Pore Pressure Gradient Prediction for Deep Well/ Southern Iraq Oilfield

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A B S T R A C T

Pore pressure prediction is crucial for drilling success and is a critical component of the 1D-MEM. It helps estimate in-situ horizontal stresses and predict the safe mud weight window for stable wellbore drilling. This study was conducted in deep well X, Field "H" in Southern Iraq, where wellbore instability causes high non-productive time and high costs of laboratory tests to measure pore pressure. Open-hole log measurements, including gamma ray log, density log, shear sonic log, compressional sonic log) to calculate vertical stress, shear stress, and formation water pressure . The Yamama Formation showed abnormal pore pressure Its value is 10285 psi compared to other formations whose value is less than 7581 psi. The Bowers original method was found to be more accurate than Eaton's method, as it failed to predict abnormal pore pressure based on the results of comparing both methods with laboratory results. Therefore, the study recommends using the Bowers original method for pore pressure calculations.

التنبؤ بتدرج ضغط المسام لبئر عميق في حقل جنوب العراق

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الملخص

يُعدّ التنبؤ بضغط المسام أمرًا بالغ الأهمية لنجاح الحفر، وهو عنصر أساسي في نموذج 1D-MEM فهو يساعد في تقدير الإجهادات الأفقية في الموقع، والتنبؤ بنافذة وزن الطين الآمنة لحفر بئر مستقر. أُجريت هذه الدراسة في البئر العميق X، الحقل "H" في جنوب العراق، حيث يُسبب عدم استقرار البئر وقتًا غير مُنتج طويلًا وتكاليف عالية للاختبارات المعملية لقياس ضغط المسام. تم استخدام قياسات سجل الآبار المفتوحة، بما في ذلك سجل أشعة جاما، وسجل الكثافة، وسجل الموجات الصوتية القصية، وسجل الموجات الصوتية الانضغاطية، لحساب الإجهاد الرأسي، وإجهاد القص، وضغط مياه التكوين. أظهر تكوين اليمامة ضغطًا مساميًا غير طبيعي، حيث تبلغ قيمته 10285 رطل/بوصة مربعة، مقارنةً بتكوينات أخرى تقل قيمتها عن 7581 رطل/بوصة مربعة. وُجد أن طريقة باورز الأصلية أكثر دقة من طريقة إيتون، حيث فشلت في التنبؤ بضغط المسام غير الطبيعي وذلك اعتماد على نتائج المقارنة بين كلتا الطريقتين وبين نتائج المختبر. لذلك، توصي الدراسة باستخدام طريقة باورز الأصلية لحساب ضغط المسام.

1. Introduction

Pore pressure (Also known as formation pressure) refers to the pressure acting on fluids trapped in the pores of rocks. Pore pressure (Pp) carries part of the vertical stress, whereas rock grains [1] hold the other part. It is a crucial factor in drilling plan, petroleum production, and geomechanical modeling and geological analyses .It significantly affects both the wellbore's deformation and the stability analysis of the drill hole [2] .The accuracy in prediction of pore pressure is a substantial for operation for minimizing the time to treatment the borehole problems and avoid drilling incidents such as stuck pipe, kicks of wells, loss of circulation, blowout, lost hole and any single or combination of these problems increase the non-productive time and

therefore the total cost of drilling if not dealt professionally[2]. The diacritical pore pressure in shale formation may be determined using sonic and resistivity logs [2].Pore pressure is classified into three classes according on its magnitude, as follows:

Normal pore pressure: This is the pressure generated by the fluid column from the formation's surface to the bottom, and it varies based on the kind of fluid, temperature gradient, gases present, and dissolved solids content, therefore, it is not constant.

Abnormal pore pressure is defined as any pore pressure larger than the forming water's hydrostatic pressure. The abnormal pressure is thought to be produced by increased hydrostatic pressure

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Subnormal Pore Pressure: The formation pressure for the stated depth is lower than the hydrostatic fluid pressure.

Pore pressure prediction has important implications in determining the success of a drilling activity. Information of subsurface pore pressure prediction in hydrocarbon exploration and production is very important. For a geologist, this information can be used to determine of hydrocarbon generation and maturation within a basin, while for Petroleum engineer pore pressure prediction is very important to maintain the production rate and for drilling engineer this information is useful for mud weigh and casing designs prior drilling activities to prevent blowout. In this study, an accurate method is found for predicting pore pressure because high cost of using laboratory tests such as (repeated formation test) to measure it, so we chose other less expensive methods, and Also the accurate values are used to help future researchers building the geo-mechanical model and calculating the rock properties and far-field stresses, and thus the safe mud weight window is predicted to prevent wellbore instability and prevent many drilling problems such as kicking, blowout and loss of drilling fluid and pipe sticking which causes high non-productive time (NPT).

