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Comparative study between density porosity and density magnetic resonance porosity: a case study of Sequoia gas reservoir, Mediterranean offshore gas, Egypt

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Abstract

This work deals with a comparative study between density porosity and density magnetic resonance porosity in late Pliocene El Wastani gas reservoir, Sequoia field, West Delta Deep Marine (WDDM). In this study, the available well logging data by collecting, gathering, uploading, analyzing, and interpreting are used. Porosity determination, from the petrophysical parameters, routinely considered the most important process. The determined porosity by the two techniques is compared. Density resulting in density porosity (PHIT-D) showed results more than 23% in gas-bearing reservoir zones and less than 22% in non-gas reservoir zones. The porosity determined from integrating nuclear magnetic resonance (NMR) with conventional density porosity resulting in density magnetic resonance porosity (DMRP) showed results less than 33% in gas-bearing reservoir zones and more than 37% non-bearing gas zones. Comparison between the results of the two techniques in gas-bearing zones, PHIT-D is increasing and DMRP is not affected. DMRP considered the best and most true porosity against gas reservoir. This comparison is valid in any gas-bearing formations by using the proposed technique.

Keywords Mediterranean offshore · Gas reservoir · Density porosity · Density magnetic resonance porosity

Introduction

Eastern Mediterranean contains countries like Egypt, which, have many discoveries of gas reservoirs in the last 10 years. The latest discovery, and so far the biggest, gas field find has been Zohr followed by, more much bigger, field of Noor area, which is close to the zones of Cypriot gas fields. The two discoveries, in the terms of the biggest proven gas reserves in all the world that make Egypt placed in the most top 10 countries present (Nestor and Costas 2019). The Mediterranean seabed geographically consists mainly of about three basins: the Levant basin, Nile Delta basin, and the Herodotus basin (Nestor and Costas 2019). Deep water in Nile Delta is interesting for gas development. Offshore discoveries play important roles such as shallow marine reservoirs of the Pliocene for the West Delta Deep Marine (WDDM) and Rosetta Fields. By combining technology of deep water drilling with 3D seismic to be tool of standard exploration, the results, oil field achieved many advances in prospectivity of Pliocene sequences and also Oligo-Miocene sequences existed in the fields of deep water offshore. Sequoia field located north of Nile Delta with about 90 km in the northeast of the Alexandria city. It lies in deep marine with water depths from 150 to750 m of the present Nile Delta (Fig. 1). Determining porosity is important rock property in gas fields when describing hydrocarbon in reservoirs. For quantifying hydrocarbon reserves, porosity considered critical parameter. Petrophysicists developed many ways to determine porosity insuring they have the accurate possible results. The

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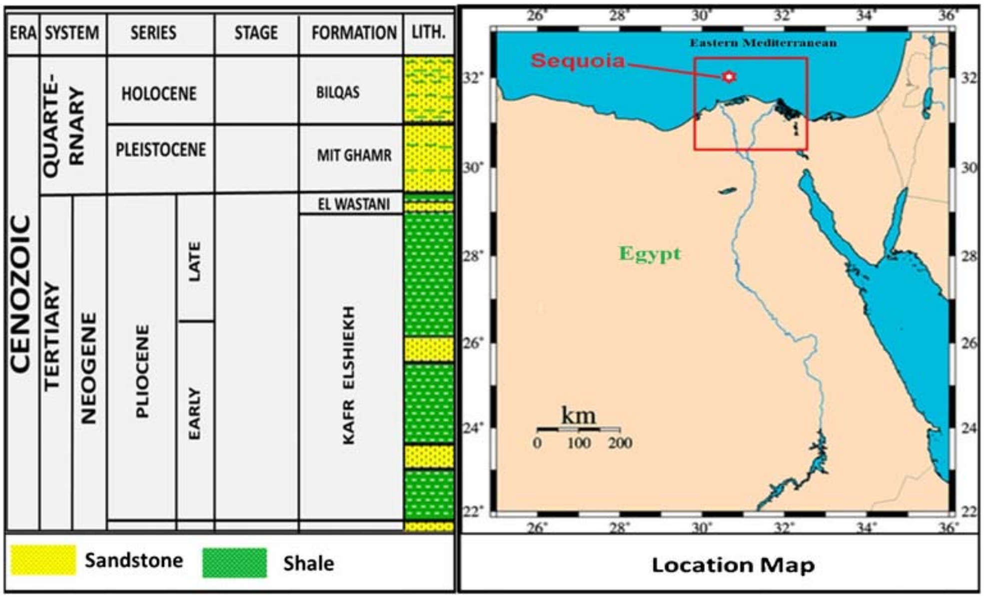


