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Prediction of Fracture Pressure Gradient in Halfaya Oilfield

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Abstract

Fracture pressure gradient prediction is complementary in well design and it is must be considered in selecting the safe mud weight, cement design, and determine the optimal casing seat to minimize the common drilling problems. The exact fracture pressure gradient value obtained from tests on the well while drilling such as leak-off test, formation integrity test, cement squeeze ... etc.; however, to minimize the total cost of drilling, there are several methods could be used to calculate fracture pressure gradient classified into two groups: the first one depend on Poisson's ratio of the rocks and the second is fully empirical methods. In this research, the methods selected are Huubert and willis, Cesaroni I, Cesaroni II, Cesaroni III, Eaton, and Daines where Poisson's ratio is considered essential here and the empirical methods selected are Matthews and Kelly and Christman. The results of these methods give an approximately match with the previous field study which has been relied upon in drilling the previous wells in the field and Cesaroni I is selected to be the equation that represents the field under study in general. In the shallower formations, Cesaroni I is the best method; while in deepest formations, Eaton, Christman, and Cesaroni I are given a good and approximately matching. The fracture pressure gradient of Halfaya oilfield range is (0.98 to 1.03) psi/ft.

Keywords: fracture pressure, fracture pressure gradient, Halfaya oilfield.

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1- Introduction

Fracture pressure is the required injection pressure to rupture the formation. While penetrating an abnormal formation pressure, the mud density should be increased to maintain the well bore stability and continue safe drilling.

However, the mud pressure should remain below the pressure that causes formation damage; that's why the estimation of fracture gradient is complementary in well design. The underground stresses which resist formation fracture can be defined as σ_x , σ_y , σ_z as shown in **Fig. 1**

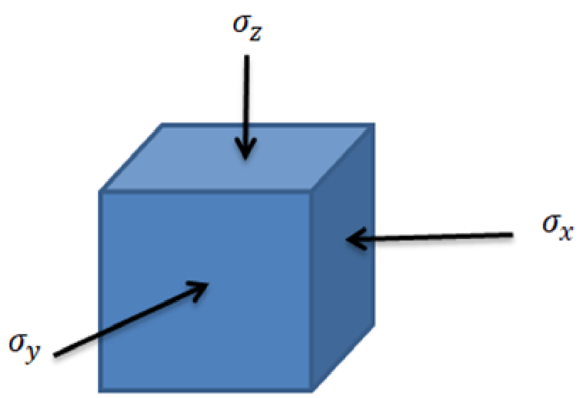

Fig. 1. Underground stresses [1].

The origin of these stresses is that; during sedimentation, grains will ensure one on the other; over time, and with continuing sedimentation the layers above a specific points causes an overburden pressure (σ) which is a combination of matrix weight and pressure of fluid within pores. Thus, the effective vertical stress (σ_z) is equal to overburden pressure above a specific point subtracted the pore pressure at this point from it. The increment of grain to grain loading due to the vertical stress will expand the grains laterally but, that prevented by the nearby grains so that horizontal stresses σ_x and σ_y will develop **[1]**. The fracture direction is perpendicular to the least stress axis. In tectonically relaxed areas, the least stress is the horizontal stress (σ_x or σ_y), therefore; the fracture direction will be vertical and the pressure causes this fracture is less than the overburden pressure; while in active tectonic areas, the least stress is the vertical (σ) which is the overburden pressure; the fracture will develop horizontally with injection pressure equal to or higher than the overburden pressure **[2]**.

The main objective of this study is determining the best empirical method that gives results of fracture pressure gradient approximated with the actual fracture pressure gradient derived from the previous studies and relied upon in drilling wells in this region.

2- Fracture pressure gradient estimation

The technique that can be taken to calculate the fracture pressure for a specific formation is in two steps;

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the first one is called predictive methods which depend on the empirical equation and data from the previous drilled wells, the second step is the actual field data after drilled the well and complete the necessary tests to record the actual fracture gradient for that formation**[1]**, **[3]**.