2. Area of the Study and its Geological Setting

H oilfield is one of the largest mature oilfields in southern Iraq. The oil-bearing formations of the H oilfield include the Tertiary Jeribe and Upper Kirkuk; Upper Cretaceous Hartha; Tanuma; Khasib; Mishrif & Nahr Umr; and Lower Cretaceous Yamama. It is established that water is available in Middle Kirkuk. In this study we estimated vertical stress and shale flag and Formation water pore pressure to calculated pore pressure for deep formation /(X) well. The study section of H oilfield is starting from Mishrif Formation (+/-2916 m) to Yamama Formation at about depth (+/-4413 m) ,which Which include this formations (Mishrif A, Mishrif B1, Mishrif B2, Mishrif C2 ,Mishrif C3, Rumaila, Ahmadi, Mauddud, Nahr-UmrA ,Nahr-Umr B, Shauiba, Zubair, Ratawi ,Yamama).

3. Methodology

The first step in calculating pore pressure for deep formations by used Techlog software, starting from the Mishrif formation (+/-2916 m) to Yamama Formation at about depth (+/-4413 m), involves gathering data from the relevant oil field, such as (gamma ray log, density log, shear sonic log, compressional sonic log) and measured data (Repeat Formation Test (RFT)) for validated. The second step is to calculate vertical stress using the density log. The third step involves calculating the shale flag using the gamma ray log and calculating Formation water pore pressure. The final step is to use Eaton's method and the original Bowers method to calculate pore pressure and verify the results by employing the Repeat Formation Test to validate or calibrate the two methods.

3.1 Overburden stress, Also known as vertical stress (Sv), is the pressure put on a point by the weight of formations that are below it and contain fluid. One of the principal strains is vertical stress, which points in the direction of the earth's core. The depth-dependent propagation of overburden pressure results in an increase in sediments [3] the overburden stress (S_v) can be estimate from Eq.1. The average formation bulk and pore pressure gradient may be used to compute the overburden stress [3].

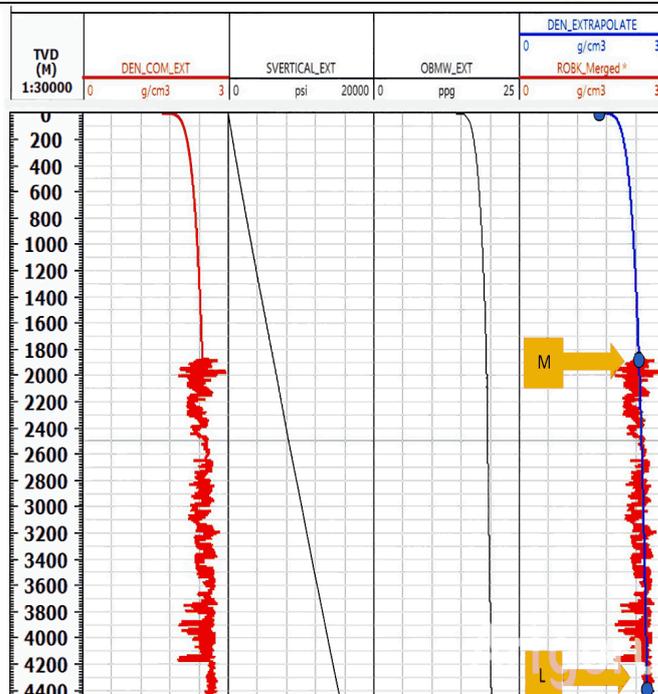$$Sv = \int_0^z \rho g\,(z)dz \quad (1)$$

Where,

G: Acceleration by gravity (m/s²).
Z: Formation depth (m).
S_v: Overburden pressure (psi).
ρ: Rocks' overall density.

Fig. 1: Vertical stresses profile integrated from bulk density for well X.