Fig. 1 Study area for offshore gas in East Mediterranean, located north of Egypt, basin of Nile Delta, concession of West Delta Deep Marine (WDDM), and Sequoia Field showing the generalized stratigraphic column and the Formation of El Wastani Pliocene (after Hanafy et al. 2018)

ultimate goal is to use these data to understand a potential production of the reservoir then ensure that its hydrocarbons could be effectively recovered (Smithson 2012). Geophysical well log data from empirical equations is conventional methods for natural fracture porosity determination (Serra 1985; Tiab and Donaldson 2004), or for its calculation at a laboratory (Tiab and Donaldson 2004). Today, although we still use sonic porosity logs, the two predominant porosity measurements are porosity from density and porosity from neutron (Smithson 2012). Gas-filled porosity is detected by the neutron porosity tool as very low porosity, while density porosity shows higher than the true real porosity. They crossover because neutron porosity is the lower values than density porosity, giving rise to crossover appear (Smithson 2012). To obtain porosity, we use density log-derived porosity (PHIT-D), but in case of gas presence, it is overestimates. The introduction to total NMR porosity into well logging industry showed many new evaluation techniques of the formations (Prammer et al. 1996; Freedman and Morris 1995; Coates et al. 1997). Integration of density as conventional well logging with NMR as advanced tools in petroleum industry has been developed recently in this study for easily and quickly identifying lithologies with some properties aspects which is associated with all the pore features presented such as the porosity, pore composition, the connectivity, and pore size distribution. NMR has been widely used in the petrophysical characterization for rocks in the petroleum reservoirs to identify storage evaluation, and fluid typing characterization for natural porous presented in materials and in porous rocks for also detecting contaminants (Timur 1969; Kleinberg and Horsfield 1990; Kleinberg and Farooqui 1993; Kleinberg and Vinegar 1996; Chuah 1996; Straley 1997; Hodgkins and Howard 1999; Coates et al. 1999; Martinez 2000; Dunn et al. 2002; Prammer 2004; Grunewald and Knight 2009; Toumelin et al. 2003; Guichet et al. 2008; Xie and Xiao 2009; Keating and Knight 2010; Yao et al. 2010; Zalewska and Cebulski 2011). The aim of the present study is to introduce a comparative study between density porosity and density magnetic resonance porosity using Sequoia gas reservoir as a case study.

Geological background and settings

Stratigraphic sequences and structural settings

The stratigraphic succession of WDDM classified by (Deibis et al. 1986) into three separate sequences: sequences of pre-Miocene, syn-Miocene, and sequences of post-Miocene. The Tortonian Wakar Formation overlies the formation of Sidi Salim and consists mainly of shales and small interbeds of the fine sand. The sequences of post-Miocene include three clear formations: Kafr El Sheikh with time early to late Pliocene, second is El Wastani timing late Pliocene, and third is Mit Ghamr-Bilqas formations which represent the Plio-Pleistocene to recent (Deibis et al. 1986). In this succession, the thickest formation is the Kafr El-Sheikh Formation which consists of shale with small sand interbeds. Significant unconformity represents in its base on top of the Rosetta Formation. El Wastani Formation (present study reservoir) overlies the formation of Kafr El Sheikh and is also composed of intercalation from sand beds with a thin shale and clay layers (Fig. 1). Sand with clay beds is the main composition of the formation of Mit Ghamr-Bilqas (Rizzini et al. 1978).

