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PORE PRESSURE PREDICTION AND COMPARTMENTALIZATION OF THE TERTIARY OIL RESERVOIRS FROM SONIC LOG IN THE KHABBAZ OIL FIELD, NORTHERN IRAQ

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Key words: Pore Pressure; Sonic Log; Eaton Methods; Khabbaz Oil Field; Tertiary Reservoirs.

ABSTRACT

The Tertiary oil reservoirs in the Khabbaz Oil Field comprise the Jeribe, Anah, Azkand, and Ibrahim formations. This study aims to manage unpredicted pressure changes that occur in wells drilled in the carbonate reservoirs, which are potentially dangerous and financially cost during petroleum exploration. It has studied from pore pressure and reservoir compartmentalization points of view. Eaton method has been used to predict the pore pressure from the sonic log data. The basic assumption for this technique is the interrelation between observed transit time from log reading and normal transit time that locates on the normal compaction trend (NCT). The bulk density is determined from sonic log and has a good match with the bulk density derived from the density log. It shows that the sonic log can be used as a good alternative to obtain the bulk density and consequently to determine lithostatic pressure. Pore pressure depends upon changes in the overburden gradient. Based on predicted pore pressure, the studied reservoirs compartmented into four pressure zones. The number of the zones is identified by using a graphical method of probability plot of the predicted pore pressure on the basis of cluster analysis. All reservoirs are assumed to be overpressured zone. According to predicted pore pressure, the Azkand Formation is the most potential reservoir because it has the highest-pressure value measured from the top of the Azkand Formation to the bottom of the Ibrahim Formation. Direct relation between pressure, temperature and thickness of hydrocarbon zones (oil and gas) gives indications that most of the studied reservoirs are of good productivity at primary recovery stage.

التنبؤ بضغط المسام وتقسيم الخزانات النفطية للعصر الثلاثي بأستخدام التسجيل الصوتي في حقل خباز النفطي، شمال العراق

حسين سعاد حسين

المستخلص

ان المكمن الثلاثي في حقل خباز النفطي يتألف من التكاوين التالية: الجريبي وعنه وازقند وابراهيم. تهدف هذه الدراسة إلى التنبأ بتغييرات الضغط غير المتوقعة التي تحدث في الآبار التي يتم حفرها في خزانات الصخور الجيرية، والتي من المحتمل أن تكون خطرة ولها تكاليف مالية خطيرة أثناء التنقيب عن النفط. لقد تم دراسة وتقسيم هذا المكمن من ناحية الخصائص المتعلقة بضغط المسام استخدمت طريقة ايتون للتنبؤ بضغط المسام من بيانات التسجيل الصوتي. تفترض هذه الطريقة أن العلاقة بين زمن انتقال الموجة (المرصود من قراءة المجس) وزمن انتقال الموجة الطبيعي يتمثل بموقع

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اتجاه الضغط العادي (NCT). تم تحديد الكثافة الكلية من التسجيل الصوتي وكان هناك تطابق جيد مع الكثافة الكلية المقاسة من سجل الكثافة. أن التسجيل الصوتي يمكن أن يكون بديلا جيدا للحصول على الكثافة الكلية، وبالتالي تحديد ضغط الغطاء الصخري. ان ضغط المسام يعتمد على التغيرات في ضغط الغطاء الصخري. اعتمادا على الضغط المسامي المتوقع، فقد تم تقسيم المكامن المدروسة الى اربع وحدات من الضغط، فضلا عن تحديد عدد من المناطق لضغط المسام المتوقع باستخدام طريقة الرسم لمخطط الاحتمالية وفق اسس التحليل العنقودي. ان جميع اجزاء المكمن يفترض فيها ان تكون منطقة ضغط زائد متوافقة مع ضغط المسام المتنبئ به. بينت نتائج الدراسة ان تكوين ازقند يعد مستودعا واعدا كون ان القيمة الاعلى للضغط توزعت من أعلى جزء فيه وصولا الى قاع تكوين ابراهيم، وأن العلاقة التناسبية بين الضغط ودرجات الحرارة وسمك النطاق الهايدروكاربوني بمحتواه النفطي والغازي قد أعطت مؤشرات ودلالات مفادها أن معظم اجزاء المكمن التي تم التحري عنها تعد ذات انتاجية جيدة وفي مرحلة الاسترجاع الاولي.

INTRODUCTION

Unpredicted pressure changes (i.e. abrupt onset of overpressure) occur in wells drilled in the carbonate reservoirs, creating potentially dangerous situations if not properly identified, understood, and managed. Overpressure in the Khabbaz Oil Field has not been mapped. Baban and Hussein (2016) reported several petrophysical properties of the Tertiary reservoirs except pressure regime in the field. The overpressure studies initially focus on describing the pressure mechanisms in the field including location, magnitude, and depth. However, faults in the field are assumed to be either dynamic (allowing gas/ fluid to migrate through) or static (not allowing gas/ fluid to migrate); but the supposition that all faults behave the same way is unreasonable and improbable (Richards *et al*., 2008). Increased understanding of the geological context and contributing factors to the overpressure in pressure cells or compartments can reduce drilling and environmental risks and financial costs during petroleum exploration. Pressure is an important fluid characteristic that is mostly used in pursuit to estimate the level of reservoir zonation and clarify the location of compartment boundaries throughout the appraisal and production of hydrocarbon reservoirs (Jolley *et al*., 2010).

The zonation of hydrocarbon segregation into various individual pressure zones happens when a flow interferes with 'sealed' boundaries in the reservoir (Jolley *et al*., 2010). These boundaries are caused by an assortment of geological and liquid dynamic influences, yet there are two fundamental categories: 'static seals' that are absolutely sealed and adequate for trapping hydrocarbon column over geological time and 'dynamic seals' which are of very low permeability flow that diminish hydrocarbon cross flow to significantly slow rates (Jolley *et al*., 2010). The dynamic seals enable liquids and pressures to equilibrate across a boundary over geological time-scales, but go about as seals over generation time-scales, since they anticipate cross flow at typical production rates, with the end goal that liquid contacts, saturation and pressures continuously isolate into 'dynamic' zones (Jolley *et al*., 2010). In this way, reservoir zonation impacts the volume of moveable oil or gas that maybe associated with any given well drilled in a field, which confines the volume of the reservoir that can be 'reserved' for that field. These reservoir compartments are established in this study on the basis of predicted pore pressure for all the reservoirs. Reservoir pressure distribution in the Kabbaz Oil Field is important from economic, environmental, and drilling safety perspectives. This study investigates the subsurface pressure distribution and reservoir connectivity in the field.