3.2 Mechanical Stratigraphy (Shale flag)

It used differentiate between shale formation and non-shale formation [4]. The profile of shale flag was calibrated with pore pressure taken from permeable layers by using repeated formation tests (RFT) of formation test (red circle in fourth track) and show good agreement as illustrated in Fig.2.
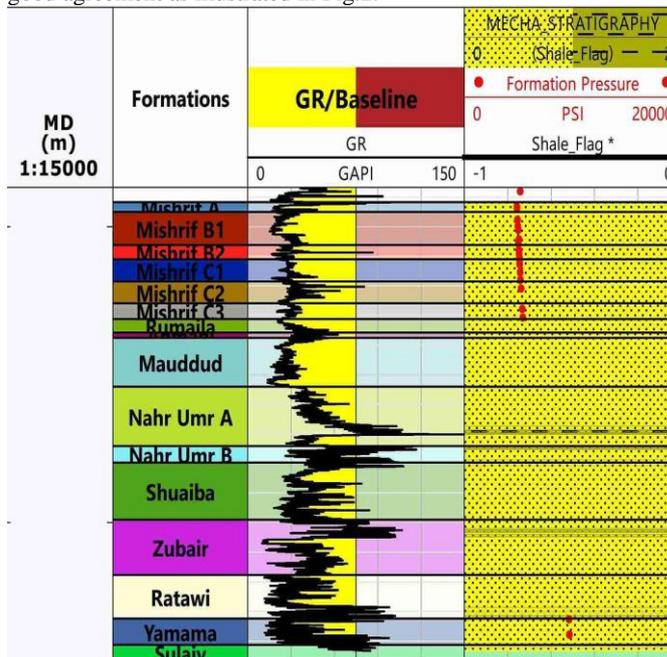
Fig. 2: Shale flag profile calibrated by pore pressure points for well X.

3.3 Formation water pore pressure (Pw), ((Hydrostatic pressure)

The Formation water pore pressure (Pw), [5], represents the mean weight of the formation water weight along the column (z). Salinity is assumed the primary factor influencing water density, with temperature and pressure having minimal effect. In this study, Equation (2) is utilized to determine formation water pore pressure.

$$P_w = \int_0^z \rho_w\, g\, dz \qquad (2)$$

Where: g represents gravitational constant (9.8 m/sec²), ρw refers to the water density (g/cm³), and z is the dense water column (m).

Water density, on the other hand, is greatly impacted by salinity, therefore it may be regarded a function of salinity, while having a

modest effect with changes in pressure and temperature and is usually ignored [6], as seen in Fig.3.
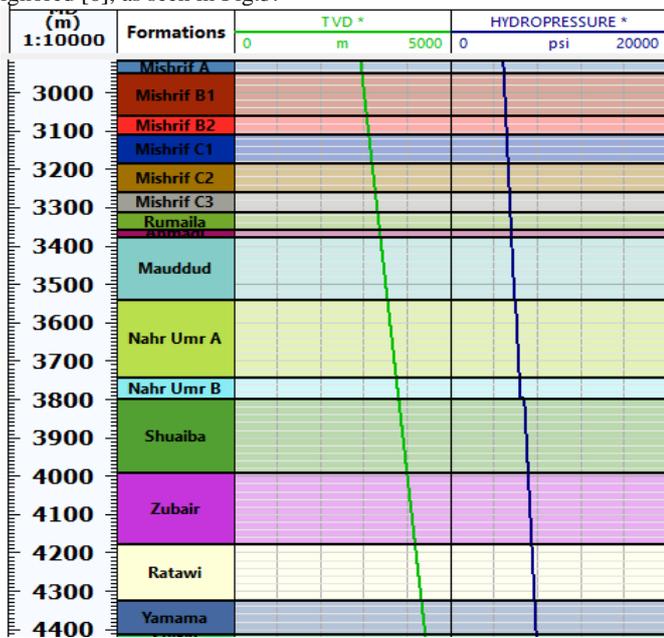

Fig. 3: Estimated Formation water pore pressure profile of well X.

4. Pore pressure estimation
There are two methods for determining pore pressure: direct and indirect methods.

4.1. Direct methods.
In permeable formations, methods like Drill Stem Testing (DST), Repeated Formation Testing (RFT), and Modular Dynamic Formation Tester (MDT) can be used to determine the normal pore pressure of the formation [7]. The Repeat Formation Tester (RFT) (and its more advanced versions like the MDT - Modular Formation Dynamics Tester) measures pore pressure by:
1. Sealing against the Formation: The RFT/MDT tool is lowered into the borehole to the desired depth. A probe or packer is extended to isolate a small section of the wellbore wall against the formation. This creates a pressure-tight seal.
2. Drawing Fluid: A small amount of fluid (typically a few cubic centimeters) is drawn from the formation into the tool through the probe. This creates a slight pressure drop in the isolated zone.
3. Pressure Buildup Measurement: The tool then monitors the pressure buildup within the isolated zone as fluid flows back into it from the surrounding formation. The rate and characteristics of this pressure buildup are analyzed.
4. Pore Pressure Determination: By extrapolating the pressure buildup curve to infinite time (theoretically), the undisturbed pore pressure of the formation at that depth can be estimated.
In essence, the RFT/MDT creates a tiny, controlled drawdown and then observes the formation's response as it returns to equilibrium, allowing for the determination of the undisturbed pore pressure, [8].