Nile Delta could be delineated by three major structural trends: the hinge line of E-W as gravitational listric normal fault delineating Messinian salt basin, NE-SW Rosetta a Pliocene wrench fault activity that represents left lateral oblique-slip fault trend, and Temsah fault of NW-SE as a right lateral oblique-slip (Aal et al. 2006). These fault trends are also parallel to the circum-Mediterranean plate boundaries and also seem to be old inherited basement faults which are rejuvenated throughout the tectonic development of the area. Rosetta and Temsah oblique-slip faults are intersecting in southern deep water block, and for that, creating a faulted regional high (Aal et al. 2006).

Natural gas in WDDM of Nile Delta, Egypt

The area of interest lies offshore in the West Delta Deep Marine (WDDM) concession. The study is applied on the intervals between depths from 1400 to 1800 m of the late Pliocene El Wastani Formation in the Sequoia Field. The operator of BG Egypt Company won the WDDM concession in 1995. The gas discoveries in the prospective block used the 3D seismic data and used direct hydrocarbon indicators, which is referred as (DHIs), such as the bright spots, with flat spots and AVO anomalies. The formations of gas-bearing zones have been discovered in the Pliocene sands. Recent exploration activity has focused on the play of slope-channel complex for the Pliocene with about six exploration discovery wells, which were drilled in WDDM. These include the Scarab/Saffron, Simian, Sienna, and Sapphire discoveries. Pliocene slope-channel systems characterize the gas reservoirs in offshore deep marine west Nile Delta as illustrated by 3D seismic geomorphology (Samuel et al. 2003; Cross et al. 2009). The upper Pliocene El Wastani Sequoia reservoir is of heterogeneous type that consists of a succession of sandstones and mudstones organized into a composite upward-fining profile as described by Cross et al. (2009). They added that the Sequoia channel system shows evidence for synsedimentary faulting, including a large-scale downdip widening of the channel and small-scale channel diversions and intraslope ponding of flows. Moreover, Mohamed et al. (2017) are in the opinion that the Sequoia field is a submarine delta slope canyon system with complex turbiditic channel-levee reservoirs.

Porosity

Porosity calculations could be determined from the conventional porosity tools which include density, neutron, and sonic and from unconventional tools such as nuclear magnetic resonance (NMR). Density tools measure the rock density (ρb). Rock porosities are usually measured from well logs and corrected using the conventional porosity corrected tools. These porosity tools are largely responsive to porosity. The total porosity (ϕt) and effective porosity (ϕe) are calculated. In gas reservoirs, if we depended on one tool, we found density porosity may read too high, in contrast, magnetic resonance porosity may read too low values. The present study depends on integration of different tools then compare between them, trying to get the most correct porosity existing in gas zones.

Methodology

Method of porosity evaluation from conventional well logging (density)

Density log readings, in some cases, are biased due to the borehole effect. So, we must make correction of porosity tool (density). Therefore, a correction is needed through the conditions of bulk density (ρb) correction:

– If Cal. $\leq 9''$ $\rho_{bcorr} = \rho_b$
– If $9'' <$ Cal. $< 10.5''$ $\rho_{bcorr} = \rho_b + [(\text{Cal.} - 9)/100]$
– If $10.5'' \leq$ Cal. $\rho_{bcorr} = \rho_b + 0.018$

Porosities obtained by the density log (PHIT-D) are calculated from the relation:

$$\text{PHIT}-\text{D}=\rho_b-\rho_{ma}/\rho_f-\rho_{ma} \quad (1)$$

where

PHIT-D	is the density porosity.
ρb	is the bulk density log input.
ρf	is the fluid density.
ρma	is the matrix density.

