fracture pressure (Amorin *et al*., 2022a) [2]. Bradley (1975) [6] defined the pore pressure gradient of a given formation as the various alterations in pore pressure as a function of depth and further estimated the pore pressure gradient of fresh water to be 0.433 psi/ft and 0.465 psi/ft for water that contains some reasonable amounts of dissolved solids.

Many correlations have been proposed to help predict the pore pressure gradients of a formation before, during and after drilling. The main reasons for the prediction of pore pressures of formations during drilling operations are to prevent downhole problems; to limit the problem associated with non-productive time; and to serve as a guide in designing drilling mud and also efficient selection of casing points (Atashbari and Tinjay, 2012) [4]. The most common correlation used today in petroleum industry is the Eaton's correlation. For the past decades, many incidents have occurred during various phases of drilling in West Africa as a result of the wrong estimation of formation pressures encountered leading to much loss of investment and non-productive times. The Niger Delta and Cameroon for instance has witnessed many kicks as a result of poor pore pressure prediction (Steve, 2015).

The estimated normal pore pressure gradient for West Africa is 0.442 psi/ft., based on the degree of compaction and type of formation (Berg, 2012) [5]. This value however can deviate from field to field, due to heterogeneity. With the aforementioned crisis associated with formation pressures, careful planning and initiation policies should be taken in predicting the pressures downhole during drilling. A pre-drill estimation of the pore pressure gradient is the standard practice for major oil companies in the world. Each of the various aspects of well planning during drilling is capital intensive and hence benefit from having good pre-drill pore pressure estimation (Mukherjee *et al*., 2009) [9]. Pore pressure gradients are more practically used in drilling engineering because the gradients are more convenient to be used to determine mud weights.

The Jubilee field is the most prolific and economical field in Ghana among others by virtue of the size of petroleum accumulation and production. The understanding of the overpressures in the subsurface of the field is very important for safe drilling operations. The Jubilee field is located in West Africa but the estimated pore pressure for the zone may not be very reliable for efficient mud programme planning therefore the need to determine the type of pore pressure gradient that exists in the formation. The field is a unitised deepwater oil development located 60 km offshore Ghana. The field was discovered by Kosmos in June 2007 with the first production achieved in the November 2010 (Sills and Agyapong, 2012) [11]. The water depth is 3,609 ft. The reservoir rock type is mainly sandstones and consists of a well consolidated formation. The primary sandstone reservoirs comprise late-Cretaceous Turonian stacked deepwater turbidite channels and fan sequence deposited in a lower-upper slope setting. An initial reservoir pressure of 5 295 psia was measured at 3,463 m TVD in the Mahogany-1 discovery well and varies from 5,000 to 5,700 psia as a function of TVD. The initial reservoir temperature varies across the field from 196 ºF to 225 ºF as function of True Vertical Depth (TVD), overburden thickness and water depth (Sills and Agyapong, 2012) [11]. This project predicts pore pressure gradient for the field using Eaton and Hubbert and Willis correlations and compares with the field's linear regression model for analysis.

Method

Secondary data for four different wells in the Jubilee field were used to predict pore pressure gradient using Eaton and Hubbert and Willis Correlations. This data consisted of drilling parameters such as pore pressures, fracture pressures at various depths at which these parameters were obtained.

Overburden stress gradient determination

Eaton proposed that the overburden stress gradient is a function of burial depths in areas of compaction and abnormal pressures. For cretaceous formations such as that of the Jubilee field, the overburden pressure gradients can be calculated by using the Eaton’s variable overburden stress gradient graph, hence overburden pressure gradients were determined using Figure 1(left).

The various depths of each of the four wells were traced on the graph to estimate the corresponding overburden stress gradient. This was used in the calculation of the pore pressure gradients using Equation 1.

