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RESEARCH ARTICLE

Fracture Gradient Prediction using a characteristic effective stress relationship

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Abstract

A relationship between the effective horizontal stress and the effective vertical stress in a rock was determined in this study. With the known relationship, the fracture gradient was obtained. An exponential relationship was assumed as existing between the stresses, and by mathematical manipulation the relationship was recast into a form which relates overburden stress to pore pressure by use of the Terzaghi`s stress equation. Solution to the derived equation gave values of the constants of proportionality, from where the value of the minimum stress was obtained. This value was then used to obtain the fracture gradient by application of the Hubbert and Willis fracture principle.
The result obtained, when tested with data from West Texas wells, compares with those obtained from the conventional methods of Eaton, and Mathews and Kelly.

1.0 INTRODUCTION

Rocks are highly anisotropic in nature, and are heterogeneous in their chemical composition. While in situ, rocks exist under condition of stresses from neighboring sediments. Before a well is drilled into the earth, the in situ stresses exist in a state of equilibrium. After the hole is drilled there will be a redistribution of the in situ stresses around the wellbore. At this point, the mud must balance the weight of the excavated materials otherwise there will be drilling problems or wellbore instability. Wellbore fracturing is one of such problems, and wellbore instability cost the drilling industry over $100 million a year worldwide, Al Ajmi,[1].

Safe drilling procedure requires that the well be planned for fracture gradient which can lead to lost circulation and damage the reservoir. At this stage, the fracture gradient can be obtained from offset well data or by use of several published models. This fracture gradient can be defined as the lowest required total stress in the well.
Even within a rock that is assumed to be homogeneous, the total stress may vary from place to place, and may change over time. Figure 1 shows the in situ stresses in a rock prior to drilling.

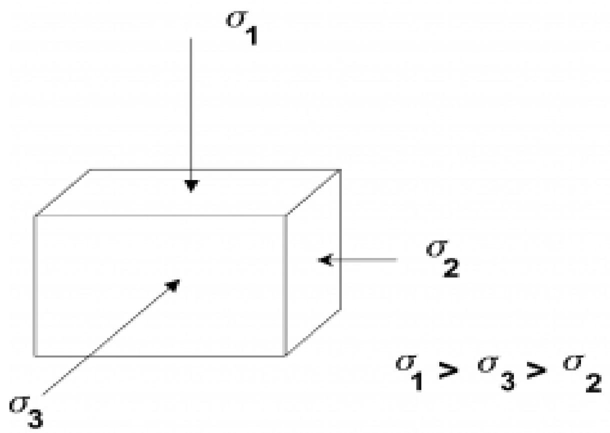

Figure 1: In situ principal stress distribution in a rock

σ_2 and σ_3 are horizontal stresses in the x and y directions while σ_1 is the vertical stress in the z direction. The horizontal stress and vertical stress bear a significant relationship with one another, and studies have shown that the magnitude of the horizontal stress and vertical stress has a major influence on fracture gradient initiation in a formation, Fjaer et al [2].
The directions of these stresses are a determining factor in the failure of the rock. Usually, the magnitudes of the stresses are not the same, and the difference between the maximum stress and the least stress in the rock can cause the rock to fail in shear.

Fractures in rocks propagate in a plane that is perpendicular to the direction of the lowest principal stress. When there is normal fault in an area, earth stresses cause a vertically oriented fracture to be initiated when the horizontal stress is the least stress, Guerard Bill [3] as shown in figure 2:

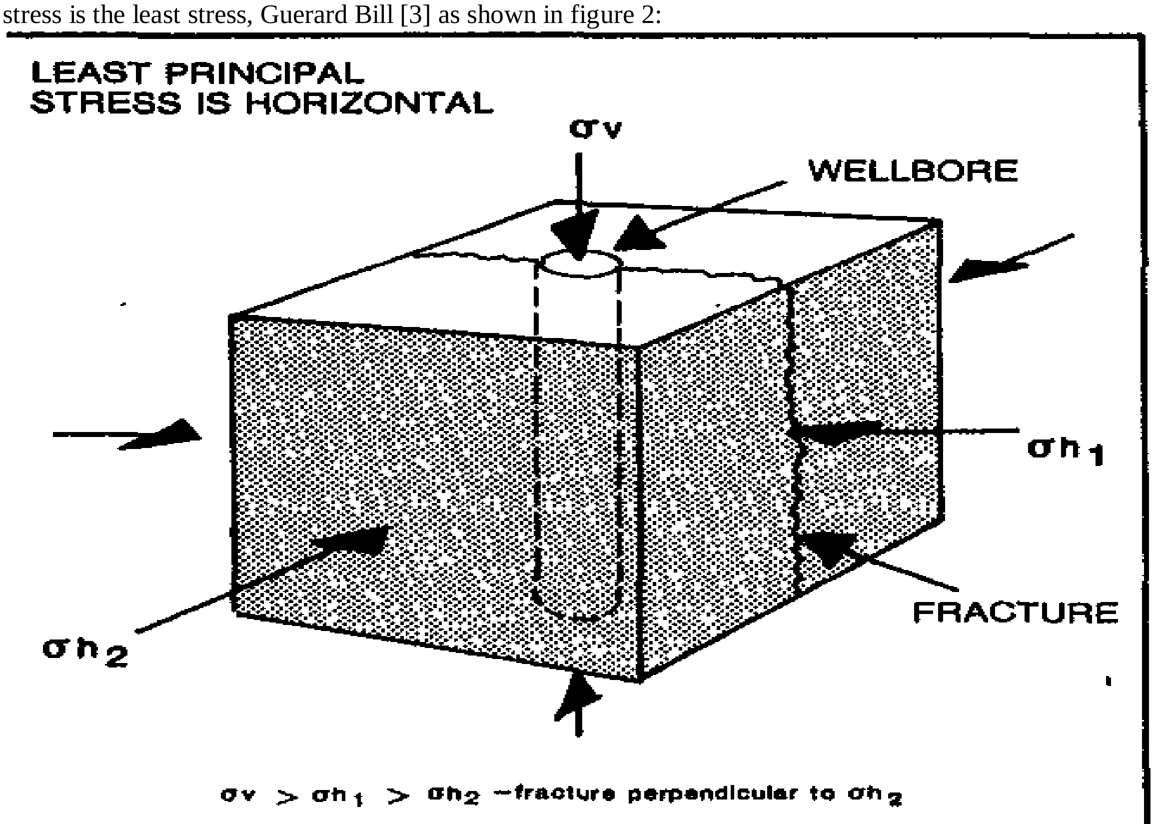

Fig 2: Fracture orientation when the lowest principal stress is horizontal (Guerard Bill).

Depending on the kind of fault system in the zone, the vertical stress can be the least, intermediate or maximum principal stress. In this study, the case for a normal fault system where tectonic activities are insignificant is considered.

1.1 OBJECTIVES

This paper strives to formulate a model for predicting fracture pressure in reservoir rocks by use of a relationship between the effective horizontal and vertical stresses in the rock.

1.2 RELEVANCE OF STUDY

When the cost incurred in a drilling operation due to wellbore instability issues is considered, the importance of a study of this magnitude cannot be overemphasized. This study is significant because of the following reasons:

- It helps in carrying out well planning for drilling operations by use of simple, fast and accurate model.
- It confirms the accuracy of the most commonly applied fracture gradient models used in the industry.

