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Comparing methods of predicting pore pressure

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Abstract--- Comparative analysis uses certain criteria to judge various alternatives in the analysis. These criteria include the values of the alternatives and the likelihood of obtaining them. The petroleum industry constantly seeks for ways to cut down cost of exploration and development. An improvement on the ability to predict events ahead of the bit is the key to achieving this goal. Estimation of pore pressure finds itself so vital in the industry, especially in planning and drilling a modern deep well. No wonder there abound several methods for its prediction. The most common methods of predicting pore pressure in the industry were compared in this study. Seismic travel time data for a well in the Louisianan basin was used for the comparison. The methods compared were the equivalent depth, ratio, Eaton, Pennebarker, Hottman and Johnson, and, Matthew and Kelly. Based on the analysis in the study, the method by Eaton is the most accurate.

Index Terms— pore pressure, Seismic transit time, cost of exploration and development, Louisianan basin, comparative analysis, normal trend line, effective stress.

1.0 INTRODUCTION

Comparative analysis uses certain criteria to judge the various alternatives in the analysis. These criteria include the values of the alternatives and the likelihood of obtaining the values. There are several methods for predicting pore pressure, yet none of them are as accurate as making down-hole pressure measurement in the wellbore. Thus, the true expected value of pore pressure in the formation is the value obtained by making down-hole pressure measurement. Therefore, accurate comparison of the alternatives is with respect to this value.

Pore pressure is the pressure of fluids in the pores of a rock formation. Pore pressure prediction is required in order to carry out safe drilling and well completion job. It is an integral process in the well planning procedure as well as the geologic evaluation of a potential trap.

Generally, techniques for predicting and detecting abnormal formation pressure are often classified as follows [1]:

- Predictive methods also called pre-drill methods.
- Real time evaluation methods applied during drilling.
- Verification methods

In the pre-drill methods, predictions are based mainly on a combination of remote data such as seismic and basin modelling, and/or by analysis of nearby wells [2]. In the case of planning a development well, emphasis is on data from previous drilling experience in the area. Prediction from surface seismic data is by estimating seismic velocities, and then utilizing velocity-to-effective stress transform appropriate for the given area. The estimated overburden stress combines with the effective stress to obtain pore pressure. The seismic data are also conditioned by gathering the signals and processing them before they are used in the transform.

In the real time evaluation methods, engineers monitor drilling and logging parameters while drilling the well. As drilling progresses into a transition zone, variations in rock properties and bit performance often provides many indirect indications of changes in formation pressure [1]. Techniques used to estimate pore pressure real time includes:

- The d_c exponent (which can also be used in predicting pore pressure)
- Measurement While Drilling and Logging While Drilling
- Kicks
- other drilling rate factors

1.1 Types of pore pressure

Practically, pore-pressure has been classed into the following three groups:

1. Normal pressure: which is the hydrostatic pressure the fluids in the formation exert above a depth of interest. It is usually expressed in terms of the hydrostatic gradient of the fluids in-situ. The normal pressure gradients for several geologic areas having considerable drilling activities are given in Table 1.
2. Subnormal Pressure: This is an abnormally low pressure in the region.
3. Abnormal pressure: this is hydrostatic pressure higher than the normal pressure in the zone. In at least a portion of most of the sedimentary basins of the world, we can find abnormal pressure.

Table 1: Normal Pressure Gradient for geologic areas

Source: Applied Drilling Engineering [1].

Geologic areas	*Pressure gradients psi/ft*
Gulf coast	*0.465*
Niger delta	*0.433*
California	*0.439*
Rocky mountains	*0.436*
West Texas	*0.442*
North sea	*0.452*

1.2 Objectives of study

The aim of this study is to quantitatively scrutinize different methods of predicting pore pressure so as to note the similarities and differences in them. It aims to determine the most accurate of all the alternatives with respect to an expected value.