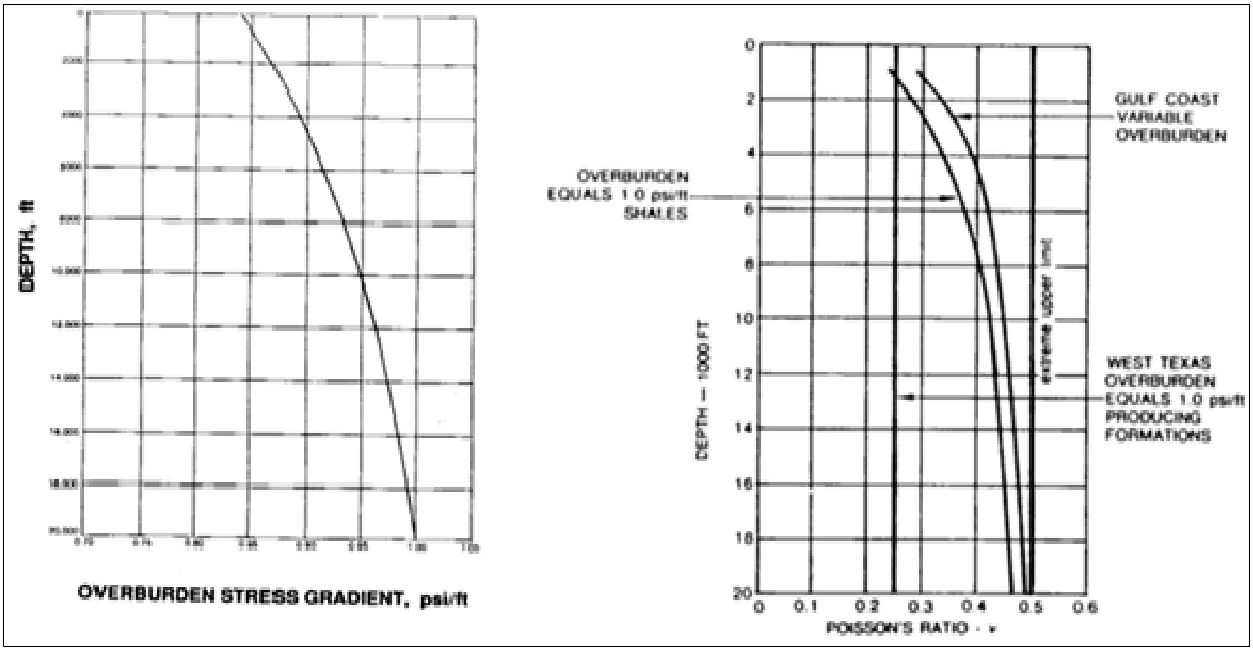

Fig 1: (Left) Eaton Overburden Stress Graph (Eaton, 1975) (Right) Poisson’s Ratio Graph at Various Depths of Interest

Determination of Poisson’s Ratio

The Poisson’s ratio was also determined for each of the four wells using the Poisson ratio graph in the Figure 1(right). For accuracy, an interpolation was performed using the boundary of the depth whose Poisson ratio was determined.

Pore pressure gradient prediction using eaton’s correlation

The pore pressure gradient at various depths were predicted using Eaton’s correlation. The overburden stress gradients at various depths were first determined using Eaton’s variable overburden stress graph. Equation 1 was used for predicting the pore pressure gradient for the Jubilee field.

$$\frac{P_p}{D} = \frac{\left(\frac{P_f}{D}\right) - \frac{v}{1-v}\left(\frac{\sigma_{ob}}{D}\right)}{\left(\frac{-v}{1-v}\right)+1} \quad (1)$$

Where

$\frac{P_f}{D}$ = fracture pressure gradient, psi/ft

v = Poisson’s ratio

$\frac{\sigma_{ob}}{D}$ = overburden stress gradient, psi/ft

$\frac{P_p}{D}$ = pore pressure gradient, psi/ft

Pore pressure gradient prediction using hubbert and willis correlation

Hubbert and Willis (1957) suggested a correlation for determining the fracture gradient based on the overburden pressure gradient and pore pressure gradient. This method was used in this research work to predict the pore pressure gradient by re-arranging the correlation and making pore pressure gradient the subject. Equation 2 was used to calculate the pore pressure gradient at various depths in the four different wells.

$$\frac{P_p}{D} = \frac{\left(3 * \frac{P_f}{D}\right) - \left(\frac{\sigma_{ob}}{D}\right)}{2} \quad (2)$$