Method of porosity evaluation by integrating conventional well logging (density) and nuclear magnetic resonance (NMR) in gas-bearing reservoir

In gas-bearing intervals, where the density porosity (PHIT-D) exceeds the NMR porosity (TCMR), the density magnetic resonance (DMRP) is calculated using the described equation (after Xiao et al. 2012).

$$\text{DMRP} = (\text{PHIT}-\text{D}*\text{w}) + (1\text{–w})*\left(\text{TCMR}/(\text{HI})_f\right) \quad (2)$$

where

w	is the weight factor. The equations to compute the weight are below.
PHIT-D	is the density porosity. The PHIT-D equation is defined above.
TCMR	is the input NMR total porosity.

For DMRP-64 method, $w = 0.6$, the computation is simplified so that DMRP ≈ (0.6 * PHIT-D) + (0.4 * TCMR).

w is the weight defined by

$$W = \left[1-(\mathrm{HI})_{\mathrm{g}}{*}P_{\mathrm{g}}/(\mathrm{HI})_{\mathrm{f}}\right]/\left[\left[1-(\mathrm{HI})_{\mathrm{g}}{*}P_{\mathrm{g}}/(\mathrm{HI})_{\mathrm{f}}\right]+\lambda\right] \quad (3)$$

which simplifies to

$$W = \left[1-(\mathrm{HI})_{\mathrm{g}}{*}P_{\mathrm{g}}\right]/\left[\left[1-(\mathrm{HI})_{\mathrm{g}}{*}P_{\mathrm{g}}\right]+\lambda\right] \quad (4)$$

where

$(\mathrm{HI})_{\mathrm{g}}$ is the hydrogen index of gas.
$(\mathrm{HI})_{\mathrm{f}}$ is the hydrogen index of the fluid. This input is not required since the $(\mathrm{HI})_{\mathrm{f}}$ term cancels in the simplified equation.
λ is the density porosity, PHIT-D.
P_{g} is the gas polarization function, where

$$P_{\mathrm{g}} = (1-\exp)\left(-P_{\mathrm{t}}/T_{1,\mathrm{g}}\right) \quad (5)$$

In the P_{g} equation, P_{t} is the polarization time for CPMG pulse (s), and $T_{1,\mathrm{g}}$ is the gas longitudinal relaxation time at reservoir conditions (sec).

Results analysis

Porosity was calculated from the two techniques. The first technique is from the conventional well logging tools (density). The second is the integration of the conventional density with nuclear magnetic resonance (TCMR), which results with