1.3 STATEMENT OF THE PROBLEM

The strength of rocks has been obtained from laboratory/field tests as detailed in the work of Fjar et al [2]. The extended leak-off test has been said to yield the best results for in situ stresses. While this method causes the loss of the oil based mud which is typically used to drill the well, the leak-off test approach has been preferred. To predict fracture gradient in a rock, knowledge of the relationship between the in situ stresses are needed. While Hubbert and Willis gave a range of values for the relationship between horizontal matrix stress and vertical matrix stress, the Ben Eaton model uses the Poisson`s ratio to relate these stresses. Although the Mathews and Kelly`s model uses the vertical to horizontal stress ratio in a formation to obtain the needed value, it is important to know if there are other mathematical ways of obtaining these relationship. Thus while developing a model for prediction of fracture gradient in a rock, the study strives to answer the following question:

- How can the relationship between horizontal and vertical stresses be used to predict fracture pressure?
- How possible is it to use values of only overburden stress and pore pressure to obtain results that relates the horizontal and vertical matrix stresses?

2.0 LITERATURE

There are several studies on the subject of fracture gradient and pore pressure determination in the industry. A recent work carried out by Eaton et al, [4], lists several of these numerous methods of predicting fracture gradient in a rock. There are also available the works of Salz, [5] and Zooback, [6].

Models used to predict fracture gradient in the industry started in 1957 by the classical work on hydraulic fracturing carried out by Hubbert and Willis, (Hubbert and Willis, [7]). Their model is based on a laboratory triaxial compression test and assumes a constant overburden gradient of $1 Psi / ft$, and states that the fracture pressure equals the pore pressure plus the minimum effective stress. For a vertical well, the minimum effective stress is a horizontal stress. They gave it that the minimum effective horizontal stress equals a fraction of the effective vertical stress which is the difference between the overburden stresses and pore pressure. According to them, this fraction was in the range of $\frac{1}{3} to \frac{1}{2}$ of the effective vertical stress. Thus, they predicted fracture gradient in the limit of a maximum and minimum value. It has been said, (Eaton et al, [4]), that the Hubbert and Willis method is not widely utilized in the industry because of its low value prediction for fracture gradient. The resulting equations of the work of Hubbert and Willis are given in equations 1 and 2:

$$F_{\min} = \frac{1}{3}\left(1 + \frac{2P}{D}\right) \quad (1)$$

$$F_{\max} = \frac{1}{2}\left(1 + \frac{P}{D}\right) \quad (2)$$

Building on the Hubbert and Willis model, Matthews and Kelly in 1978, (Mathews and Kelly, [8]), developed a model for predicting fracture gradient by assuming a variable matrix stress coefficient, K_i . The matrix stress coefficient relates the actual matrix stress condition of the rock to that of a normally compacted one. Values of the matrix stress coefficient are determined empirically for a given area by use of the fracture initiation pressure in the area. Their model can be given as in equation 3:

$$\frac{F}{D} = \left(\frac{S}{D} - \frac{P}{D}\right)K_i + \frac{P}{D} \qquad 3$$

Eaton (Eaton,[9]) also expanded the work of Hubbert and Willis and formally introduced the Poisson`s ratio of rocks and a variable overburden gradient. For him, the effective horizontal stress caused by the effective vertical stress is a function of the Poisson`s ratio of the rock and this is given as:

$$\sigma_h = \left(\frac{\mu}{1-\mu}\right)\sigma_v \qquad 4$$

Where

σ_v = effective stress or effective vertical stress, σ_h = effective horizontal stress, and $\mu =$ Poisson`s ratio.

$$\sigma_v = \sigma_o - p \qquad 5$$

$$\sigma_h = \sigma_H - p \qquad 6$$

Thus upon substitution into the Hubbert and Willis model, the Eaton fracture gradient is given as in equation 7:

$$F = \left(\frac{\sigma_o - P}{D}\right) * \left(\frac{\mu}{1-\mu}\right) + \frac{P}{D} \qquad 7$$

Where σ_o = overburden stress, P= pore pressure and μ is the Poisson ratio.

The Eaton`s model and that of Mathews and Kelly are similar and can produce similar results as can be seen in the result section of this work.