Where

$\frac{P_f}{D}$ = fracture pressure gradient, psi/ft

$\frac{\sigma_{ob}}{D}$ = overburden stress gradient, psi/ft

$\frac{P_p}{D}$ = pore pressure gradient, psi/ft

Fracture pressure gradient determination

- The following steps were considered in determining the fracture pressure gradient.
- The hydrostatic pressure was determined using Equation 3. The results obtained at various depths were then added to the Leak-off test pressures to determine the fracture pressure.

$$P_h = 0.052 \times MW \times D \quad (3)$$

- A graph of fracture pressure versus depth was plotted and the line-of-best-fit was inserted. The equation of the line was determined and used to estimate the fracture pressures at various depths concerned with this work for the four wells.
- Eaton and Hubbert and Willis correlations were then used to determine the pore pressures of the formation.

Figure 2: shows the fracture pressures against various depths that was used in determining the fracture pressure gradient for this work.

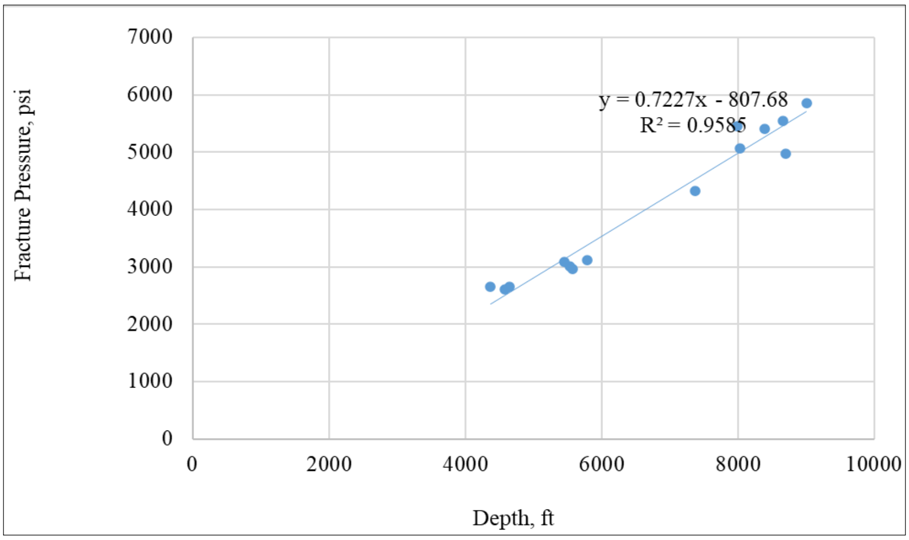

Fig 2: Fracture Pressure Versus Depth

Equation 4 was obtained after plotting fracture pressure against depth and this was used to estimate the fracture pressure at the various depths in the four different wells with an accuracy of about 96% ($R^2 = 0.9585$).

$$y = 0.7227x - 807.68 \quad (4)$$

Results

Figures 3 and 4 show the pore pressure results using the Eaton's and Hubbert's and Willis Correlations and field data for the four different Wells.