1.3 Significance of study

The importance of this study cannot be overemphasized considering the huge sums of money involved in hydrocarbon exploration. For good drilling job, kicks and blowouts should be controlled at the same time that fracturing is monitored. A blowout is characteristic of oil spill which degrades the environment. For example, in an offshore environment it can be a threat to aquatic life which is a source of livelihood. Overpres-

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sure prediction is requisite for the design of drilling program, casing design as well as choosing rig capacity. Pore pressure prediction helps to reduce well construction risk, save drilling hour as well as cut down drilling cost. Thus, this study can be applied in the following areas:

- Drilling engineering especially in planning and drilling a modern deep well
- Well completion and work over operations in casing designs and cement placement jobs
- In control of wellbore for kicks and blowouts
- Reservoir engineering for material balance computations

1.4 Statement of the problem

Accurate knowledge of pore pressure is a key requirement for safe well planning in any kind of formation. There are several methods for predicting pore pressure, and all of them are suppose to produce the same value of pore pressure in the rock. This is not usually the case as there are variations in the values obtained. Thus, this study wish to use real data to compute pore pressure values using different methods so as to observe similarities and differences in them and also strife to know why this is so. Therefore, in carrying out this study, some basic questions are envisaged:

- Have the existing methods lived up to performance in predicting pore pressure?
- How best can pore pressure prediction methods be compared?
- What are the key challenges in pore pressure predictions?

1.5 Scope of study

The study includes methods for predicting pore pressure due to undercompaction phenomenon. It does not consider real time and post drill methods.

2.0 LITERATURE

Only a few comparative analyses on pore pressure prediction methods exist in literature. Although the industry has made undoubted progress in the understanding of pore pressure in recent years there are no fundamental change in the techniques used to predict pore pressure. The level of sophistication has indeed improved but there are still variations in pore pressure predictions methods. To predict pore pressure, certain techniques and correlations are employed.

2.1 Relationships used for pore pressure prediction

Most methods of predicting pore pressure are based on Terzaghi`s effective stress principle [3], which implies that elastic wave velocities are a function of the effective stress tensor. The effective stress tensor is the difference between the total stress tensor and the pore pressure. From Terzaghi`s work, the total stress equation is written as (1):

$$S = \sigma + P \quad . \quad . \quad . \quad . \quad .. \qquad (1)$$

S = the total stress, σ = the effective stress and P = the pore pressure.

From density-sonic log transform couple with estimate of average sediment density from the top of the logged interval to the seabed we derive the total stress [2].

In addition, the effective stress is the principal driving mechanism for the compaction of compressible sediments. Under normal conditions, the magnitude of the effective stress increase with depth and this invariably lead to a reduction in porosity. Laboratory studies [4], [5], confirm that effective stress controls the compaction that take place in porous granular media.

2.2 Porosity-based methods

These methods rely on the normal compaction trend of sediments in a basin as far as it is derivable. Working with this trend, it is assumed that compaction solely control porosity [2]. The formation is young, fine-grained sediments with similar lithology and of low temperature. According to him, porosity based pore pressure prediction method does not always deliver satisfactory results. This he said was either because these assumptions are not valid, or because there are insufficient data.

2.2.1 Eaton`s method

The Eaton`s method compares an in-situ physical property to a normally compacted equivalent physical property at the same depth [2]. It is valid as long as the normal curve can be constructed for all depth of interest. This method typically applies to seismic or acoustic velocity data and to resistivity data. The form of the equation for velocity data is given below:

$$p = \sigma_o - (\sigma_o - p_n)\left(\frac{v_i}{v_n}\right)^3 \qquad (2)$$

Where P = predicted pore pressure, σ_O = overburden pressure, P_n = hydrostatic pressure, V_n = normally compacted velocity and V_i = observed interval velocity from seismic data.

2.2.2 Equivalent depth method

This method also uses a reference normal compaction curve. The procedure here is to compare the observed attribute with the depth at which the observed attribute would at the normal compaction curve [2]. This equivalent depth can then be used to compute the magnitude of the effective stress if the magnitudes of the three principle stresses are known. The pore pressure is then calculated by subtracting the vertical effective stress from the vertical stress at the depth of the observed attribute. The implicit assumption is that porosity is controlled only by effective stress, driven by mechanical compaction. By this method, the effective stress at the observed depth and that at the equivalent depth are the same. The formula can be given as in (3):

$$p = p_n + (\sigma_o - \sigma_{on}) \qquad (3)$$

Where P = pore pressure in psi/ft, P_n = normal pore pressure at equivalent depth in psi/ft, σ_O = overburden stress at depth in psi/ft, σ_{On} = normal overburden at equivalent depth in psi/ft.