2.1. Predictive Methods

These methods required the estimation of the minimum stress value; according to Terzaghi's equation, the minimum effective stress value could be found from the following equation:

$$\sigma_3 = S_3 - P \tag{1}$$

Since the minimum stress (S_3) is the required value, equation (3-12) could be written in term of it as follow:

$$S_3 = \sigma_3 + P = K_3 * \sigma_z + P \tag{2}$$

To calculate the minimum stress (S_3) for a specific formation, the value of (K_3) which is the Ratio of the effective stresses (horizontal to vertical) should be estimated. There are two methods for K_3 estimating: (1) using of Poisson's ratio (2) empirical methods **[4]**.

a. Poisson's Ratio Methods

1- Hubbert and Willis method

Hubbert and Willis method in fracture pressure gradient estimation depends on three variables: pore pressure, overburden stress, and Poisson's ratio. Thus, Hubbert and Willis equation for estimating the fracture pressure gradient is as follow[2]:

$$\frac{P_W}{D} = \left(\frac{v}{1-v}\right) * \left(\frac{\sigma}{D} - \frac{P}{D}\right) + \frac{P}{D} \tag{3}$$

In their method, they assumed a constant overburden gradient equal 1 psi/ft and constant Poisson's ratio equal 0.25; therefore, their equation will be the equation (4):

$$\frac{p_w}{D} = \left(1 + \frac{2p}{D}\right) * \frac{1}{3} \tag{4}$$

In geolog software[4], there are two options available:

- Input Poisson's ratio value manually (Constant or Curve).
- Bounds values (minimum 1/3 and maximum 1/2).

If the second option is selected, a minimum and maximum fracture pressures gradient are estimated.

2- Cesaroni Method

Cesaroni method estimated fracture pressure gradient depending on the mechanical behavior of rocks, and there are three formulas available **[5]**:

- For elastic rocks behavior with little or no mud filtrate because of rapid mud cake forming or low permeable formation, the differential pressure is totally supported by the borehole wall. The fracture pressure gradient is estimating by the following equation:

$$\frac{P_W}{D} = \left(\frac{2*v}{1-v}\right) * \left(\frac{\sigma}{D} - \frac{P}{D}\right) + \frac{P}{D} \tag{5}$$

- For elastic rocks behavior with high mud filtrate invasion; the following equation is used:

$$\frac{P_W}{D} = 2 * v * \left(\frac{\sigma}{D} - \frac{P}{D}\right) + \frac{P}{D} \tag{6}$$

- For plastic rocks behavior like shale, marl, and salt; the equation of fracture pressure gradient is:

$$\frac{P_W}{D} = \frac{\sigma}{D} - \frac{P}{D} \tag{7}$$

3- Eaton Method

Eaton method for estimating fracture pressure gradient suggest the same equation of Hubbert and Willis method (equation (3)) but with variable Poisson's ratio modeled as a function of depth for Deep Gulf of Mexico and Shelf (shallow water) formations **[6]**.

4- Daines Method

Daines equation[7] is the same as Eaton equation (eq. (3)) by adding Superimposed tectonic stress term, the equation will be as follows **[7]**:

$$\frac{P_W}{D} = \sigma_t + \left(\frac{v}{1-v}\right) * \left(\frac{\sigma}{D} - \frac{P}{D}\right) + \frac{P}{D} \tag{8}$$

Daines suggested that the determination of σ_t from the first leak-off test while drilling and kept constant, the principle of the tectonic stress remaining constant in the entire well section. Therefore; in geolog software[4] σ_t is a function of effective vertical stress σ_z and can be expressed as the following equation:

$$\sigma_t = \sigma_z * \beta \tag{9}$$

Where: β is Daines tectonic stress factor, the final equation of Daines's method in geolog is as follow:

$$\frac{P_W}{D} = \beta * \left(\frac{\sigma}{D} - \frac{P}{D}\right) + \left(\frac{v}{1-v}\right) * \left(\frac{\sigma}{D} - \frac{P}{D}\right) + \frac{P}{D} \tag{10}$$

b. Empirical Methods

1- Matthews and Kelly Method

Mathews and Kelly developed Hubbert and Willis method by using a variable stress ratio between the effective horizontal and vertical stresses, not a constant value of 1/3 **[8]**.