GEOLOGICAL SETTING

The Khabbaz Oil Field is located in Kirkuk Governorate, about 20 Km SW Kirkuk City between Bai Hassan and Jambour oil fields. Tectonically, it is located in the Foothill Zone (Fig.1). It extends parallel to the Kirkuk Oil Field, about 23 Km SW of Baba Dome and covers approximately 72 Km^2. A total of 22 wells of all types have been drilled since 1976. According to the classification of Al-Mehaidi (2009) for the Iraqi oil fields, it is considered as one of the big productive oil fields in the northern part of Iraq and the field is expected to contain about 500 – 1000 million barrels of oil reserve within two main reservoir packages known as the Cretaceous and Tertiary reservoirs.

This study focuses on the Tertiary reservoirs in the Khabbaz Oil Field. The Tertiary reservoirs in this field include the Middle Miocene Jeribe Formation in addition to the Oligocene Anah, Azkand, and Ibrahim formations as determined by the Northern Oil Company (NOC) geologists (Baban and Hussein, 2016). The depth intervals and thickness of the studied formations in well Kz-16 are shown in Table 1. The lithological composition of the studied formations in well Kz-16 is illustrated in Fig.2.

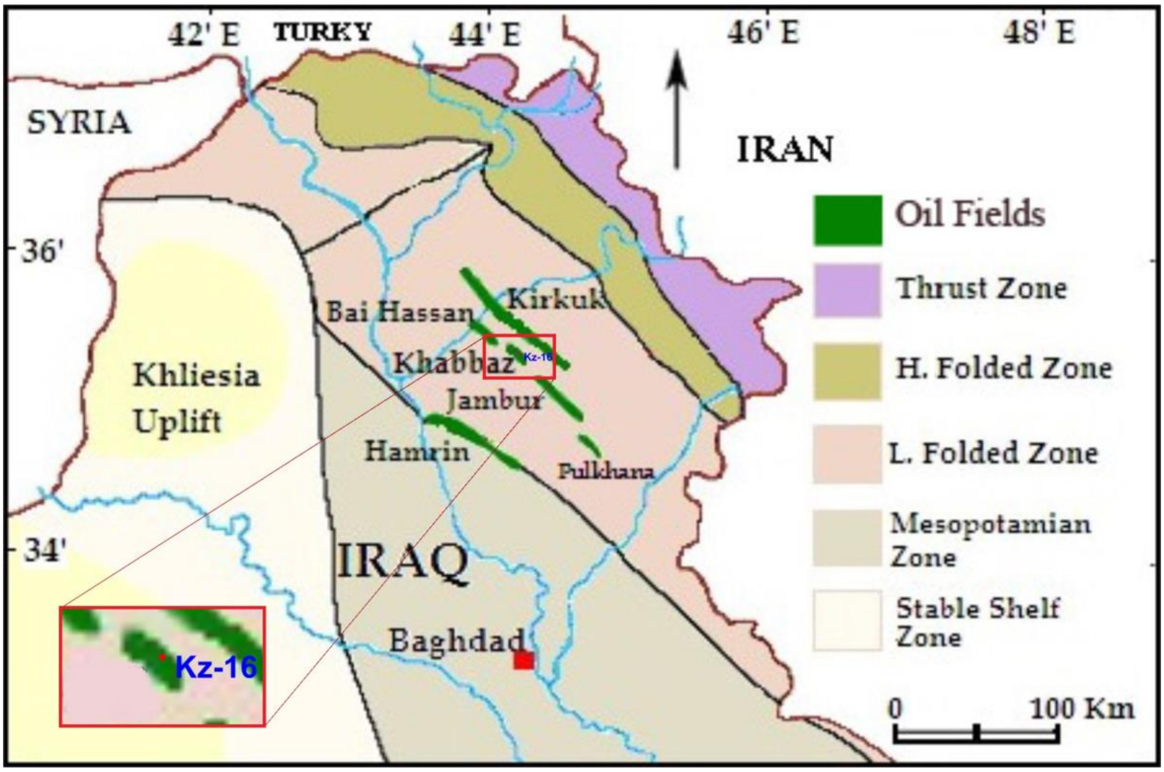

Fig.1: Tectonic and location map of the Khabbaz Oil Field
(after Buday and Jassim, 1986)

Table 1: Depth intervals and thicknesses of the Jeribe, Anah, Azkand, and Ibrahim formations in well Kz-16

Formation	Depth interval (m)	Thickness (m)
Jeribe	2145 – 2158	13
Anah	2158 – 2195	37
Azkand	2195 – 2281	86
Azkand/ Ibrahim	2281 – 2312	31