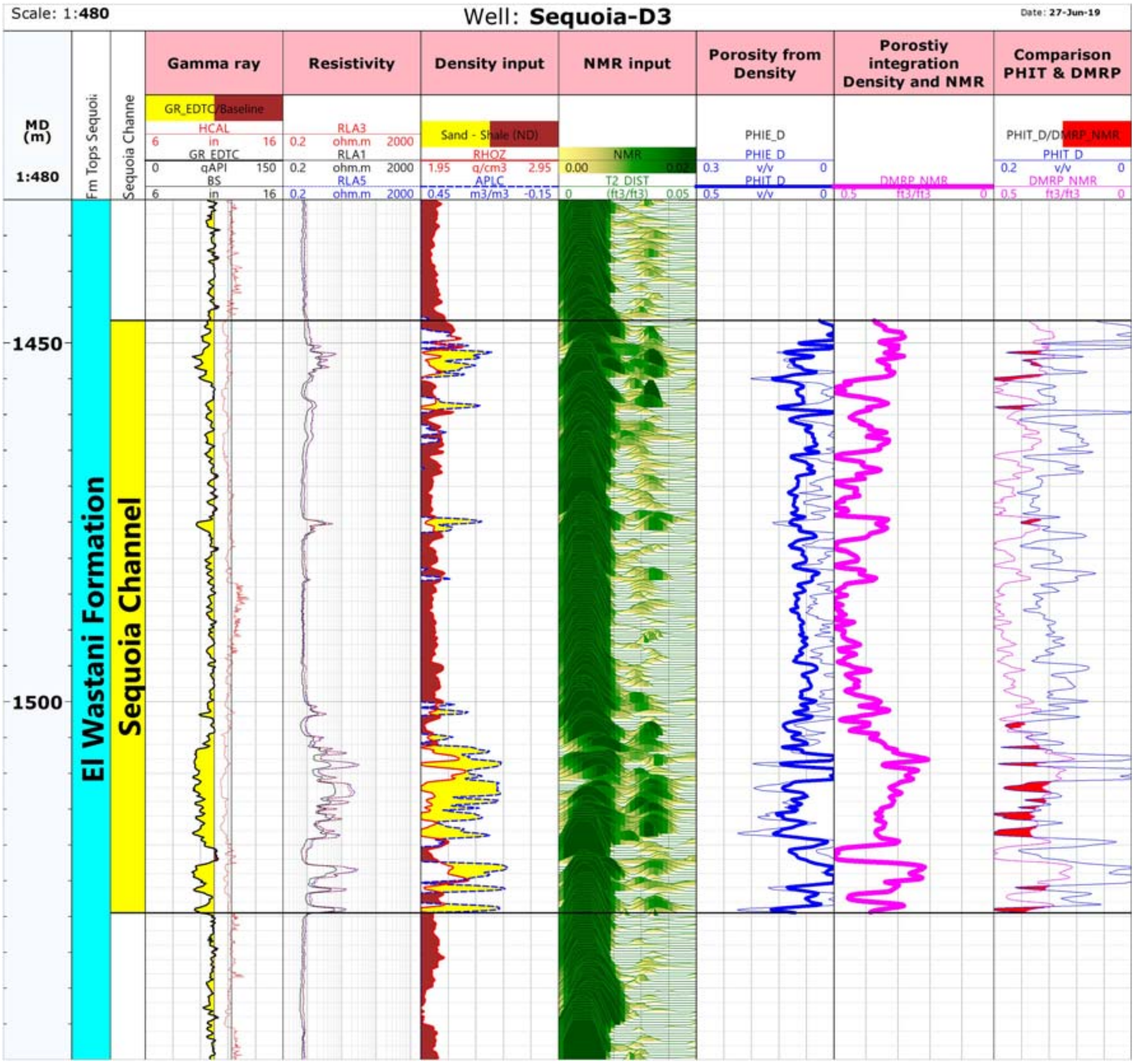


Fig. 2 Logs from Sequoia-D3 well. The well is drilled in Eastern Mediterranean sea, West Delta Deep Marine concession (WDDM). Gamma ray (GR) and the bit size (BS) are displayed in the track named gamma ray. Deep resistivity and shallow resistivity are also displayed in the track named resistivity. Bulk density (RHOZ) and neutron (APLC) are displayed in track named density input. Distribution of NMR transverse-relaxation time (T2_DIST) is displayed in track named NMR input. Interval from 1505 to 1525 m is gas bearing. Result porosity from density and DMRP is also displayed in next tracks. Comparison for conventional density porosity (PHIT-D) and DMRP porosities is displayed in next tracks. Examples of how we uploaded every well for using all data available

what called the density magnetic resonance porosity (DMRP) as shown in Fig. 2.

Porosity results from density technique

Density porosity (PHIT-D) results are summarized in Table 1 in each of the following: zones bearing gas, zones not bearing gas, and for the median of all zones. The highest values of density porosity exist against gas-bearing zones then zones not bearing gas. PHIT-D highest values in the gas-bearing zones values were about 29% in Sequoia-D5 (Fig. 4c), while in the zones that not bearing gas record the lowest values, about 7% with Sequoia-D3. Gas-bearing zones show much higher values than other zones which not bearing gas with density porosity values > 23% (Fig. 4a), and in the zones not bearing gas are quite low for all Sequoia channel with values less than 22% (Fig. 4b). Median in the all zones is still quite low with values less than 21% (Fig. 4c).