To calculate a fracture gradient by this method one must use the following procedure:

- Estimate the formation pore pressure.
- Determine the effective stress. Since, the overburden gradient is equal to 1 psi/ft as their assumption, therefore; the effective stress calculated from the following equation:

$$\sigma_z = 1.0 * D - P \quad (11)$$

- Determine the depth Di which is the depth of the normal matrix stress (σ_z) from the following equation:

$$\sigma_z = 1.0 * D - 0.465 * D$$
$$D_i = \frac{\sigma_z}{0.535} \quad (12)$$

- Determine K_i from D_i value and Fig. **2**.
- Calculate the fracture pressure gradient from Matthews and Kelly method using the following equation:

$$\frac{P_w}{D} = K_i\left(\frac{\sigma z}{D}\right) + \left(\frac{P}{D}\right) \quad (13)$$

In geolog software [4], the overburden gradient could be calculated or put a fixed value equal 1psi/ft.

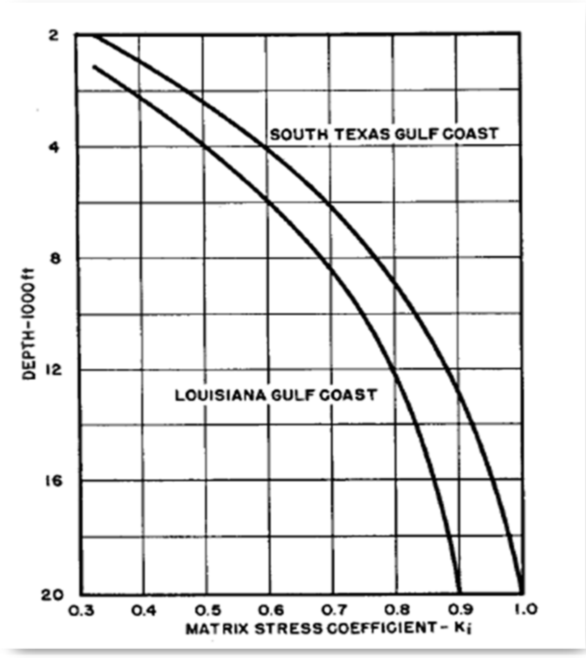

Fig. 2. Matrix stress coefficient of Matthews and Kelly method **[8]**

2- Christman Method

Christman method in prediction fracture pressure gradient depends on the empirical estimation stress ratio (K_c) ; thus, the fracture pressure gradient equation is **[9]**:

$$\frac{P_w}{D} = K_c\left(\frac{\sigma}{D} - \frac{P}{D}\right) + \frac{P}{D} \quad (14)$$

In geolog, the stress ratio estimation is valid either from density log or water depth.

2.2. Verification Methods

It is the actual value of fracture pressure for the next section obtained from the test at the casing shoe of the previous section after it had been cemented; the important of that test is to verify that the cement of casing and the formation below can endure the wellbore pressure required to complete drilling safely to the next target depth **[1]**.

Formation integrity test (FIT) is usually used to identify the fracture gradient for a specific formation; In fact, FIT has more than meaning including:

- Limit test which is carried out to a specific point below the fracture pressure of that formation.
- Leak off test which is carried out to the point that the formation leak off.
- Formation breaks down test which is carried out to the point that the formation fracture.
- Fracture gradient test it is Continue after the formation fracture, the importance of this test is to determine the minimum horizontal stress of earth.

The full FIT gives a complementary fracture data of the formation **[3]**.

3- Area of Cases Study

The area under study represent by Halfaya oilfield; it was discovered since 1976 by well (HF-1). The structure was defined by 2D seismic data shot during 1976 and 1980. Up to June 2010, eight wells were drilled by Missan Oil Company (MOC). The deepest well (HF-2) reached a depth of 4788m, down to the Lower Cretaceous Sulaiy formation. Significant oil accumulations have been discovered in multiple reservoirs of Tertiary and Cretaceous formations and the re-estimated initially oil in place is about 18.179 billion barrels in June 2017. The methods are applied by using logs and drilling data of HF010-N010.

4- Calculations

The general fracture pressure gradient equation required two inputs which are overburden pressure gradient and pore pressure gradient; the overburden pressure gradient is the pressure exerted, on a specific point, by the total weight of both the rock's grains and fluids within the pores. The density of the combination is called the bulk density (ρ_b). The overburden pressure gradient varies with depth because of the variations of formation density; this is a result of the variations in the types of rocks, the densities of fluids, and the compaction degree of rocks **[11]**.