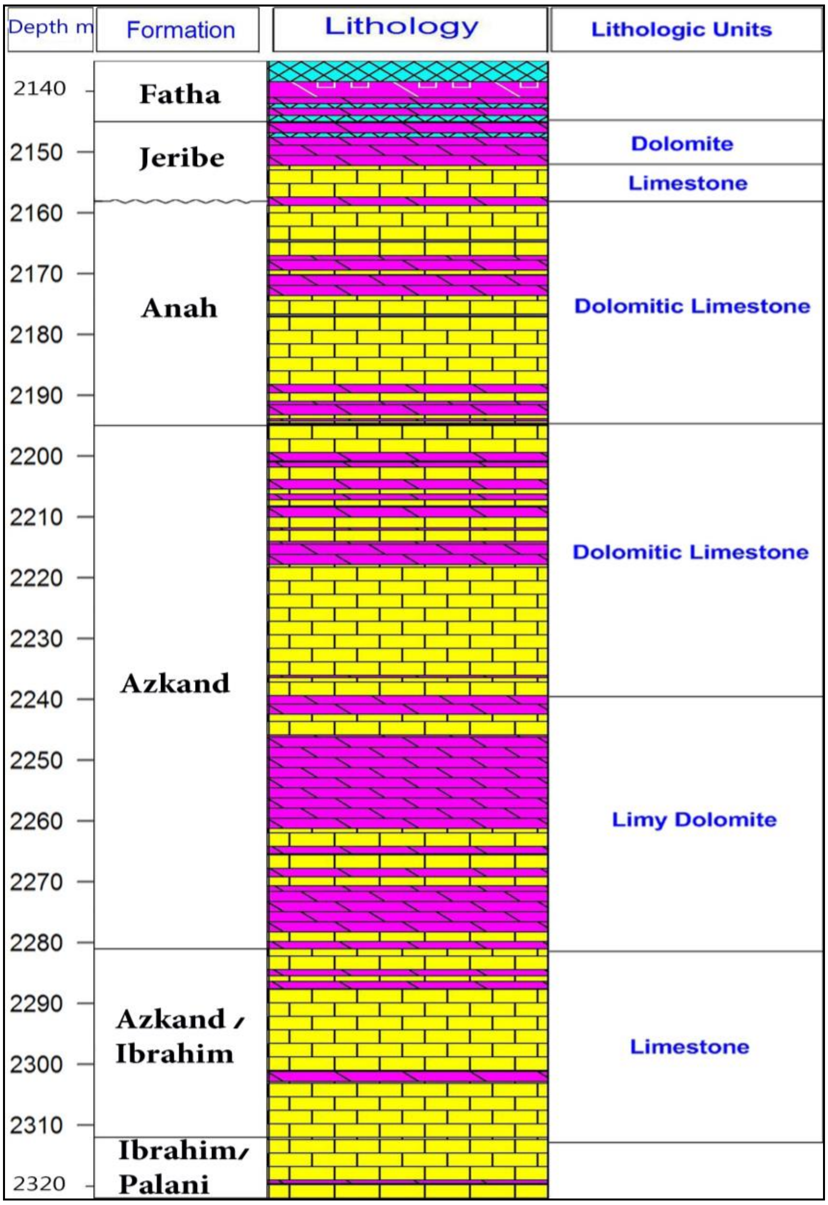

Fig.2: Lithological column of the studied formations in well Kz-16
(after Baban and Hussein, 2016)

- **Jeribe Formation**

The Jeribe Formation is generally described as organic detrital limestone and demonstrates a heterogeneous formation. It was defined by Bellen (1957, in Bellen *et al*., 1959) from the type locality near Jaddala village in Jabal Sinjar. The formation presumed to be Early Miocene age. However, the formation was later included within the Middle Miocene sequence (Jassim and Buday, 2006). A Middle Miocene age is indicated by the presence of the *Orbulina* datum near the base of the formation (Prazak, 1974). The Jeribe Formation in the Khabbaz Oil Field is overlain by the transition beds of the Fatha Formation and underlain unconformably by the Anah Formation (Baban and Hussein, 2016). Buday and Jassim (1986) suggested that the Jeribe Formation was deposited in lagoonal, backreef, and reef environments.

- **Anah Formation**

The Anah Formation was defined for the first time by Bellen in 1956 in the Euphrates valley; west of Al-Nahiyah village close to Anah town (Bellen *et al*., 1959). A supplementary type section was studied in Qara Chuqh anticline. In the type locality section, it is composed of gray, brecciated, recrystallized, detrital, and coralline limestone beds, but in the supplementary type section, it consists of gray, dolomitized, and recrystallized limestone beds, massive in the lower part, becoming thinner bedded upwards. The formation is mostly a reef deposit, alternating with backreef, miliolid facies. The Anah Formation in the study area is overlain by the Jeribe Formation and underlani by the Azkand Formation (Baban and Hussein, 2016).

- **Azkand Formation**

The Azkand Formation was defined by Bellen in 1956 in the Azkand cirque of the Qara Chuqh structure in which it is comprised of about 100 m thick massive, dolomitic, and recrystallized, generally porous limestone (Bellen *et al*., 1959). The formation is of forereef facies. The lower contact with the Baba Formation is unconformable in the type area. The Azkand Formation in the Khabbaz Oil Field is overlain by the Anah Formation and underlain by the Ibrahim Formation. As the lower contact of the formation with the Ibrahim Formation cannot be easily distinguished, therefore, the interval between both formations is named as Azkand/ Ibrahim in the final reports of the wells drilled in the field. Accordingly, the same informal name of Azkand/ Ibrahim Formation has been used in this study to describe the beds which are neither proper Azkand nor proper Ibrahim Formation but are a transition between both (Baban and Hussein, 2016).

- **Ibrahim formation**

The Ibrahim Formation was defined by Bellen (1957, in Bellen *et al*., 1959) from well Ibrahim-1 in the Sheikh Ibrahim structure of the Foothill Zone, NW of Mosul. It comprises 56 m of globigerinal marly limestone with specks of pyrite and occasional glauconite and fauna of planktonic foraminifera. It was deposited in a basinal environment and has been provisionally assigned a Late Oligocene age. Ibrahim Formation in the studied area is overlain by the Azkand Formation and underlain by the Middle Oligocene Palani Formation (Baban and Hussein, 2016).

MATERIALS AND METHODOLOGY

On the basis of comparison of undercompacted shale with normally compacted shale, there are many different methods of estimation, including Eaton, Ratio and Equivalent Depth. This needs the precise determination of Normal Compaction Trends (NCT) and assumes the direct relationship between the porosity and the pressure anomaly. Eaton's Method is generally accepted as being the most applicable in most regions of the world and is, therefore, widely used in the industry. The advantage of Eaton's Method is that it can be modified, based on regional experience to provide an accurate model throughout (Hawker, 2001).