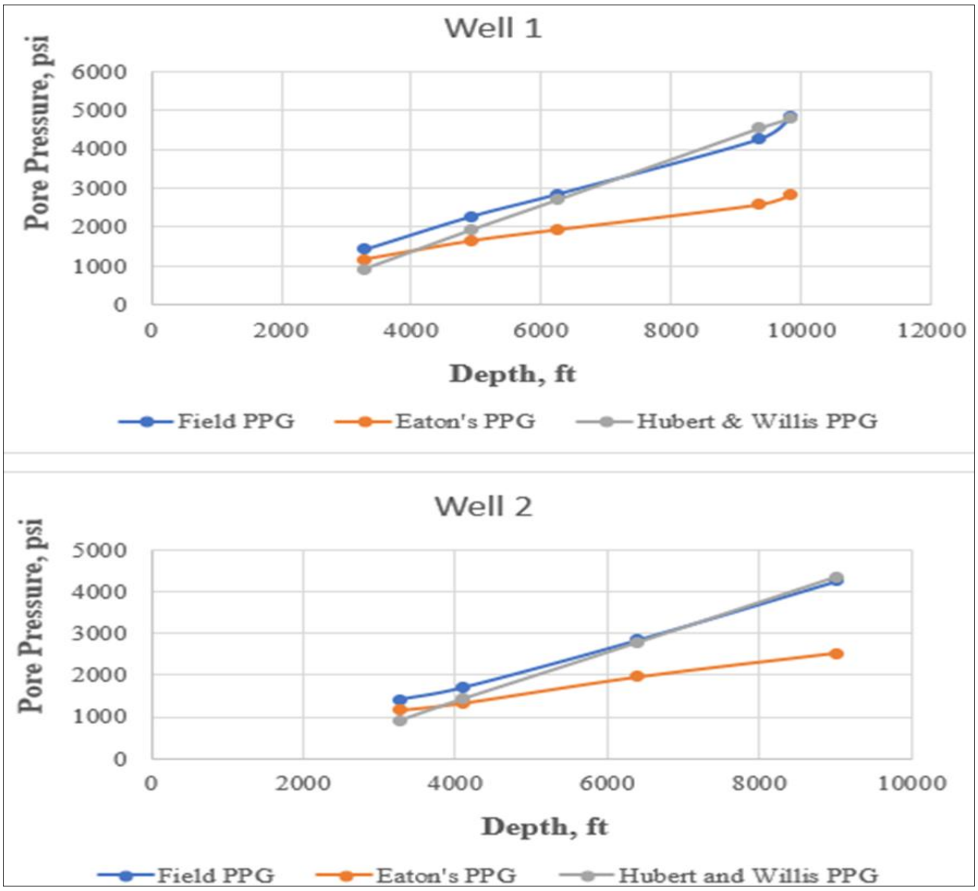

Fig 3: Pore Pressure result for Well 1(above) and Well 2(below)

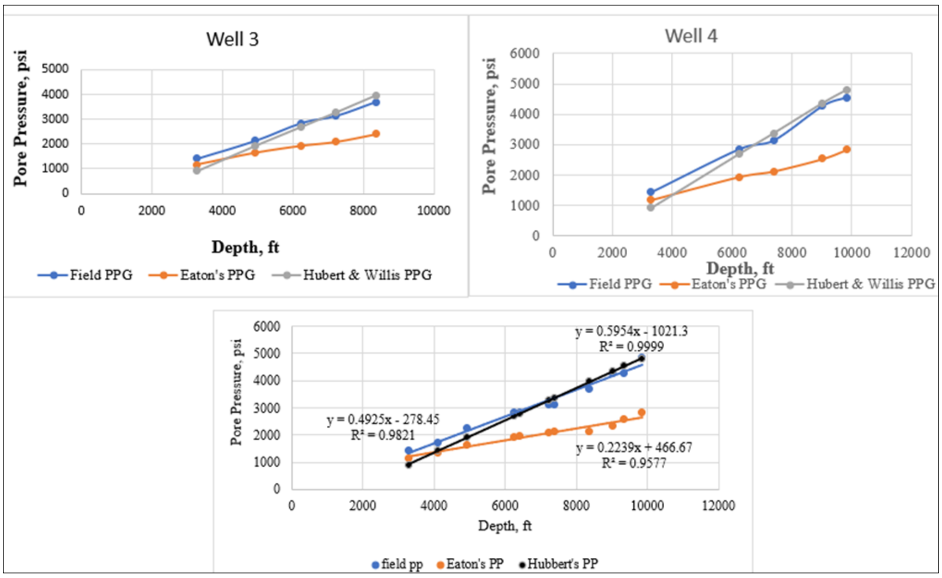

Fig 4: Pore Pressure result for Well 3 and 4 (above) Pore Pressure Versus Depths for Field, Eaton's and Hubbert's Correlation (below)

Table 1 shows the summary of the various correlations used in predicting the pore pressure gradients with their equations obtained after inserting the lines of best fit and their co-efficient of variation (R^2) as shown in Figure 4(below).

Table 1: Methods Used for Prediction, their Equations and Co-efficient of Variation

Method of Prediction	Equation	Co-efficient of Variation (R^2)
Field	$y = 0.4925x - 278.45$	0.9821
Eaton's	$y = 0.2239x - 466.67$	0.9577
Hubbert's and Willis	$y = 0.5954x - 1021.3$	0.9999

Where y is pore pressure, x is depth.