In a recent work by Contreras et al, [10], it was said that values obtained from application of these methods do not reflect specific strata characteristics because they are purely correlative. According to them, this can lead to erroneous results and improper selection of surface equipments. They said to circumvent this problem a more effective calculation can be obtained by relating fracture gradient calculations to values obtained from field test in specific zones in order to ensure an explicit calibration of the calculation method.
Here in this study, a theoretical model based on the relationship between the effective vertical and horizontal stresses will be made. The result will confirm the values obtainable by use of pre-existing models.

2.1 THE LEAK-OFF TEST

This is an experimental method of predicting the fracture gradient in the rock and it is widely employed in the industry. In this method, the following steps, (Dosunmu, [11]) are used to carry out the test:

- Run and cement casing
- Drill out approximately 10 ft below the casing seat
- Close the blow out preventers
- Pump slowly and monitor the pressure

On completion and collection of data from the test, the plot of pressure against volume of mud used can be shown as in figure 3.

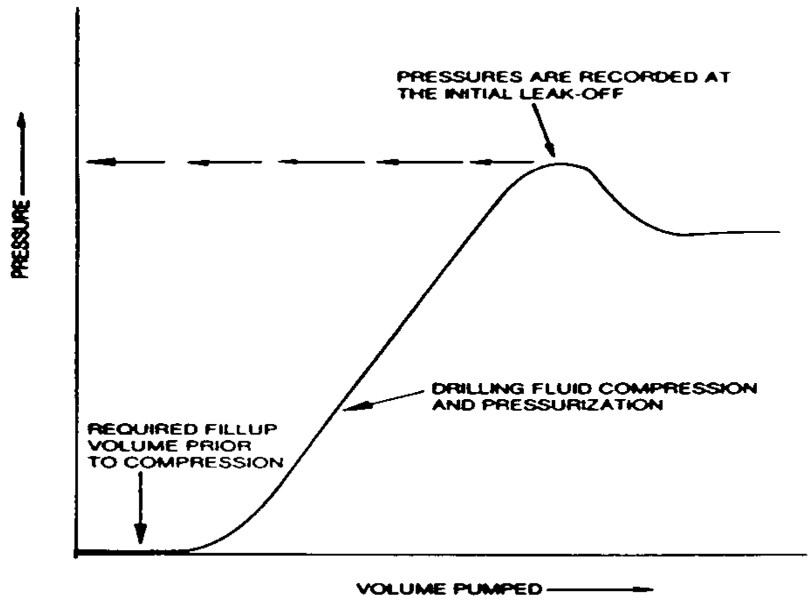

Figure 3: Typical results from a leak-off test

The results of a leak-off test are useful in determining the fracture gradient in the rock because it gives the response of rocks to stresses. For more accurate information, the extended leak-off test can be used, Fjaer et al [2]. It is similar to the leak-off test but the pumping continues after fracture point until the fluid has entered the undisturbed zone of the rock. This test is seldom employed in the industry because of the loss of oil base mud, which is quite expensive to purchase. If this test gives the most accurate value of the strength of the rock, it should be used only after appropriate economics has been carried out.

3.0 METHODOLOGY

This section focuses on the scheme used to derive a model for predicting fracture pressure in rocks. The development is based on the work of Hubbert and Willis, who gave the equation for determining fracture gradient as equal to the value pore pressure plus the minimum effective stress. For a well where the vertical stress is the largest, the minimum effective stress becomes the minimum effective horizontal stress. The formula for the fracture gradient can be given as in equation 8:

$$p_f = p + \sigma_{\min} \qquad 8$$

Where p= pore pressure and $\sigma_{\min}$ is the minimum effective horizontal stress in the rock.

A relationship between the effective horizontal stress and the effective vertical stress was assumed. Mathematical manipulations were used to recast this equation into a form which fits into a straight line graph. To obtain values for the minimum effective stress in a formation, well data (of overburden stress and pore pressure) in the formation was used to obtain the constant which relates the effective horizontal stress to the vertical matrix stress. This can also be achieved by plotting a graph of the overburden against the pore pressure at various depths in the formation. The slope of the straight line obtained gave the value of the constant.