Entire pore pressure prediction methods are based on the postulation that pore pressure impacts compaction-dependent shale properties like porosity, density, and sonic interval transit time. The effective stress approach is the most superior standard to use in an entirely distinct desirable manner (Azadpour and Manaman, 2015). Therefore, most pore pressure predictions depend on Terzaghi (1943) equation (Equation 1) that reveals the relationship between overburden pressures (S), pore pressure (P), and effective stress (σ). Terzaghi Equation is amplified to solid rock as:

$$P = S + \sigma \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

HYDROSTATIC PRESSURE

Hydrostatic pressure is a function of fluid density and the height of the fluid column. It can be expressed by equation No. 2:

$$P = \rho * g * h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 2$$

where:
P: hydrostatic pressure, **kilopascal (Kpa), where** pound per square inch (psi) = 6.9 kpa; ρ: fluid density, psi/ft; h: height of the fluid column, ft; g: gravity acceleration, N/kg

The average hydrostatic pressure of the study area was determined by the Northern Oil Company (NOC) as 10.5 Kpa. Pressure is also frequently expressed in terms of a pressure gradient, which is a function of the fluid density and depth. It can be expressed by equation No. 3:

$$P = (P2 - P1) / (D2 - D1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3$$

where:
P2 and P1: are the different pressures measured at depths D2 and D1, respectively.

LITHOSTATIC PRESSURE

Lithostatic pressure is the combined weight per unit area of the overlying sediments and fluids at a specified depth. It is also commonly referred to as overburden, overburden pressure, overburden stress, or Sv (vertical stress) and can be calculated by equation No. 4:

$$S = \rho_b * TVD * 9.81 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 4$$

Where:
S: lithostatic pressure (Kpa); ρ_b: average bulk density (gm/cc); TVD: true vertical depth from datum (m).

The bulk density is a function of the rock matrix, fluid densities, and porosity. The bulk density from density log can be used, but this study attempts to examine all parameters from sonic log including the bulk density which is expressed by equation No. 5:

$$\rho_b = 3.28 * \Delta T / 89 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 5$$

where:
ρ_b: bulk density (gm/cc); ΔT: interval transit time (usec/ft).

The result of the bulk density from sonic log has a good match to the bulk density from the density log (Fig.3). It shows that the sonic log can be a good alternative to obtain the bulk density and consequently to determine lithostatic pressure. The significance of lithostatic pressure to pressure evaluation is two-fold as follows (Skinner, 2016).

a- When the pore pressure reaches lithostatic pressure, all the weight of the overburden is being supported by the fluid; therefore, there is effectively no matrix support. If the rock is unconsolidated, grain-to-grain cohesion will be rejected; the rock will then behave as a non-Newtonian liquid. If the rock is consolidated, the increasing fluid pore pressure typically induces hydraulic fracturing before lithostatic pressure is reached (depending on the tensile strength of the rock).
b- Most methods for estimating pore pressure in shales use the lithostatic pressure as an input; therefore, the more precise it can be calculated, the more confidence is in the pressure prediction.

Eaton (1972, 1975) used to predict the pore pressure from sonic log data. This method assumes the relationship between the observed transit time from log reading parameter and normal transit time that locates on the NCT parameter. Pore pressure depends upon changes in the overburden gradient. In the shale region, firstly, the NCT should be built as early in the well as possible. Secondly, draw the normal compaction seen through zones of normal formation fluid pressure for the area (Fig.4). Where pore pressure gradually rises through a transition zone, directing into the main overpressured zone. It can be represented by equation No. 6:

$$P/d = S/d - (S/d - P/d_n) * (\Delta T normal/\Delta T\ observed)^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

where:

P/d: Pore pressure gradient (Kpa/m); S/d: Overburden pressure gradient (Kpa/m); P/d_n: Normal pore pressure gradient (Kpa/m); ΔT normal: (shale) interval transit time (usec/ft); ΔT observed: interval transit time value where the isodensity line will be plotted (usec/ft)

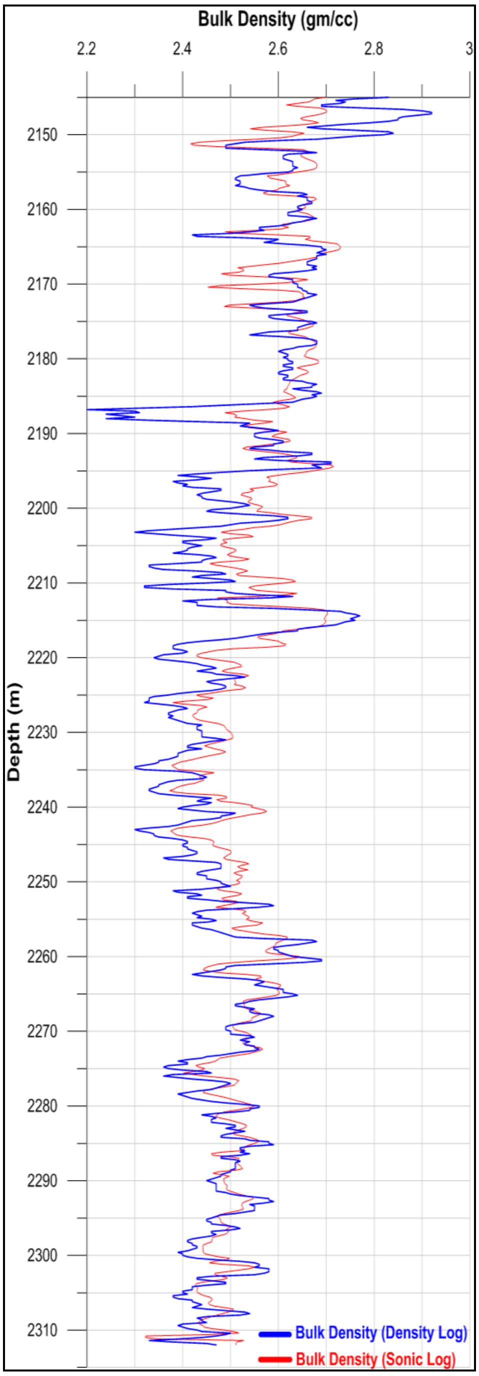

Fig.3: Comparison between the bulk density from sonic log and the bulk density from density log