Porosity results from integration density and NMR techniques for gas-bearing reservoir

Results of density magnetic resonance porosity (DMRP) are summarized in Table 1 in each of the following: zones bearing gas, then zones not bearing gas, and median of all zones. Lowest values for DMRP in gas-bearing zones were about 21% with Sequoia-D3 (Fig. 4c), while in zones not bearing gas record highest values that were about 48% with Sequoia-D3. Gas-bearing zone values showed lower values other than zones that not bearing gas with the DMRP values < 33% (Fig. 4a), and in zones not bearing gas are still quite higher for all the Sequoia channel with about values > 37% (Fig. 4b).

Discussion

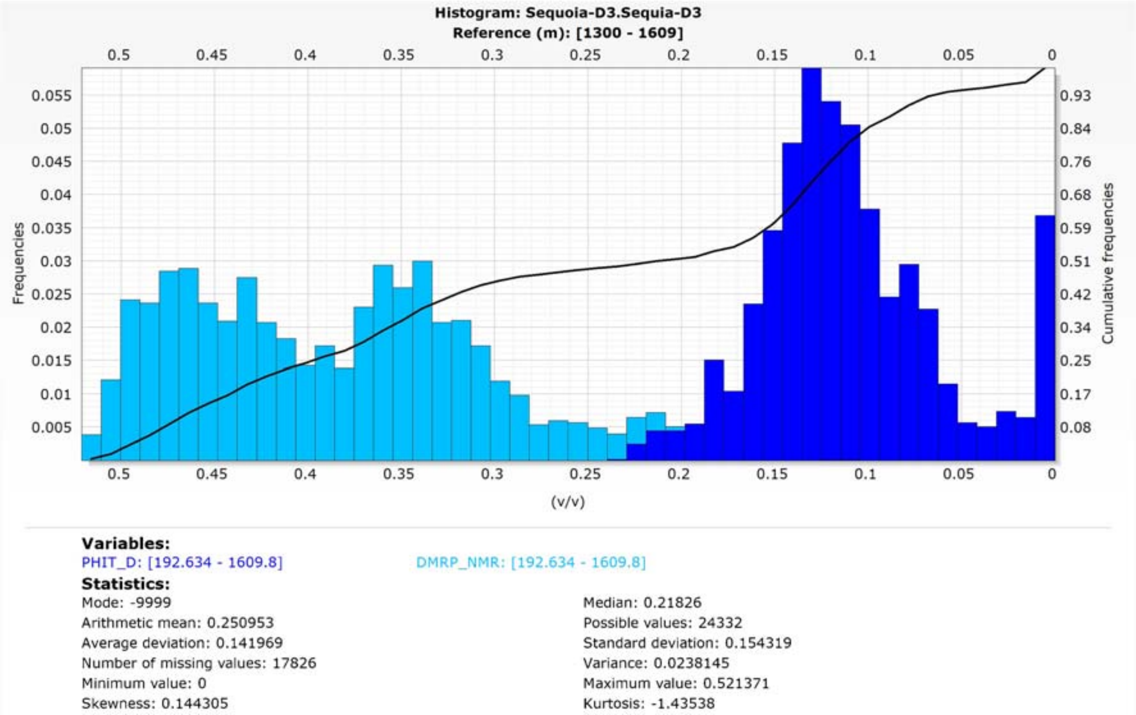
The density porosity from PHIT-D and from DMRP shows the best high degree of correlation (Fig. 3). Porosities from the two techniques generally follow the similar trend to the other wells and that in all the studied wells (Fig. 4). The PHIT-D shows reverse agreement and contrast for DMRP in all the gas-bearing zones (Figs. 3 and 4).

Discussion in a comparison between PHIT-D and DMRP

The histogram (Fig. 3) shows PHIT-D very clear low values and DMRP in high values. The PHIT-D takes the right portions on the horizontal axes and the DMRP takes the left portions. Putting the two variables in a one track (Fig. 2) shows the clear separation between them, except in some portions where both of them break the separation

Table 1 Summary of porosity evaluation total density porosity (PHIT-D) and effective density porosity (PHIE-D) from conventional well logging tools (density) and porosity by combining conventional density with nuclear magnetic resonance (NMR) in the gas-bearing reservoir (DMRP). Values of porosity in zones bearing gas, zones that not bearing gas, and all zones together in median, as well as some characteristics of evaluation formation for El Wastani such as channel names, channel boundaries, net, gross, not net, and the net to gross ratios