With field data giving an Equation 5 with a Co-efficient of Variation (R^2) of 98.21% (0.9821), it can be used to predict the pore pressures of the field with an error of less than 2%. This therefore suggests that the pore pressures in the four different wells correlated well. The pore pressure gradient using the field data was 0.481.

$$y = 0.4925x - 278.45 \quad (5)$$

Eaton's Correlation

The average deviation of the Eaton's correlation from the average field pore pressure gradient was approximately -50% (Figure 5). Thus, the use of this correlation with data gathered underestimates pore pressure gradient of 0.241. The use of this estimated pore pressure gradient by Eaton's correlations will esult in lower mud window design (underbalanced drilling operation) with associated wellbore instability problems. These deviations could be due to estimation of overburden pressure and Poisson's ratio designed for other fields.

Hubbert and Willis' Correlation

The Hubbert and Willis' method gave an error deviation of +24% from the average field pore pressure gradient. This means that there is an increase in the actual field pore pressure gradient by a factor of 0.597 (Figure 5). This will result in overestimation of the pore pressure gradient but generally, it is better to overestimate than to underestimate pore pressures. But this will reduce the drilling window. Comparing Hubbert and Willis' correlation to that of the Eaton's, it would be better to use Hubbert's and Willis Method in predicting the pore pressure gradient for the Jubilee Field.

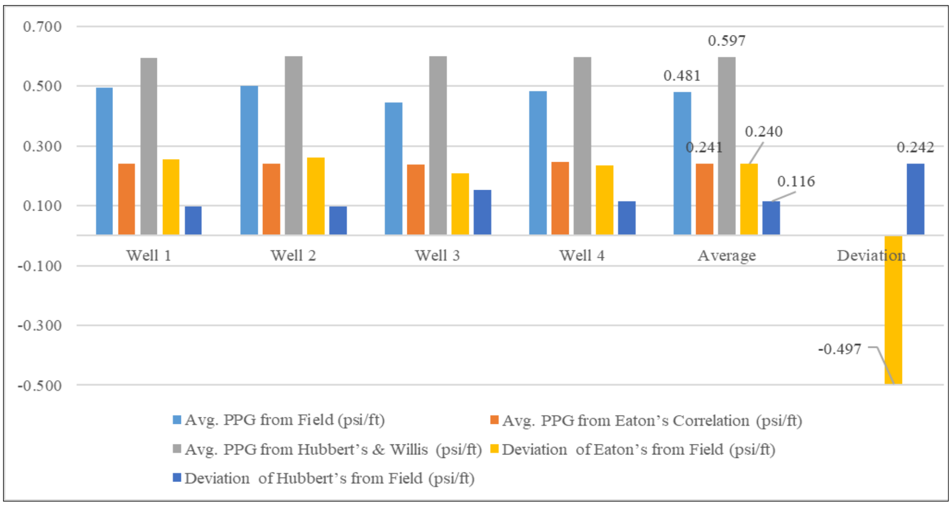

Fig 5: Average Pore Pressure Versus Depths for Field, Eaton's and Hubbert's Correlation with Deviation

Conclusions

Accurate prediction of pore pressure gradients is a major component of exploration risk analysis and knowledge of the formation pore pressure for any overpressure is a very important factor in the evaluation of oil and gas fields. The pore pressure gradients of four different wells in the Jubilee Field were comprehensively investigated and compared using field data, Eaton’s approach as a function of fracture pressure and Hubbert and Willis’ approaches. Based on the available data gathered, and analysis, it can be concluded that:

1. The prediction of the pore pressure gradients using Eaton’s correlation without the use of data from geophysical survey or offset wells may not give reliable pore pressure results. It underestimates the pore pressure by about 50%.
2. Hubbert and Willis’ correlation gave a better pore pressure prediction over that of Eaton but overestimated the pore pressure by about 24%.
3. The pore pressures from the field data gave a strong correlation among the four different wells with an error of prediction less than 2%.

Based on the results obtained, it is therefore recommended that, to predict the pore pressure gradient for the Jubilee Field, the mathematical model can be relied on to predict for other wells. Further works should consider other oil and gas fields like the Sankofa Field and the TEN Field.

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