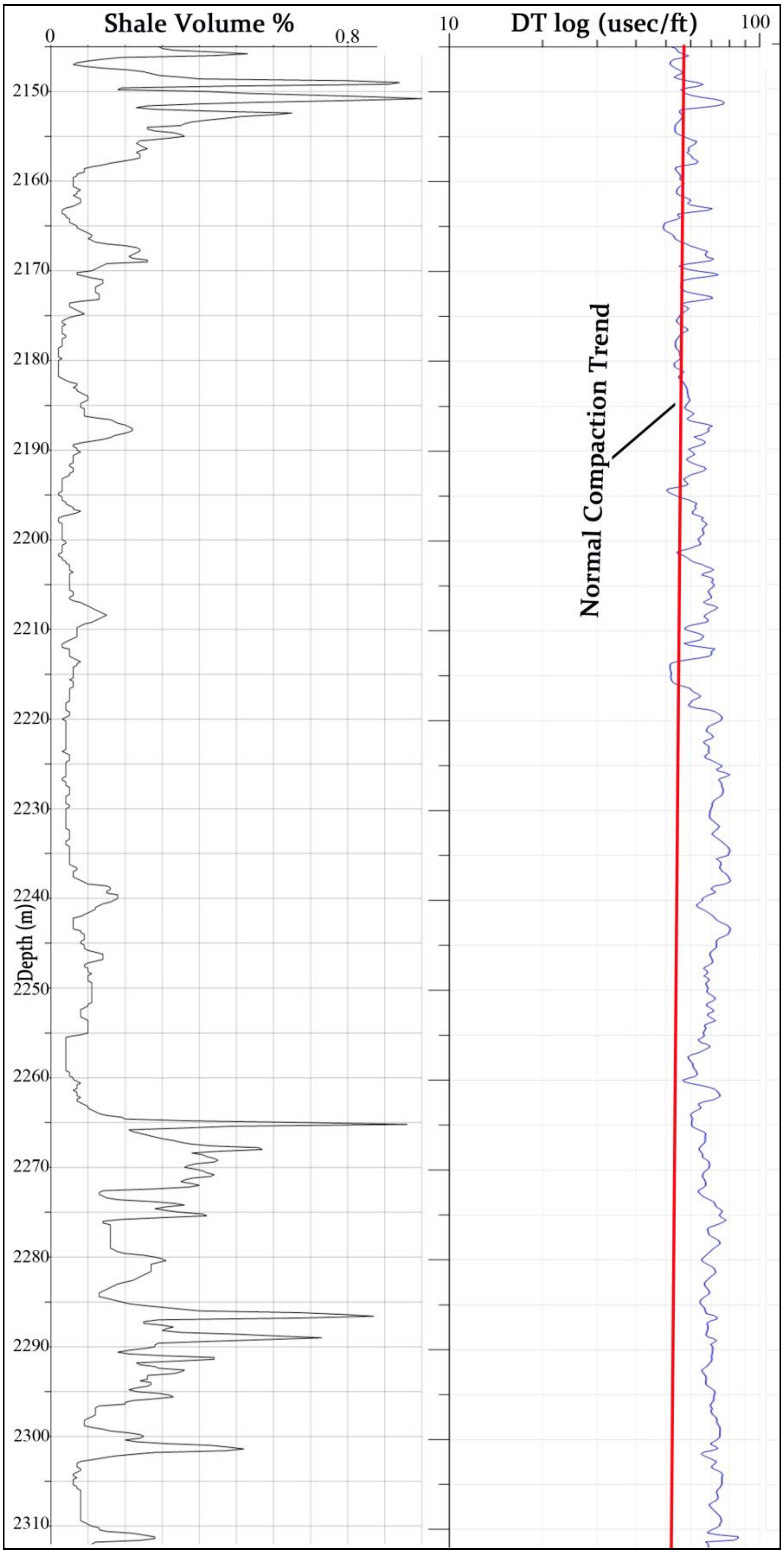

Fig.4: Shale volume and normal compaction trend for the studied reservoirs

FRACTURE PRESSURE

Any rock has a finite strength that is dependent on its lithology/composition, stress condition, and existing weaknesses (i.e., faults or fractures). The amount of pore pressure of the rock can tolerate before failure is the fracture pressure. Above this, the minimum stress exceeds the tensile strength of the rock. Determining the fracture gradient requires data on the stress conditions existing in the formation. The stresses are a function of the tectonic and sedimentation histories of the region during the formation of the basin. Three principle stresses that act on the rock orthogonal to each other at depth (Fig.5) (Skinner, 2016).

Fracture gradient estimates are fundamental to predict the pressure required to hydraulically fracture a formation. Eaton's (1969) method constructs the theory established by Hubbert and Willis (1957) and assumes that rock deformation is plastic. Accordingly, the Poisson's ratio and overburden vary with depth. Poisson's ratio has to be derived from regional data for fracture pressure, pore pressure, and overburden pressure according to equation No. 7:

$$F/d = (S/d - P/d) * (\mu / 1-\mu) + P/d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 7$$

where:

F/d: Fracture gradient (Kpa/m); P/d: Pore pressure gradient (Kpa/m); S/d: Overburden pressure gradient (Kpa/m); μ: Poissons ratio