4.0 THEORY AND ANALYSIS

4.1 THEORY

To obtain the value of the fracture gradient in a rock, the minimum effective stress has to be determined. A valid relationship between the vertical and horizontal matrix stress can be used to obtain this minimum stress. From the relationship, the constants of proportionality can be determined by use of data from the field.

From the Terzaghi`s equation, the vertical and horizontal stresses can be written as:

$$\sigma_1 = \sigma_v + p \qquad 9$$

$$\sigma_2 = \sigma_{h2} + p \qquad 10$$

$$\sigma_3 = \sigma_{h3} + p \quad 11$$

Assuming the relationship between the effective stress and effective vertical stress is given as an exponential equation such that:

$$\sigma_h = \sigma_v e^{-Z} \quad 12$$

Substituting equations 9 and 10 into equation 12 will produce equation 13:

$$\sigma_H - p = (\sigma_o - p)e^{-Z} \quad 13$$

Further mathematical arrangements will recast equation 13 into equation 14:

$$\sigma_o = (1 - e^Z)p + \sigma_H e^Z \quad 14$$

Equation 14 will yield a straight line, with a slope of $1 - e^Z$, for a plot of σ_o vs p, using data from the given formation.

By use of the normal conditions in the formation, equation 14 takes a new form as in equation 15:

$$\sigma_{on} = (1 - e^Z)p_n + \sigma_{Hn} e^Z \quad 15$$

Assuming that the normal horizontal stress in the formation equals the horizontal stress at depth of interest:

$$\sigma_H = \sigma_{Hn} \quad 16$$

Solving equations 14 and 15 simultaneously yields equation 17:

$$Z = Ln\left\{1 - \left(\frac{\sigma_o - \sigma_{on}}{p - p_n}\right)\right\} \quad 17$$

Where σ_o is the overburden stress which is computed using available technology in the zone, σ_{on} is the normal overburden in the zone, p is the pore pressure, and p_n is the normal pore pressure in the zone.

4.2 Procedures for predicting fracture pressure using the characteristic stress approach

- Specify the zone where rock exist and get rock data
- Get the normal conditions of overburden and pore pressure in the field
- Calculate the stress constant
- Obtain the value of the minimum effective stress
- Add the minimum effective stress to pore pressure to get the fracture gradient

4.3 RESULT TESTING

A Texas Gulf Coast well has a pore pressure gradient of 0.735 psi/ft. Well depth = 11,000 ft.
Calculate the fracture gradient in units of psi/ft using the Hubert and Willis, Mathews and Kelly, Ben Eaton and the Characteristic stress constant.
Summary of the results is given in tabular form below.

4.3.1 HUBBERT AND WILLIS

$$F_{\min} = \frac{1}{3}\left(1 + \frac{2P}{D}\right)$$

$$F_{\min} = \frac{1}{3}(1 + 2 * 0.735) = 0.823 Psi/ft$$

$$F_{\max} = \frac{1}{2}\left(1 + \frac{P}{D}\right)$$

$$F_{\max} = \frac{1}{2}(1 + 0.735) = 0.8675 Psi/ft$$

4.3.2 MATHEWS AND KELLY

$$\frac{F}{D} = \left(\frac{S}{D} - \frac{P}{D} \right) K_i + \frac{P}{D}$$

With p=0.735 psi/ft and overburden gradient of 1 psi/ft, the effective stress is $\sigma_e = 1 - 0.735 = 0.265 Psi / ft$