4.2 Indirect methods
This methods commonly used because the direct methods are costly, risky, time-consuming and provide a poor measure in some intervals. Furthermore, direct methods cannot be used to quantify pore pressure in shale (impermeable zone) or clay rocks, [9]. Therefore, geophysical measurement is used to provide a continuous profile of pore pressure along the interval of interest, then to minimize suspicion in the determined pore pressure can by matching with point of formation pressure which measuring by direct method. In addition, calibrated profile for direct pressure measurements to minimize suspicion in the determined pore pressure [10].
The most popular indirect methods for determining pore pressure in the oil industry is the Eaton's method and Bower's method.

4.2.1 Eaton (1975) presented general equation form as expressed in Eq.3, which utilized in this study to calculate the PP for the non-shale zone [10]. The slight deviation between projected pore pressure and actual formation pressure is regarded as realistic.
In this study, the profile of normal pressure (Hydrostatic pressure, Ph) was calculated using the Eq.2, and the profile of geo-pressure was

calculated using the Eaton method (1969), [11] which expresses by Eq.3. The linear interpolation method, on the other hand, was used to predict the pore pressure in permeable limestone (production section) as shown in Fig.4 under the name (PPRS EATON S), and the resultant profile was calibrated against actual pressure point measurements from indirect methods to minimize the uncertainty of the estimated pore pressure) as shown in Fig.4 under the name (formation pressure).

$$Pp = \sigma v - (\sigma v - Ph) * a * \left(\frac{\Delta tnorm}{\Delta t}\right)^n \qquad (3)$$

Where,
ρw: the water density (g/cm^3),
g: gravitational constant (9.8 m/sec^2),
z: the dense water column (m).
Δt: is the slowness from sonic log in shale formation.
"a" & "n": are fitting factors; Eaton factor and Eaton exponent, respectively. The default values are a=1 and n=3.
Ph: is the hydrostatic pressure.
Δt_{Norm}: Is the normal slowness in shale formations.

4.2.2 Bower's method was introduced by Bowers 1995; this method considers two main mechanisms as a source of overpressure generation: compaction disequilibrium and unloading due to fluid expansion. In compaction disequilibrium conditions, Bowers (1995) used the following equation:

$$v_p = v_0 + A \, \sigma_e \, B \qquad (4)$$

Where, v_p is the velocity at a given depth and v_0 the surface velocity (normally 5000 ft/sec), σ_e is the vertical effective stress A and B are the parameters calibrated with offset velocities versus effective stress data. In unloading conditions, Bowers (1995) proposed the following empirical relation:

$$v_p = v_0 + A \, [\sigma_m a \, (\sigma_e/\sigma_{max})^{1/U}]^B \qquad (5)$$

Where, U is the unloading parameter, σmax is the maximum effective stress and, vp, $v0$, σe, A and B are same as above. Both methods of Bowers have been applied on our available data (Fig.4) with $v0$= 5000 ft/s, Bowers A =4.457 & B = 0.8. [12].
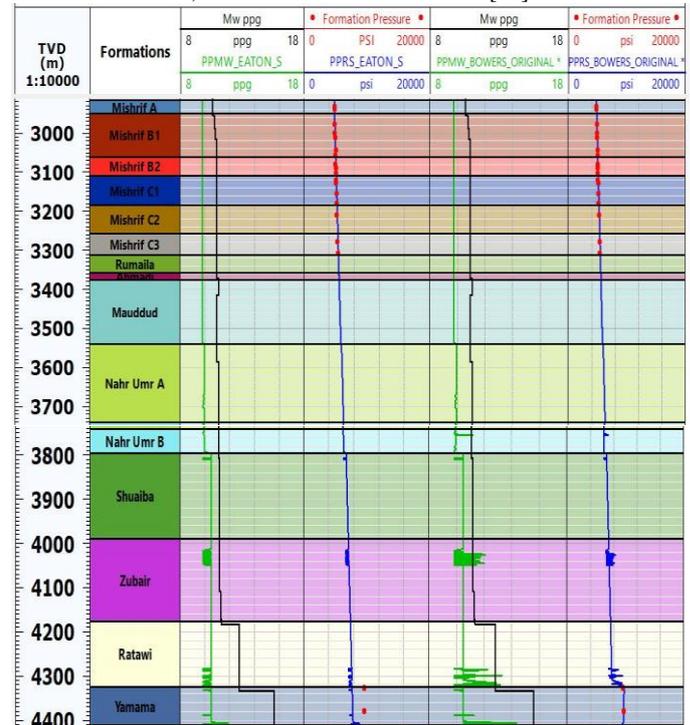