Name of well	Properties	Zone bearing	Used units	Sapphire-1	Sequoia-D1	Sapphire-2	Sequoia-D3	Sequoia-D5
Name of formation			--	El Wastani	El Wastani	El Wastani	El Wastani	El Wastani
Name of channel	Sequoia		--	Channel of Sequoia	Channel of Sequoia	Channel of Sequoia	Channel of Sequoia	Channel of Sequoia
Tops and bottoms	Channel top		m	1461	1521.91	1534.10	1446.89	1450.21
	Channel bottom		m	1587.03	1654.39	1577.18	1529.49	1627.09
Pay zone	The gross		m	127.02	132.48	43.08	82.61	176.88
	The net		m	28.66	58.14	25.3	25.78	74.18
	The not net		m	98.31	74.36	17.87	56.85	130.86
	The net/gross		%	23.1	78.1	58.1	31.1	42.1
(Density porosity) conventional well logging tool	(PHIT-D) total density porosity	The gas	%	26	23	24	23	29
		The not gas	%	15	10	09	07	22
		The all zone	%	16	09	10	12	21
	(PHIE-D) effective density porosity	The gas	%	21	22	23	21	25
		The not gas	%	05	03	01	05	04
		All zone	%	08	01	07	03	08
DMRP integrating NMR with density in the gas-bearing zone	(DMRP) density magnetic resonance porosity	The gas	%	33.01	24.01	25.01	21.01	29.01
		The not gas	%	39.01	37.01	43.01	48.01	47.01
		The all zone	%	46.01	33.01	39.01	40.01	42.01



Variables:

PHIT_D: [192.634 - 1609.8] DMRP_NMR: [192.634 - 1609.8]

Statistics:

Mode: -9999
Arithmetic mean: 0.250953
Average deviation: 0.141969
Number of missing values: 17826
Minimum value: 0
Skewness: 0.144305
Median: 0.21826
Possible values: 24332
Standard deviation: 0.154319
Variance: 0.0238145
Maximum value: 0.521371
Kurtosis: -1.43538

Fig. 3 Displaying comparisons in a histograms, conventional well logging tool porosity (PHIT-D) compared with the density magnetic resonance porosity (DMRP), for the Sequoia reservoir in El Wastani Formation

in a very similar way (portions shaded in red colors). The interpretation of this action is that in the zones that not bearing gas, clear high values in DMRP and low values for PHIT-D (Fig. 4b), but once there is gas in reservoir, everything changes in a reverse manner so the PHIT-D values increase and DMRP values have a slight decrease or stay relatively constant such in Fig. 2 log depth from 1505 to 1525 m and in (Fig. 4a). There is an increasing density porosity in gas zones because of the gas that reduces the bulk density measurement or because of the wrong fluid density that was used in the computation. DMRP behaves some kind in a similar way like nuclear magnetic resonance porosity, but the DMRP module computes the gas-corrected porosity based on the density