The depth where at normal condition the stress equal 0.265 psi/ft is:

$$S_n = P_n + \sigma_n$$

$1.00 * D_i = 0.465 * D_i + 2,915$

$D_i * (1 - 0.465) = 2,915$

$$D_i = \frac{2915}{1 - 0.465} = 5449 \, ft$$

From the graph of matrix stress coefficient, the value can be traced as shown in the figure 5:

$$K_i = 0.685$$

$$F = \frac{0.685 * 2915}{11000} + 0.785 = 0.9165 Psi / ft$$

4.3.3 BEN EATON

$$F = \left(\frac{\sigma_o - P}{D} \right) * \left(\frac{\mu}{1 - \mu} \right) + \frac{P}{D}$$

From figure 6 and figure 7, at a depth of 11000 ft, the overburden gradient is $0.96 Psi / ft$ and the Poisson`s ratio is 0.46, thus:

$$F = (0.96 - 0.735) * \frac{0.46}{1 - 0.46} + 0.735 = 0.9266 Psi / ft$$

4.3.4 THE CHARACTERISTIC STRESS METHOD

The result for the fracture gradient computation is shown in the MS excel spreadsheet below

		MS Fracture Compute			
Well Data Inputs				**Texas Gulf Coast**	
Pn	0.465	psi/ft			
P	0.735	psi/ft			
σon	1	psi/ft			
σo	0.96	psi/ft			
Well Data Outputs					
Stress constant , Z		Min Effective stress		Fracture Gradient	
0.13815		0.195968	psi/ft	0.930968	psi/ft
Normenclatures					
Pn is the normal pore pressure					
P is the pore pressure					
σon is the normal overburden pressure					
σo is the overburden pressure					

The various values obtained are compared in table 1.

Table 1: Comparison of results

Model	Result in psi/ft
Hubbert and Willis Minimum	0.823
Hubbert and Willis Maximum	0.8675
Mathews and Kelly	0.9165
Ben Eaton	0.9226
Characteristic stress Models	0.93

4.4 DISCUSSION

The characteristic stress model yields fracture gradient values strong enough for use in the industry. The value obtained is close to that of the Ben Eaton`s model. It utilizes the same set of data employable by the Eaton`s fracture gradient model. In the computation, the normal overburden pressure gradient was assumed equal 1 psi/ft.

A more accurate result for any zone would be obtained by use of data derived from the zone. This is expected since the data are more representative of the formation in question. For example, allowing the normal overburden gradient to be 1.02 psi/ft, using data from Texas gulf coast, the result of the fracture gradient will change a little in value as shown in the MS spread sheet below:

		MS Fracture Compute			
Well Data Inputs				**Texas Gulf Coast**	
Pn	0.465	psi/ft			
P	0.735	psi/ft			
σon	1.02	psi/ft			
σo	0.96	psi/ft			
Well Data Outputs					
Stress constant , Z		Min Effective stress		Fracture Gradient	
0.200671		0.184091	psi/ft	0.919091	psi/ft
Normenclatures					
Pn is the normal pore pressure					
P is the pore pressure					
σon is the normal overburden pressure					
σo is the overburden pressure					

Here, the fracture gradient resembles that of the Mathews and Kelly. If the normal overburden gradient equals the variable overburden gradient, it becomes difficult to estimate fracture gradient as it assumes that value of the overburden gradient as shown:

		MS Fracture Compute			
Well Data Inputs				Texas Gulf Coast	
Pn	0.465	psi/ft			
P	0.735	psi/ft			
σon	1.02	psi/ft			
σo	1.02	psi/ft			
Well Data Outputs					
Stress constant , Z		Min Effective stress		Fracture Gradient	
0		0.285	psi/ft	1.02	psi/ft
Normenclatures					
Pn is the normal pore pressure					
P is the pore pressure					
σon is the normal overburden pressure					
σo is the overburden pressure					

From the characteristic stress constant, it can be observed that as the horizontal stress tend to the value of the overburden, the fracture gradient tend to that of the overburden. This can be explained by the Eaton`s model as the point of plasticity when Poisson`s ratio equals 0.5.

5.0 CONCLUSIONS

The fracture gradient in a rock has been determined by use of an exponential relationship between the effective vertical stress and the effective horizontal stress, in this study. The model successfully predicts values accurate enough to represent fracture gradient in the industry. It also has similar behavior to the Ben Eaton`s fracture gradient model.