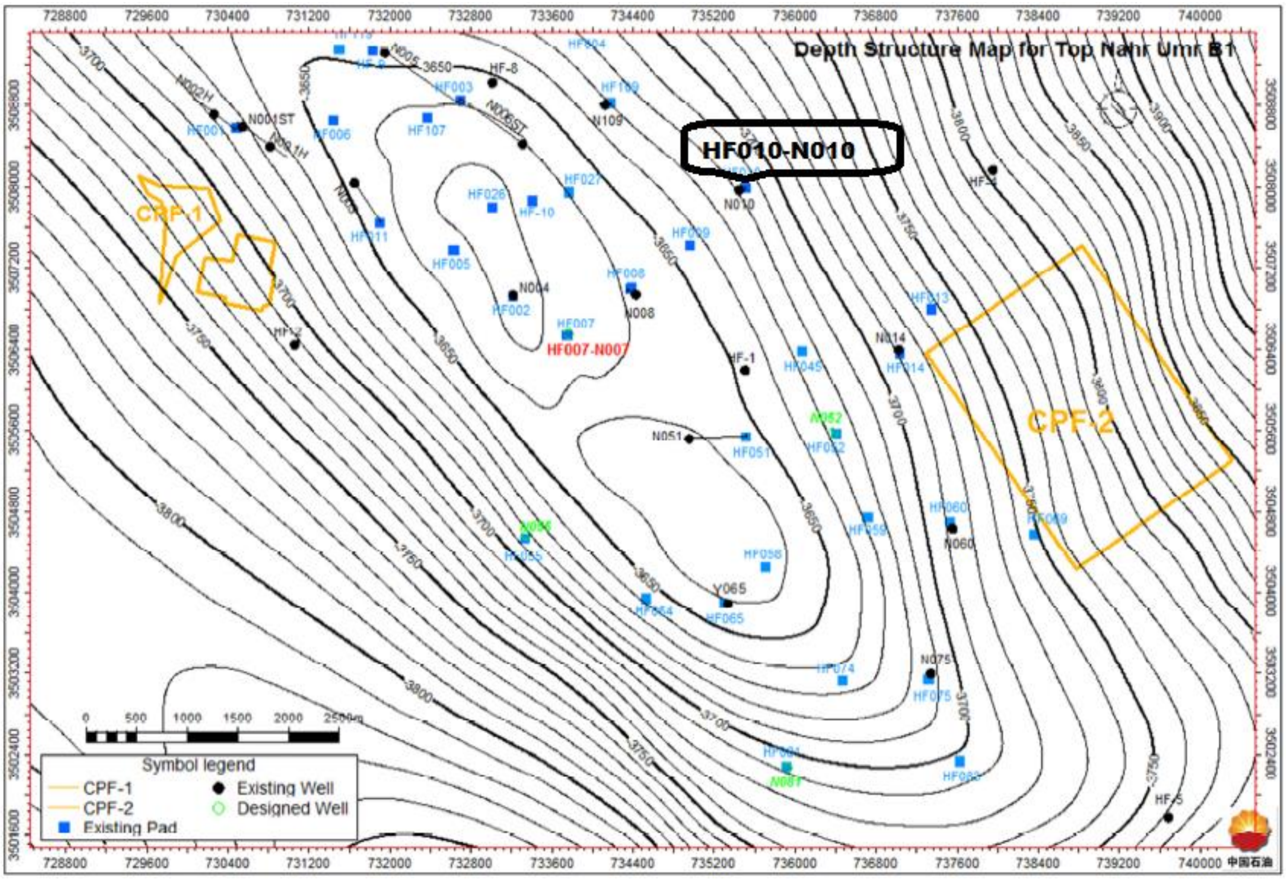

Fig. 3. HF010-N010 location in the top of Nahr Umr B structural map, Halfaya oilfield **[10]**.