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2.2.3 Ratio method

This method uses data on the seismic plot to determine pore pressure. The model for predicting pore pressure can be given by:

$$P_p = P_n \frac{v_n}{v_i} \qquad (4)$$

2.3 Correlations used to estimate Pore pressure

Once the pressure gradient of a formation has been known, it becomes very easy to predict the pressure existing at depth of interest. This is a quick guild to the estimation of pore pressure real time. Several researchers have used the interval transient time data to estimate the pressure gradient of formations form where pore pressure is estimated. They include:

1. Pennebaker [6], used the transient time ratio of (t/t_n) to estimate pressure gradient. From this, pore pressure can be estimated.

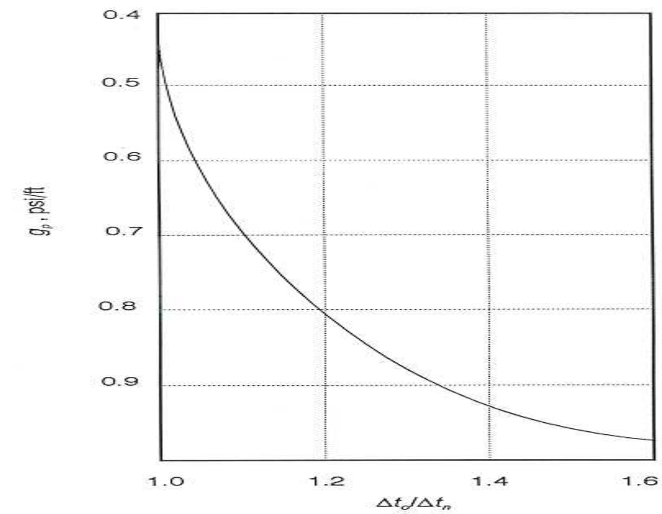

Fig.1. pressure gradient correlation by Pennebaker

2. Hottman and Johnson [7], gave a correlation between interval transit time difference ($t-t_n$) and pore pressure using a Cartesian plot.

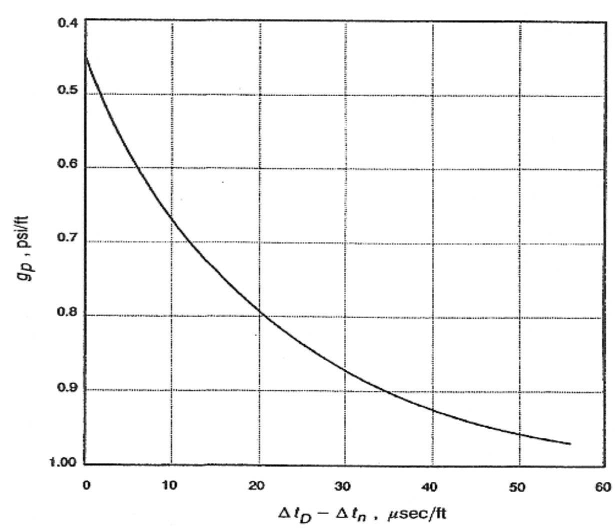

Fig.2. pressure gradient correlation by Hottman and Johnson

3. Mathews and Kelly [8], gave a relation between the difference in interval transit time, $(t-t_n)$ and pressure gradient but used a semi-log plot.

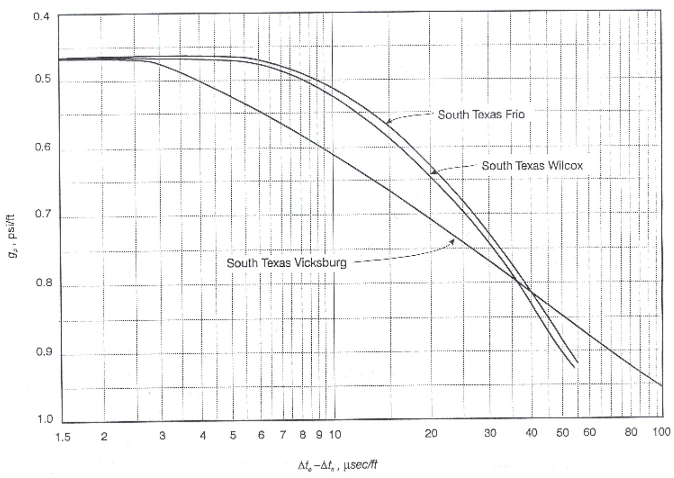

Fig.3. pressure gradient correlation by Mathews and Kelly

Eaton et al [9], investigated currently applied technologies used to predict, detect, and evaluate the magnitudes of abnormal pressure and fracture gradient in the earth crust. They carried out a wide literature search which covered most of the published articles concerning the subject. They made a detailed interview of Thirty (30) companies which included international major oil companies, drilling contractors and service companies from the US, Canada and South America. They also used actual well and formation data to evaluate pore pressure and fracture gradient at various depths. They went further and statistically determined the methods from the interview. According to them, the best methods employed by drilling personnel for pore pressure prediction are the Hottman and Johnson, Equivalent depth and the Eaton methods. They ranked Eaton method as the most accurate.