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Appendages

MATHEWS AND KELLY`S MATRIX STRESS COEFFICIENT

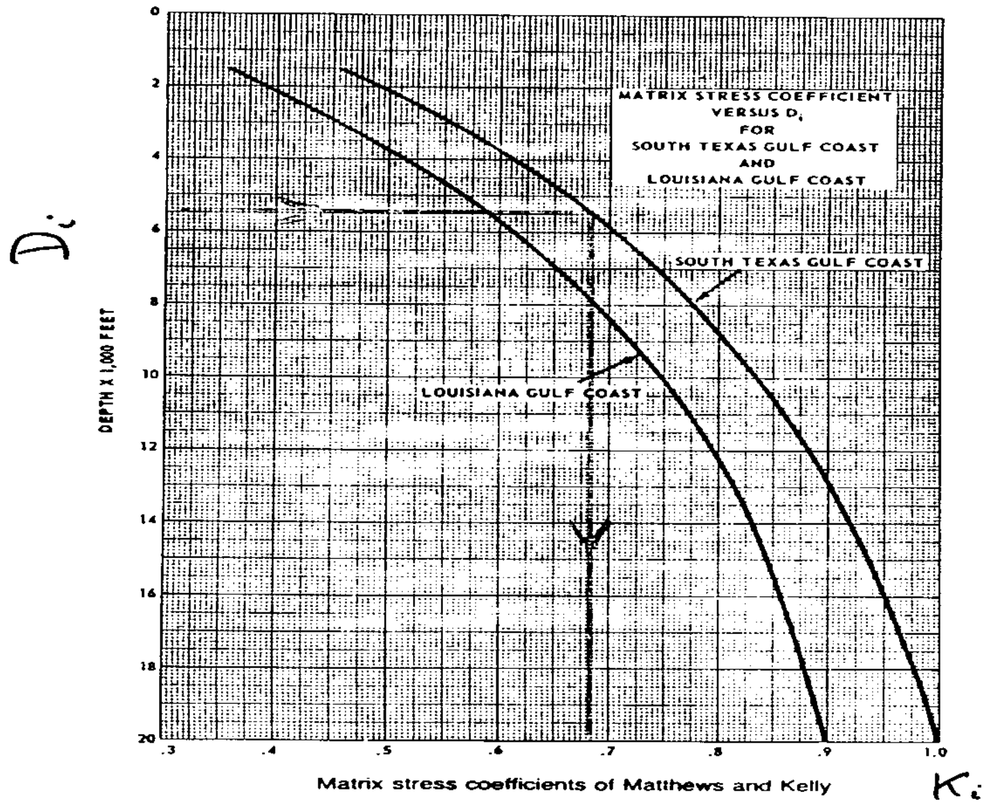

Fig 5: matrix stress coefficient (Matthews and Kelly)