Fig. 4: Estimated pore pressure profile by Bower's original method and Eaton method of X.

5.   Results and Discussion

Pore pressure, vertical stress, shale flag, and formation water pore pressure change as a function of depth. The results appeared as follows based on the Fig.4 and Table 1:

- Yamama formation of the southern Iraqi oilfield is an abnormal pore pressure formation; On the contrary, other formations are natural pressure formations.

- Furthermore, the computed MW profile (PPMW_EATON_S) was calibrated against the actual mud weight values utilized to drill the examined intervals for X by decreasing the MW from Eaton's approach such that it does not exceed the actual MW from the final geological report, as shown in track 5 of (Fig.4). Mud weight should always be greater than pore pressure to limit or prevent the onset of instability problems during drilling, such as rock collapse.

- In Fig.4, a good match is shown between the pore pressure calculated by the Bower's original method (blue line in the last track) and the RFT (red dots), especially in the Mishrif and Yamama formations.

- In Fig.4, there is a good agreement between the pore pressure calculated by the Eaton method (blue line in the fourth track) and the RFT (red dots), especially in the Mishrif Formation, while there is no agreement in the Yamama Formation, Eaton method does not predict the abnormal pore pressure because it highly sensitive to the accurate definition of the normal compaction trend, where errors lead to significant prediction inaccuracies. It primarily identifies overpressure from disequilibrium compaction, often failing to account for other mechanisms like clay diagenesis or fluid expansion. The method relies on an assumed constant empirical exponent, which can vary with geological conditions and introduce error. Its effectiveness is Also limited in complex, heterogeneous formations and high-temperature environments where rock behavior becomes non-linear.

Table 1: Pore Pressure Prediction by Eaton and Bowers methods

Formation	σv(Psi)	Pp by Eaton(Psi)	Pp by Bowers(Psi)
Mishrif A	10048	5000	5008
Mishrif B1	10240	5000	5008
Mishrif B2	10600	5000	5008
Mishrif C1	10784	5367.2	5370
Mishrif C2	11000	5400	5402
Mishrif C3	11398	5400	5402
Rumaila	11400	5400	5402
Ahmadi	11442	5568	5571
Mauddud	11870	5800	5803
Nahr Umr A	12579	6197.9	6198.1
Nahr Umr B	13000	6217.4	6218.2
Shuaiba	13470	7000	7003
Zubair	14166	7377.2	7379
Ratawi	14693	7574	7581
Yamama	15086	8256	10285

6.   Conclusions

This study was conducted to assess pore pressure across the time extending from the Mishrif formation to the Yamama formation,. The following conclusions were reached:

- In this location, the overburden pressure gradient varies and increases with depth.

- A good match was obtained between the rock mechanical parameter calculated by correlations and measured data (core mechanical laboratory tests (triaxle test), repeated formation tests (RFT), and mini-fracture testing).

- The Eaton method measures the natural pressures of the formations, so there is a difference between measuring the pressure using the RFT test and the Eaton method in the Yamama Formation, as the RFT test measures the pressures of the formations regardless of the type of pressure, while the Eaton method only measures the natural pressures of the formations.

- The Yamama Formation is considered a high-pressure formation

- The Bowers original method is better than the Eaton method for calculating pore pressure because it predicts abnormal pore pressure and highly accurate as it accounts for the non-linear relationship between velocity, effective stress, and overburden pressure, especially in high-pressure environments. It effectively models overpressure generated by multiple mechanisms, including both disequilibrium compaction and fluid expansion/chemical processes. The method incorporates variable exponents that are calibrated to specific geological settings, providing greater flexibility than constant-exponent approaches. This allows for more reliable predictions in complex formations Therefore, future researchers are advised to rely on the Bowers method to calculate the pore pressure used in other calculations, such as predicting the safe mud weight window.

7.   References

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