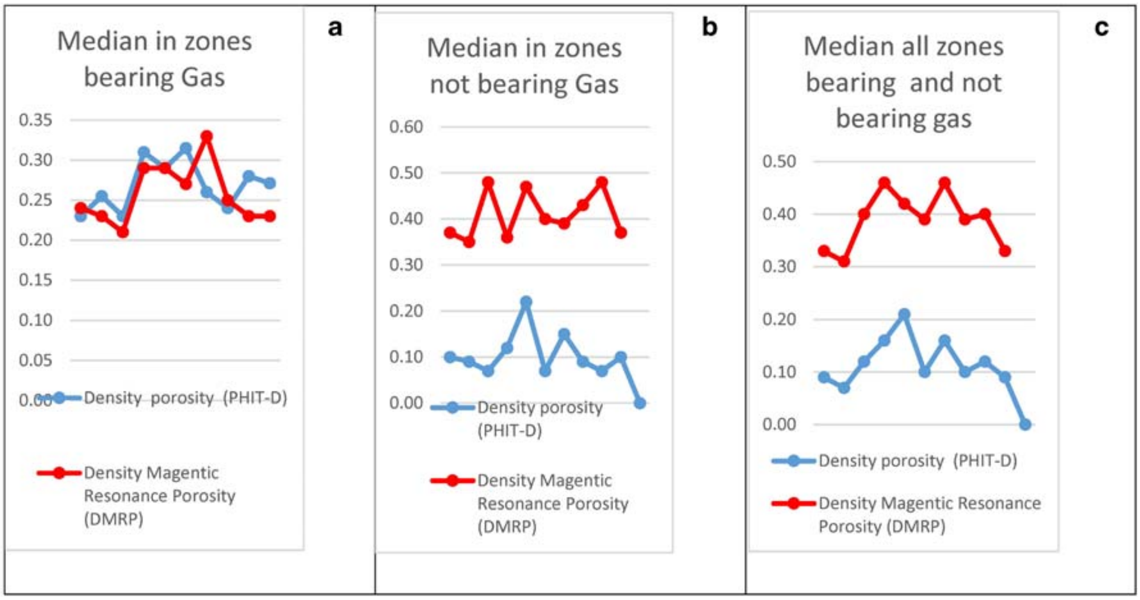


Fig. 4 Porosity analysis from conventional well logging tool porosity (PHIT-D) with density magnetic resonance porosity (DMRP). **a** In gas-bearing zones PHIT-D and DMRP. **b** In zones that not bearing gas PHIT-D and DMRP. **c** In median for both zones bearing gas and zones that not bearing gas PHIT-D and DMRP

magnetic resonance (DMR) model. The model of DMR takes the advantage for the bulk density responses and measurements of magnetic resonance porosity, but just when gas exist, so this model is only could be valid for applying in gas reservoirs. The DMR method has the advantage of avoiding the use of fluid density and gas hydrogen index (HI) at reservoir condition for gas correction. This advantage allows us to increase logging speeds, as we do not need full polarization for gases (Galarza et al. 1997; Abushanab et al. 2005). Finally, in no gases to depend on, the (NMR) nuclear magnetic resonance is recommended, it is very useful, but once there is gas, we have to use the DMRP. By this comparison, the failure of conventional tools alone against gas bearing is noted. But by combing conventional with advanced NMR, the DMRP is obtained, which considered the best and most true porosity against gas reservoir. This comparison is valid in any gas-bearing formations by using the proposed technique.

Conclusion

Through analysis, it is a clear fact that DMRP technique is more accurate and much more applicable than the conventional tools alone, especially, in cases of gas. Interpretation results were achieved by the Schlumberger software. Moreover, applying the interpretations of DMRP on studied wells with all needed data and logs was discussed in this paper in detail. Finally, we have concluded and stated a unique privileges in using DMRP technology for all well logging world and the useful of it in enhancing the industry of oil in general, more and more in case gas reservoirs. The importance of DMRP is because density porosity may read too high, because the gas reduces the bulk density measurement, or because the wrong fluid density was used in the computation. The NMR porosity may read too low and that because gases have low hydrogen index and in a usual way have not been polarized in a sufficient manner due to its relatively long longitudinal relaxation time. So, integration between conventional porosity and NMR resulting in model of density magnetic resonance porosity (DMRP), which, is considered the best and most advantage in gas zones, because it computes the gas-corrected porosity based on the density magnetic resonance (DMR) model. The DMR model takes advantage of the responses of the bulk density and magnetic resonance porosity measurements when gas is exist, so it is only valid to gas reservoirs. Then, porosity precisely could be estimated by this combination in any formations bearing gases by using the technique proposed in this study. Core samples should be drilled before this technique is applied as a routine analysis for determining all parameters. Combined NMR with conventional logging is considered the most accurate technique than other conventional tools alone especially in gas-bearing formations.

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