In geolog software[4], the overburden pressure module computes overburden pressure from integrating bulk density log values over depth by the following equation:

$$PRESS_{OB} = air\ press + water\ press + 0.4334 * \int_0^D \rho_b(D)\, dD \quad (15)$$

Where the water pressure is used for only offshore situation, and the 0.4334 factor is used for converting density (g/cc) to pressure, air pressure is calculated in an onshore situation using equation (16).

$$Air\ press = (ELEV_{MEAS_{REF}}) - (SURFACE_{ELEV}) * 0.001 * 0.4334 \quad (16)$$

The pore pressure gradient is estimated by Eaton's method using dc-exponent data as the following equation **[12]**:

$$\frac{P}{D} = \frac{S}{D} - \left[\frac{S}{D} - \left(\frac{P}{D}\right)_n\right]\left(\frac{dco}{dcn}\right)^{1.2} \quad (17)$$

If density log information is not available for all intervals, it is often estimated from sonic transit time (P-wave velocity); in IP software there are three methodologies those of Gardner **[13]** Bellotti et al **[14]** and Lindseth **[14]** and the following equations represent these methods respectively:

$$\rho_b = a{v_p}^b \quad (18)$$

Where: a and b are constants

$$\rho_b = 3.28 - \Delta t/89 \quad (19)$$

$$\rho_b = 2.75 - 2.11(\Delta t - 47)/(\Delta t + 200) \quad (20)$$

Where, eq. (19) is for consolidated formations and eq. (20) for unconsolidated formations.

$$\rho_b = (v_p - 3400)/(0.308 * v_p) \quad (21)$$

Overburden gradient could be calculated for any point by dividing the overburden pressure of this point by its depth. The Poisson's ratio can be measured in laboratory either by dynamic method using pules velocities of longitudinal and shear waves which are called the indirect method or directly by static method **[16]**; if the core sample is not available for a specific interval, it can be calculated either from velocities, VpVs ratio, or using moduli (bulk modulus and shear modulus). Geolog software provides the possibility of estimating it from compressional transit time (Δt), shear transit time (Δts), and bulk density (ρ_b). Then the following equation is used in calculation **[4]**:

$$v = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)} \quad (22)$$

When Δts data is not available for a specific depth, it could be estimated from compressional transit time using the Greenberg-Castagna empirical relationships for different minerals in IP software as follow **[17]**:

$$V_S = a.V_P^2 + b.V_P + c \quad (23)$$

Where: a, b, and c are constants depending on the lithology of the intervals.

5- Results

The methods result approximately match the results of the previous study (Field Development Plan Revision No.1 of Halfaya Contract Area, Iraq/ by PetroChina Company for Missan Oil Company) **[10]** which have been relied upon in drilling the previous wells, the results are inserted in Fig. **4** and Fig. **5**.

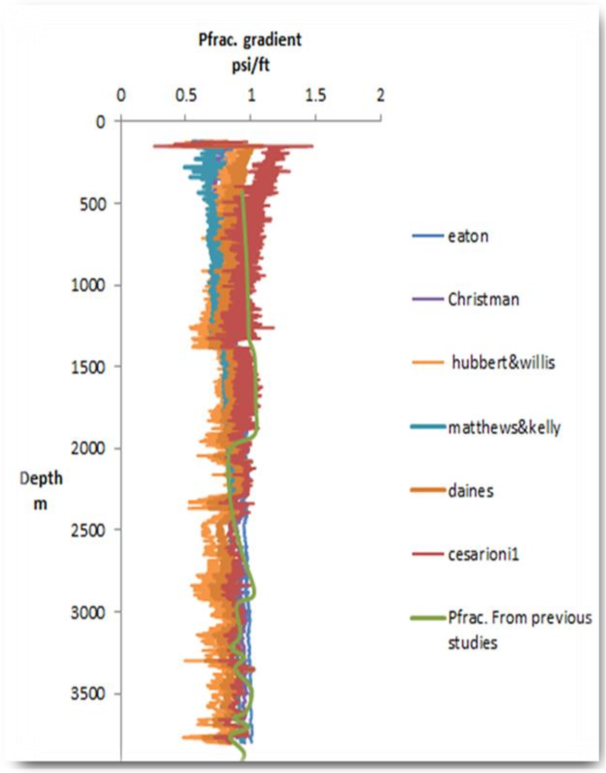

Fig. 4. Comparison between methods selected to estimate the fracture pressure gradient in Hafaya oilfield

Fig. **4** shows that, as the comparison with the actual fracture pressure gradient (a study by PetroChina company for Missan Oil Company[10] which is current practice in the oilfield, the green curve),

Hubbert and Willis method which is the orange curve gives the lowest value, the results of Daines method (the brown curve) and Mathews and kelly method are low, the results of Eaton and Christman methods at the deepest formations (about 2000 m and deeper) are given a good match, and Cesaroni I which is represented by equation (5) is given the best match for all formations.