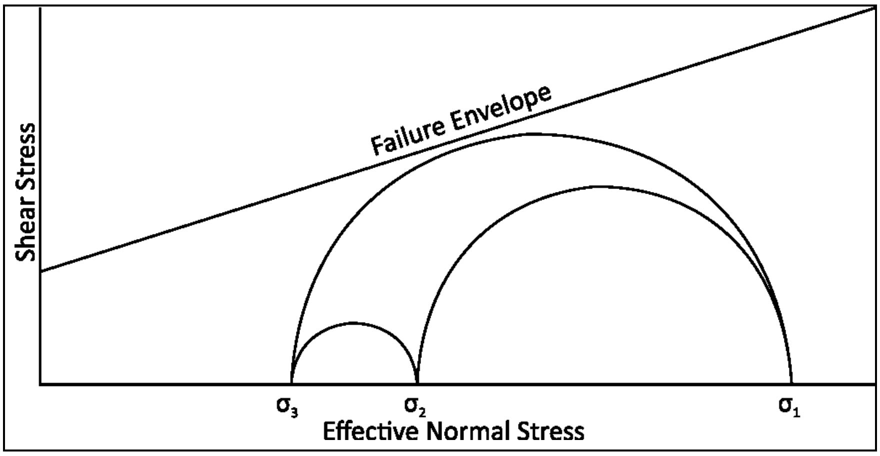

Fig.5: A diagram showing the three principles stresses that act on the rock orthogonal to each other at depth (Skinner, 2016)

Eaton's (1969) method is furthered by Anderson *et al*. (1973), who calculated Poisson's ratio based on shale index (Ish) derived from Gamma ray log (Fig.4) according to equation No. 8:

$$Ish = (GR_{log} - GR_{min}) / (GR_{max} - GR_{min}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 8$$

Where:

GR_{log}: Average gamma over selected depth interval

GR_{min}: Minimum gamma from given formation or geological period

GR_{max}: Maximum gamma from given formation or geological period

$$\mu = A * Ish * B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 9$$

Where:

μ: Poissons ratio

Ish: Shale index

The constant A and B relate to a plot of Poisson's ratio against shaleness index (Biot, 1955), defining the gradient and Y-axis intersection (Fig.6).

A = gradient of line = 0.05 / 0.4 = 0.125
B = Y - axis intersection = 0.27

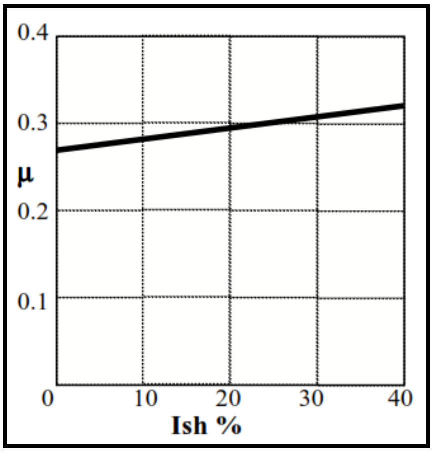

Fig.6: Plot of Possison ratio (µ) against shaliness index (Ish) (Biot, 1955)

RESULT AND DISCUSSION

Carbonate reservoirs ensured within the overpressure zone will behave reservoir potential with considering the role of carbonates as cap rocks or permeability barriers. Figure 2 shows an anhydrite bed in the Fatha Formation, which is located above the older Tertiary reservoirs.). Reservoirs are enclosed system due to entrapment by a cap rock (Fatha Formation) and containing a given fluid volume (Fig.7), which causes the system to be potential and become overpressurized (Fig.8). Accordingly, most of the pore pressure across the studied reservoirs is overpressured, but the magnitude of this pressure is variable. Many factors affected these variations, such as temperature, permeability, porosity, fluid movements, and fluid types.

The reservoir is compartmented into four reservoir pressure zones. The number of the reservoir pressure zones is identified, using a graphical method of probability plot of the predicted pore pressure on the basis of cluster analysis and the range of pore pressure for each reservoir pressure zone was identified by colored dots (Fig.9). The best pressure zones are zone two and three, which have good and high-frequency values. The pressure of the both mentioned zones is mostly located in the Anah and Azkand formations. The most important zone is zone three, which is mostly located within Azkand Formation and has a pressure range of 38 – 47 Mpa for the studied reservoirs. So, according to Figures 8 and 9, the Azkand Formation has the best reservoir potentiality. Anah and upper part of Azkand/ Ibrahim formations have a good reservoir potential compared to Jeribe and the lower part of Azkand/ Ibrahim formations. In addition to reservoir study, it is very important to use pore pressure datato properly plan drilling a well, both safely and economically. The isodensity lines (Fig.8) are also vital because they allow mud densities to be optimized to provide sufficient balance against pore pressure.