3.0 METHODOLOGY

The petroleum industry constantly seeks for ways to cut down cost. An improvement on the ability to predict events ahead of the bit is a key to achieving this goal. Prediction of pore pressure finds itself so vital in the industry especially in planning and drilling a modern deep well, no wonder there abound several methods used to get it.

This section focuses on the method adopted in this study.

3.1 Data collection

The source of data for analysis in this study is through secondary data sourcing. The use of seismic data from a well offshore Louisiana aided the analysis.

3.2 Method of analysis

From the interval transit time, pore pressure at a depth of 19,000 ft was predicted using different methods. After this, the arithmetic average of the various alternatives was calculated. This value was taken as the expected value of the pore pressure in the formation. Afterwards, statistical analysis of the results was carried out by calculating the absolute deviation from the mean.

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3.3 Accuracy of the models

The fraction of absolute error, e, was used as the measure of merit. It was calculated by (5):

$$|e| = \left| \frac{x - \bar{x}}{\bar{x}} \right| \quad . \quad . \quad . \quad . \quad . \qquad (5)$$

x = the value used and $\bar{x}$ = the mean of all the values used.

The original pore pressure from down-hole measurement was not given as a priori and so the calculated mean was used for the analysis.

The alternative that gave value closest to the expected value was ranked as most accurate. This alternative is the one having the least fraction of absolute error.

4.0 ANALYSIS OF RESULTS

Table 2 shows the well data obtained from the Louisianan basin.

Table 2. Well data from Louisiana basin [1]. (Adapted from tamu-pemex, pore pressure prediction.ppt, slide 18)

TABLE 2.7—AVERAGE INTERVAL TRANSIT TIMES FOR A SOUTH LOUISIANA MIOCENE PROSPECT[28]

Interval (ft)	Midpoint (ft)	Average Transit Time (μsec/ft)
4,000 to 5,000	4,500	98
5,000 to 6,000	5,500	93
6,000 to 7,000	6,500	86
7,000 to 8,000	7,500	84
8,000 to 9,000	8,500	84
9,000 to 10,000	9,500	78
10,000 to 11,000	10,500	75
11,000 to 12,000	11,500	80
12,000 to 13,000	12,500	81
13,000 to 14,000	13,500	84
14,000 to 15,000	14,500	82
15,000 to 16,000	15,500	95
16,000 to 18,000	17,000	95
18,000 to 20,000	19,000	95
20,000 to 21,000	20,500	93
21,000 to 22,000	21,500	93

The normal pressure gradient in the basin is 0.465 psi/ft. Equivalent depth is at 2500 ft and overburden gradient is 0.995 psi/ft.

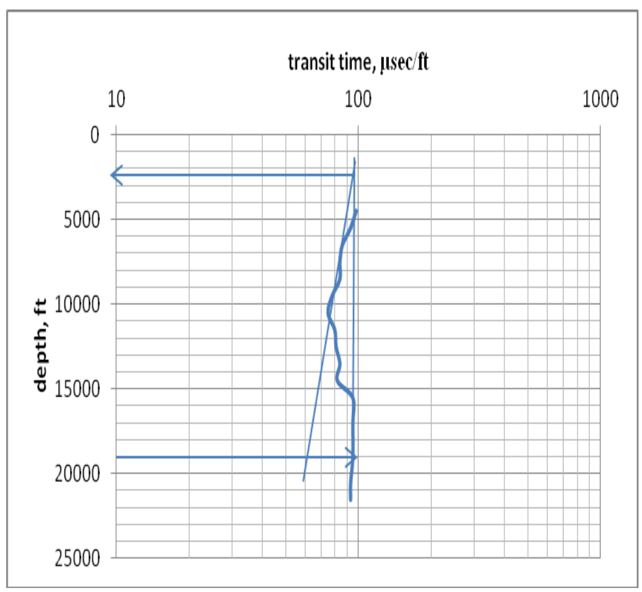

Fig.4. depth vs transit time plot

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4.3 Analysis of result

Computation of results is given in the excel spreadsheet that follows:

			COMPUTATIONS FOR GULF COAST WELL					
	Data Input							
σo	0.995	psi/ft	To	95	µsec/ft	Z	19000	ft
Pn	0.465	psi/ft	Tn	60	µsec/ft	Ze	2500	ft
Equivalent Depth Method			Ratio Method			Eaton`s Method		
Pne	1162.5	psi	to	95	µsec/ft	to	95	µsec/ft
σoe	2487.5	psi	tn	60	µsec/ft	tn	60	µsec/ft
σo	18905	psi	pn	8835	psi			
p	17580	psi	p	13988.75	psi			
p	0.925263	psi/ft	p	0.73625	psi/ft	p	0.861476	psi/ft
Pennebarker correlation			Hottman &Johnson			Matthew & Kelly		
to/tn	1.583333		to-tn	35	µsec/ft	to-tn	35	
p=f(to/tn)	0.97	psi/ft	p=f(to-tn)	0.9	psi/ft	p=f(to-tn)	0.8	psi/ft
	Mean value	0.865498	Psi/ft					

4.4. Discussion of results

The results show that the values are not all the same. For example, the ratio method gives a value of 0.68 psi/ft while the Hottman and Johnson method gives a value 0.87 psi/ft. The difference between these results is quite significant and can be costly to drilling job. It is indicative of an error somewhere.

By use of the values obtained from the various alternatives, the most accurate method is that obtained by use of the Eaton`s method. It is closest to the average value.

The method by Hottman and Johnson, and that by Mathews and Kelly both use the difference between the interval transit time at the needed point and that at the normal line, $t_o - t_n$, to compute the pressure gradient. Yet the values obtained from them are different. This difference is probably due to the assumptions used in generating the correlations. This can be a major challenge in pore pressure prediction methods. Some are valid while others are definitely not.

The ratio method gave a very different result, which underestimates the mean value. Compared with the Eaton`s method, there seems to be a significant error in the development of the model.

Selection of a slightly different normal compaction trend shows that the equivalent depth changes to 2000ft with a normal transit time of $65 \mu \sec / ft$. With this, the various values obtained are given next.

			COMPUTATIONS FOR GULF COAST WELL					
	Data Input							
σo	0.995	psi/ft	To	95	µsec/ft	Z	19000	ft
Pn	0.465	psi/ft	Tn	65	µsec/ft	Ze	2000	ft
Equivalent Depth Method			Ratio Method			Eaton`s Method		
Pne	930	psi	to	95	µsec/ft	to	95	µsec/ft
σoe	1990	psi	tn	65	µsec/ft	tn	65	µsec/ft
σo	18905	psi	pn	8835	psi			
p	17845	psi	p	12912.69	psi			
p	0.939211	psi/ft	p	0.679615	psi/ft	p	0.825236	psi/ft
Pennebarker correlation			Hottman & Johnson			Matthew & Kelly		
to/tn	1.461538		to-tn	30	µsec/ft	to-tn	30	
p=f(to/tn)	0.94	psi/ft	p=f(to-tn)	0.87	psi/ft	p=f(to-tn)	0.77	psi/ft
	Mean value	0.837344	Psi/ft					

This reveals that only the equivalent depth method has its value increased while other methods have their values reduced. Similar shift in the normal compaction trend in the opposite direction reveals an increase in values for other methods, but a decrease in value for the equivalent depth method. The equivalent depth method tend to overestimate or underestimate pore pressure based on whether the equivalent depth is toward the surface or towards the target.

All the methods have a common value, which equals the normal pressure gradient, at the point where the equivalent depth equals the depth of interest and the normal transit time equals the recorded transit time. Outside this point, there seems to be an inability to accurately model deviations from normal trend.

5.0 CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

Based on the results obtained in this study, the following can be drawn

- Porosity based pore pressure prediction models does not give accurate results unless an appropriate normal compaction curve has been defined.
- The inability to accurately model deviations from normal trend line is the major reason while different methods of pore pressure prediction do not give equal results.

5.2 Recommendations

- Porosity based models should be employed only when appropriate normal compaction curves are defined for the field
- Offset wells should always be used to calibrate prediction results
- Direct pressure measurements should be taken in the life of the well so as to check for the consistencies of models used to get pore pressure results.
- For seismic data, the use of the equivalent depth method should be a last resort.

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