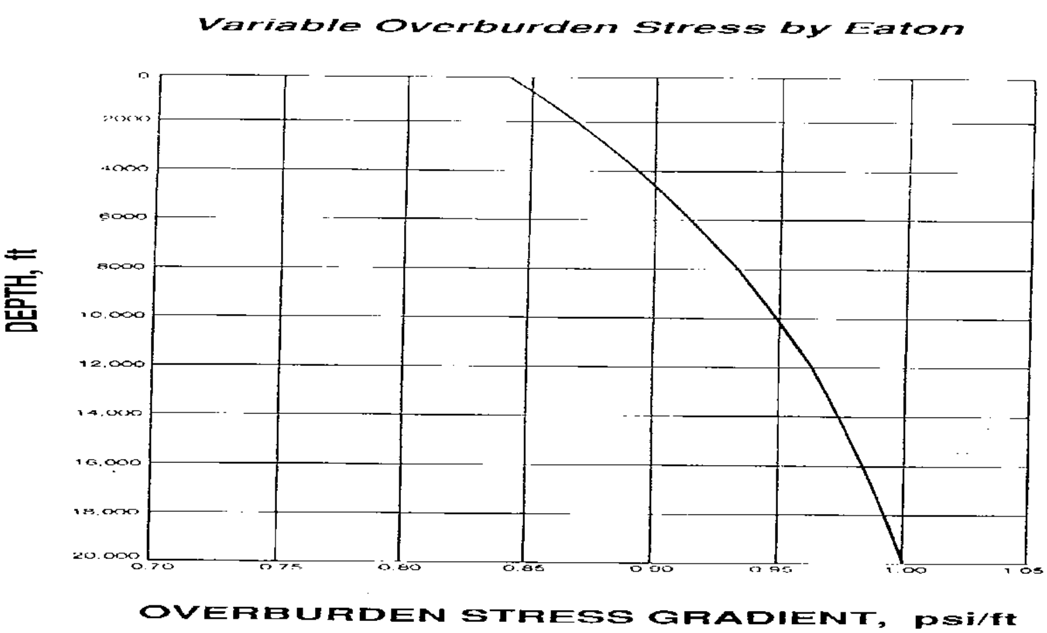

Fig 6: variable overburden stress (Eatons)

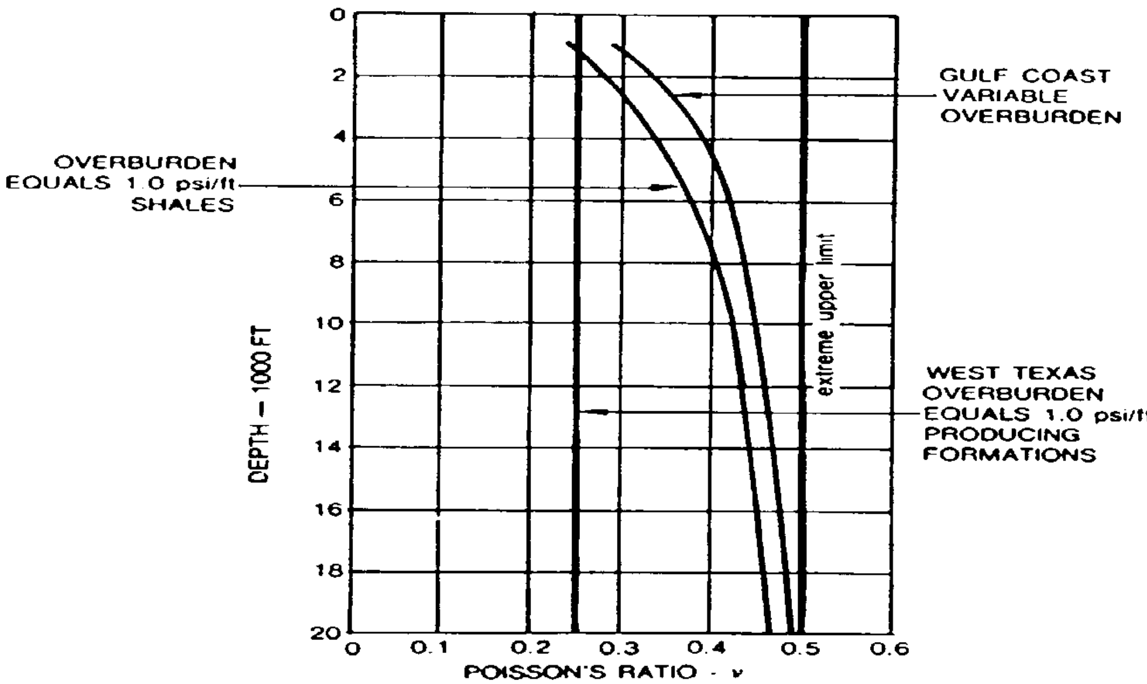

Fig 7: Poisson`s ratio