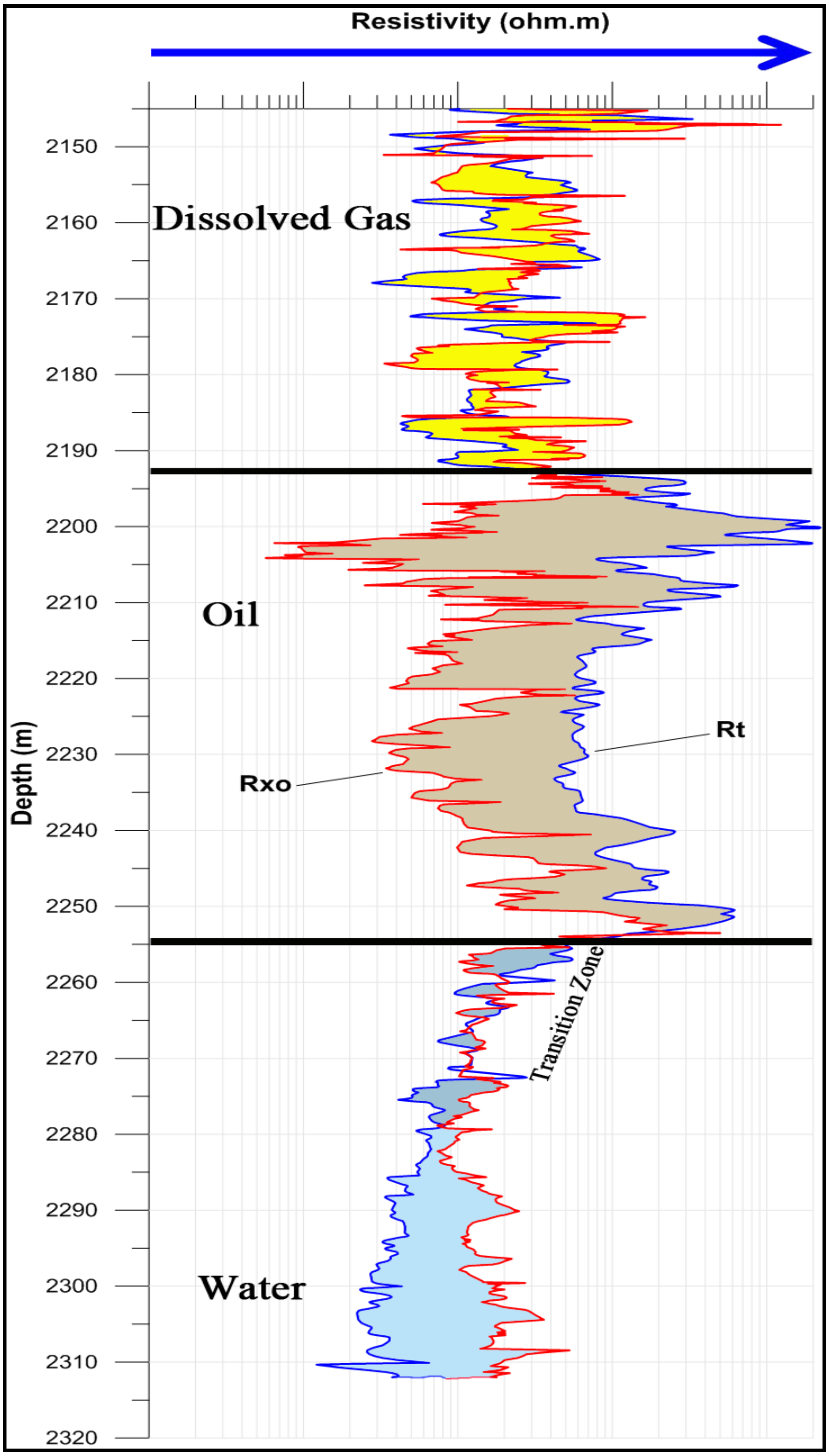

Fig.7: Fluid contacts for the studied reservoirs from resistivity of flushed zone (Rxo) and resistivity of uninvaded zone (Rt)

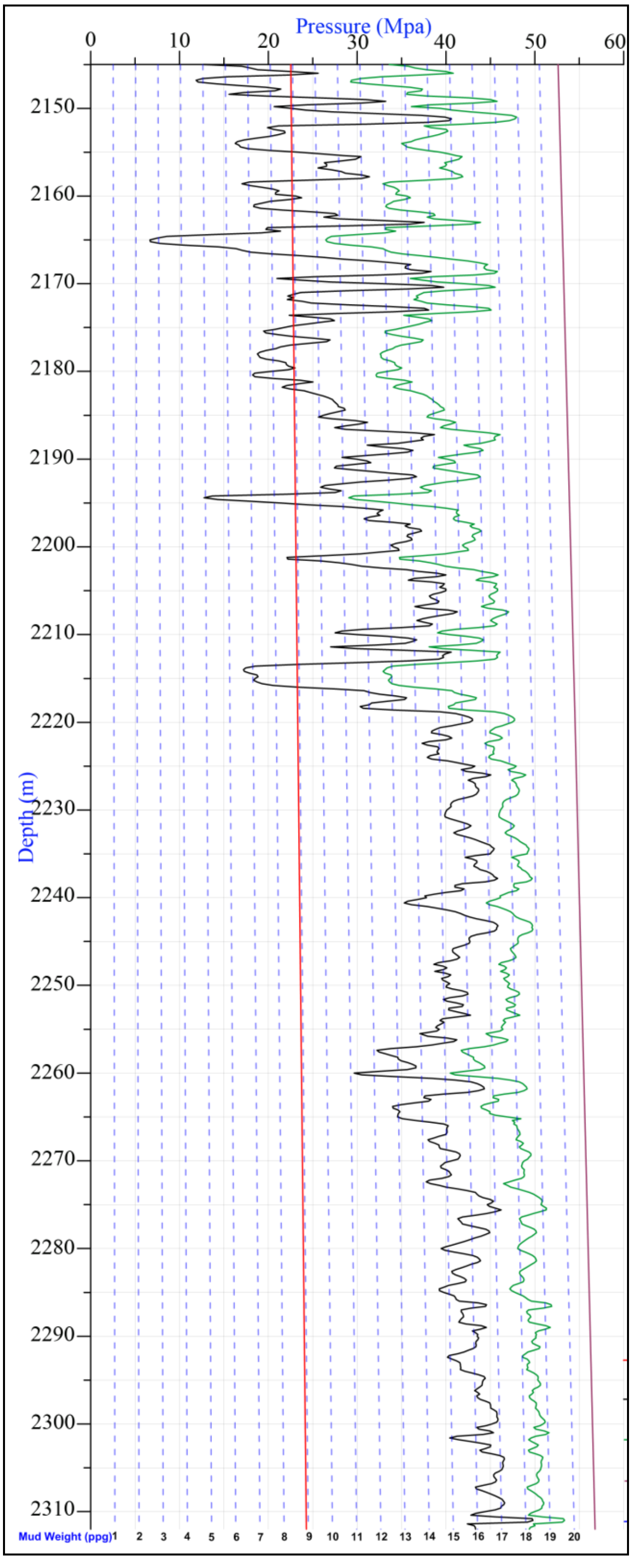

Fig.8: Pore pressure, fracture pressure, hydrostatic pressure, overburden pressure, and isodensity line for the studied reservoirs