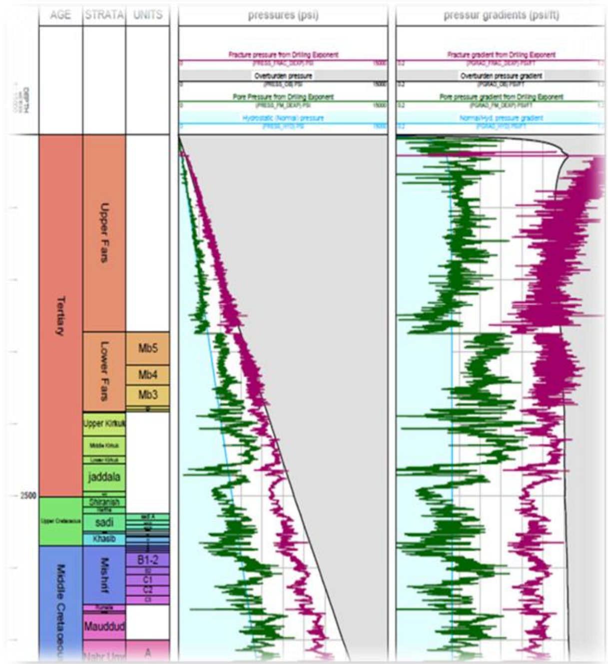

Fig. 5. Hydrostatic, overburden, pore and fracture pressures and their gradients of Halfaya oilfield (HF010-N010) (fracture pressure gradient by Cesaroni I).

In Fig. **5**, the pore pressure gradient (the green curve) is estimated by Eaton method using dc-exponent data and the fracture pressure gradient (the purple curve) is estimated empirically using Cesaroni I method which gives a good match as mentioned in Figure (4); and the results fracture pressure gradient for Halfaya oilfield are summarized as follow:

- The fracture pressure gradient of Upper Fars formation ranges (0.9-1.0) psi/ft.
- The fracture pressure gradient of Lower Fars formation is equal (1.0) psi/ft
- Fracture pressure gradients of Upper Kirkuk, Middle Kirkuk, and Lower Kirkuk are equal (0.95) psi/ft.
- The fracture pressure gradient of Jaddala formation reduces to (0.85) psi/ft; since it is an abnormally low-pressure formation.
- The fracture pressure gradient of the deepest formations (Shiranish, Hartha, Tanuma, Khasib, Mishrif, Rumaila, Ahmadi, Mauddud, and Nahr umr) ranges (0.8- 0.9) psi/ft.

6- Discussion

The best method in estimating fracture pressure gradient to avoid problems develop in a formation and design an optimal drilling fluid program with right casing seat is that the leak-off test which is the only one that gives an exact value of the fracture pressure gradient.

However, for economic reasons the empirical methods are the alternative selection, every method have a weak point must be taken into account and they are summarized as follow:

- Hubbert and Willis's method imposes a constant overburden pressure gradient and constant Poisson's ratio and these assumptions are inaccurate, the overburden pressure gradient showed in Figure (5) is vary and increase with depth; also, Poisson's ratio depends on the type of rocks in the formations; so that, it gave incorrect results as compared with the actual fracture pressure gradient.
- Matthews and Kelly method suggest a constant overburden pressure gradient equal (1.0) psi/ft which is the same assumption as Hubbert and Willis method and this method is not applicable in abnormal high pressure formations because the stress ratio used in formations with high pore pressure is equal the normal pore pressure in deepest depth and in this area (Halfaya oilfield) we have an abnormally high-pressure formations such as Lower Fars and Mishrif formations as shown in Fig. **5**.
- Christman method depends on empirical techniques in estimating stress ratio which adds a percentage of inaccuracy.
- The tectonic stress factor in Daines method is assumed.
- In Eaton's method, Poisson's ratio modeled as a function of depth for Deep Gulf of Mexico and Shelf (shallow water) formations and it may be equivalent to the formation under study or not.