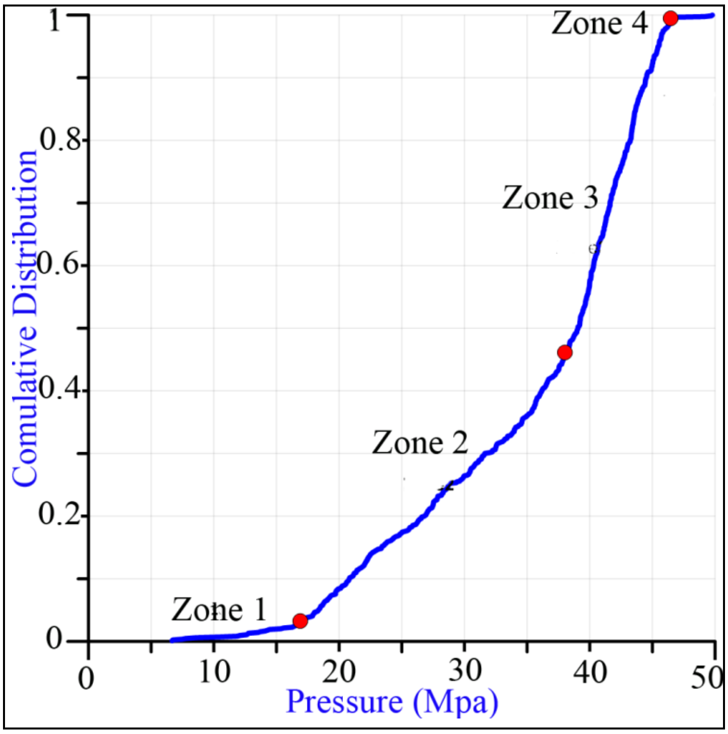

Fig.9: Reservoir compartmentalization based on predicted pore pressure for the studied reservoirs

Reservoir temperature changes in oil and gas accumulations lead to changes in volumes of gas, fluids and container rock. Temperature expansion causes a decline in oil and water viscosity and an increase in gas viscosity. The temperature development in the closed reservoir permits formation pressure increase. Reservoir temperature drops hydrocarbon compound production and manages to ruins of precious products (condensate, viscous oil, and paraffin), that is why oil fields (especially waxy oil) are elaborated with an increase of reservoir pressure (Dowdle and Cobb, 1975). Figure 10 shows a relation between the pressure and the temperature of the studied reservoirs. It can be evidence to the enclosing system and presence of overpressure across the studied reservoirs.

There are many reasons to show abnormality in pore pressure magnitudes and variations according to its depth and location (Fig.8). The highest overpressure zone exists within the Azkand/ Ibrahim Formation, while the most potential reservoir is the Azkand Formation. This is due to the permeability barriers or the pores maybe not effective in the Azkand/ Ibrahim Formation. Shale content is high in the Azkand/ Ibrahim Formation relative to the Azkand Formation, which makes the pores more isolated and degrades permeability (Fig.4). Pore isolation leads to increase in the confining pressure. The Azkand Formation has less pore pressure value, which maybe due to having a good permeability. Permeability relates the rate at which a given fluid will flow along with the line of such a pressure drop (Hawker, 2001). The fluid types determine the flow properties of that fluid; therefore, relates to permeability and time in the occurrence of overpressure zones (Hawker, 2001). The Jeribe and Anah formations have the same story as the Azkand/ Ibrahim Formation, but they have less pore pressure because the overburden effect of the Azkand/ Ibrahim Formation is higher than that in the Jeribi and Anah formations. The similarity of pore pressure and fracture pressure curves as well as the hydrocarbon movability, which is related to permeability, indicate the presence of fracture across the studied wells, especially in the Azkand Formation.

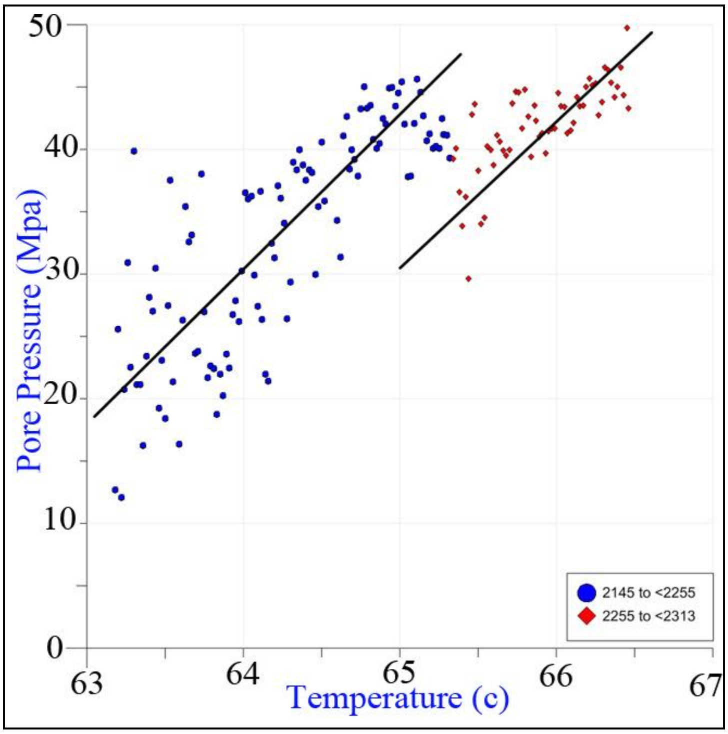

Fig.10: Covariation between pore pressure and temperature for the studied reservoirs

CONCLUSIONS

- The studied reservoirs are mostly considered as overpressured zones.
- Based on the predicted pore pressure, the studied reservoirs are compartmented into four pressure zones, where the highest value is found in zones three and four at the top of the Azkand Formation to the bottom of the Ibrahim Formation.
- The presence of overpressure across the reservoirs is due to an enclosed system, which was entrapped by a caprock of the Fatha Formation, and increased temperature of the reservoirs.
- The variation of the overpressure value through the studied reservoirs is caused by overburden effects, which increases with depth. It indicates the presence of permeability barriers and also pores may be not connected somewhere.
- Direct relation between pressure and temperature and thickness of hydrocarbon zones (oil and gas) gives indications for most of the studied reservoirs to be good productive reservoirs at the primary recovery stage.

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