7- Conclusions

In this work, the methods of Huubert and willis, Cesaroni I, Cesaroni II, Cesaroni III, Eaton, and Daines were selected. Also, Poisson's ratio was considered crucial and the empirical methods selected are Matthews and Kelly and Christman. The following conclusions were driven from the study:

1- Cesaroni I give the best results of the fracture pressure gradient in Halfaya oilfield as the comparison with previous field study (Field Development Plan Revision No.1 of Halfaya Contract Area, Iraq/ by PetroChina Company for Missan Oil Company).
2- The fracture pressure gradient is directly proportional to the pore pressure gradient.

Nomenclature

Symbols	Description	unit
Air PRESS	air pressure	psi
D	Depth	m
d	Drilling exponent	-
dc	Correct drilling exponent	-
dcn	Normal dc	-
dco	Observed dc	-
$DEPTH_{BML}$	Mean sea level depth	m
D_i	Depth of normal matrix stress	ft
$ELEV_{MEAS_{REF}}$	Elevation of measurement reference	m
GR	Gamma ray	GAPI
K_3	The ratio of horizontal effective stress to vertical effective stress	-
K_i	Matthews and Kelly matrix stress coefficient	-
P	Pore pressure	psi
p_w	Fracture pressure	psi
$PRESS_{HYD}$	Hydrostatic pressure	psi
$PRGRD_{water}$	Water pressure gradient	Psi/ft
S	In-situ stress	psi
S_3	Minimum in-situ stress	psi
$SURFACE_{ELEV}$	Elevation of drilling surface	M
V_p	Compressional velocity	ft/us
V_s	Shear velocity	ft/us
Water press	Water pressure	psi
Greek Symbols	Description	unit
σ	Vertical stress (overburden pressure)	psi
σ_x	Horizontal effective stress in x direction	psi
σ_y	Horizontal effective stress in y direction	psi
σ_z	Vertical effective stress	psi
σ_3	Minimum effective stress	psi
σ_t	Superimposed tectonic stress	psi
v	Poisson's ratio	-
Δt	Sonic compressional transit time	us/ft
Δt_s	Shear transit time	us/ft
β	tectonic stress factor	-
ρ_b	Bulk density of rock	gm/cc

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التنبؤ بتدرج ضغط التكسير في حقل حلفايه النفط

الخلاصة

يعتبر التنبؤ وتقدير تدرج ضغط التكسير عملا مكملاً في تصميم البئر ويجب أن يؤخذ بنظر الاعتبار عند اختيار وزن طين الحفر الآمن وتصميم الأسمنت وتحديد مقعد التغليف الأمثل لتقليل مشاكل الحفر الشائعة. قيمة التدرج الدقيق للكسر الناتجة من الفحوصات التي تجرى على البئر أثناء الحفر مثل leak–off test ، formation integrity test ، cement squeeze ... الخ ؛ ومع ذلك ، لتقليل التكلفة الإجمالية للحفر ، هناك عدة طرق يمكن استخدامها لحساب تدرج ضغط الكسر المصنفة في مجموعتين: الأولى تعتمد على نسبة بواسون للصخور والثانية هي طرق تجريبية بالكامل. في هذا البحث ، الطرق المختارة هي Huubert and willis, Cesaroni I,: Cesaroni II, Cesaroni III, Eaton, and Daines حيث تعتبر نسبة بوايسون ضرورية هنا والأساليب التجريبية المختارة هي Matthews & Kelly و Christman وتعطي نتائج هذه الطرق تطابقًا تقريبًا مع الدراسة الميدانية السابقة التي تم الاعتماد عليها في حفر الآبار السابقة في الحقل وتم اختيار Cesaroni I لتكون المعادلة التي تمثل الحقل تحت الدراسه بصوره عام في الطبقات ذات الاعماق الضحله ، ان طريقة Cesaroni I هي الافضل ؛ بينما في الطبقات العميقه فإن كل من طريقة Eaton, Christman, و CesaroniI تعطي تطابق جيد ومتقارب. ان تدرج ضغط التكسير في حقل حلفايه النفطي يتراوح بين (0.98 و 1.03) psi/ft.