Integration of mud logging and wire-line logging to detect overpressure zones: a case study of middle Miocene Kareem Formation in Ashrafi oil field, Gulf of Suez, Egypt

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Abstract

The aim of this study is the integration of mud logging and wire-line logging data to detect overpressure zones in Kareem Formation (Middle Miocene), Ashrafi Field, Gulf of Suez, Egypt. The study is performed for the three wells Ash_H_1X_ST2, Ash_I_1X_ST, and Ash_K_1X. The prediction of the abnormal pressure is a quite important factor in the design of the well, where it contributes to avoid many problems during the drilling process and maintain the formation fluids. The abnormal pressure zones occur due to major changes in lithology, petrophysical properties, and fluid type, where these factors lead to differences in pore pressure from hydrostatic pressure, and their prediction is achieved by utilizing rock cuttings, *D*-exponent, and methane gas; in addition, the porosity and water saturation are estimated from mud logging as real-time data and compared to wire-line logging (resistivity, porosity, and permeability) to determine these zones. The concept of detecting abnormal pressure zones in this study is based on defining the marked changes in the *D*-exponent trends that arise from the variations of the fluids and the lithology of the Kareem Formation. Therefore, these trends are integrated with the petrophysical parameters such as resistivity, porosity, and permeability from wire-line logging to detect the overpressure zones. So, the overpressure zones are detected in the intercalated sand and shale intervals of the studied wells within the Kareem Formation and are mostly marked by a decrease in the reservoir quality such as permeability, as well as an increase in the resistivity and *D*-exponent. The thickness of the overpressure zone in Ash_H_1X_ST2 well is influenced by the marl content that reaches up to 80%. The integration results are summarized to determine the average depths of the overpressure zones for the Kareem Formation in the three studied wells. The zone average depths in the Ash_H_1X_ST2 well range from 6022.50 to 6093.30 ft, whereas the zone top is detected in the Ash_I_1X_ST well at the top of the Kareem Formation (6580.00 ft), and the zone bottom at average depth of approximately 6704.20 ft, in addition, the zone average depths in the Ash_K_1X well range from 7718.33 (top) to 7833.33 ft (bottom).

Keywords Overpressure · Wire-line logging · Mud logging · *D*-exponent · Kareem formation · Gulf of Suez

Introduction

The Ashrafi field is located at the east of Ashrafi Island, far 66 km from the North of Hurghada town in the south-west section of the Gulf of Suez where the location map of

the Ashrafi field and the studied wells are shown in Fig. 1. For the ten potential reservoir units in the Gulf of Suez, the Kareem Formation represents 23% oil produced from this basin, also the petrophysical properties of this formation are including gross thickness that reaches to 200 m, the porosity which ranges from 7 to 33%, and the permeability that ranges from 20 to 730 mD (Salah and Alsharhan 1997).

The Ashrafi Field is divided into three fields: the main field, the southwest field, and the north field. The choosing of wells locations is based on their coverage of the three geological blocks. Therefore, two wells Ash_H_1X_ST2 and Ash_I_1X_ST are representing the blocks H and I of the main field and the other north field location in block K is studied by the Ash_K_1X well. Thus, the detection of overpressure zones is very serious to maintain hydrocarbon

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Fig. 1 Location map of the studied wells in Ashrafi Field, Gulf of Suez

fluids and modify the drilling plan of new development wells in the Ashrafi field.

The abnormal pressure zones are due to the quick compaction of shale sediments, which is considered as one of the very important conditions to create these zones. The generation of abnormal pressure in the pore spaces happens if a pressure seal (impermeable barrier) is present, and fluids trapped and cannot escape (El-Werr et al. 2017). The abnormal pressure must be controlled to prevent dangerous

problems such as stuck drill pipes and blowout of wells during drilling operation (Danenberger 1993).

The petroleum studies confirmed that, when the mud column pressure increases, this gives a low rate of penetration (ROP) (Jorden and Shirley 1966). Also, with increasing the depth during drilling, the rate of penetration decreases due to the increase of compressibility of rocks and hardness. The normal trend of pressure reverses during pressured zones (Boatman 1967). Thus, the overpressure zones should be

controlled by raising the mud weight and there are many studies, which used the density and resistivity records to detect these zones, by Hottmann and Johnson (1965), Morris and Biggs (1967) and Burke et al. (1969).

The pressure created for the fluids in the pores is called the formation pressure or pore pressure. This pressure is determined by comparing the density, neutron, sonic, and resistivity responses from the wire-line logs. In addition, the pore pressure can be detected indirectly through caving, gas, mud weight, and rate of penetration of the formation (Mouchet and Mitchell 1989).

The concept of detecting overpressure zones by integrating analysis of mud logging records with wire-line logging techniques is carried out in this study through the following correlations:

- Plotting the formation resistivity, porosity, and permeability from wire-line logging with the drilling exponent (D).
- Correlating of water saturation estimated from methane gas which exits from the formation while drilling with the formation resistivity and the permeability estimated from wire-line logging to detect and confirm overpressure zones.
- Comparison of porosity estimated from mud logging by using profitability index (PI) and porosity from wire-line logging as another tool to predict overpressure zones.

These overpressure zones and correlations are interpreted with lithology variations and hydrocarbon content for Kareem Formation in three structurally blocks H, K, and I in Ashrafi Field, Gulf of Suez.

Geological settings

The depositional settings of the Kareem Formation are alluvial fans in the Miocene, presented on both margins of the Gulf of Suez, also recorded in the southern and central onshore portions of the basin. The alluvial fan lithology is a well to moderately sorted grains, coarse-grained sandstones, and conglomerates. The deltaic fan is dominated in the southern Gulf of Suez in Hareed, East Zeit, Esh Mellaha, and Ashrafi areas and consists of interbedded sandstones, shales, and limestones. The submarine fan produces a thick extensive porous sandstone, considered as a reservoir rock. The eustatic sea-level variations created anhydrite/carbonate precipitation in the marginal areas during the early phases of Kareem Formation deposition (Alsharhan and Salah 1994, 1995).

The Dongying Depression of the Bohaiwan Basin in China is similar to the deposits of Kareem Formation, where

these deposits are characterized by different sedimentation environments, that cause to form the complex lithologies and create the overpressure zones associated with the hydrocarbon fluids in the intercalated sandstones and mudstones intervals (Xie et al. 2001; El-Araby et al. 2009).

According to the surface and subsurface data, the Gulf of Suez is divided into pre-rift, syn-rift, and post-rift units; The pre-rift units include Proterozoic basement to Upper Eocene sediments, the syn-rift units include Upper Oligocene to Miocene sediments and contain source, reservoir, and seal lithologies, whereas the post-rift units include sediments of Pliocene to Pleistocene age (Abd El-Naby et al. 2010). The general stratigraphic column of the Gulf of Suez is shown in Fig. 2 (Darwish and El-Araby 1993).

The separation of the African and Arabian plates in Late Oligocene—Early Miocene time is due to the Neogene continental rift system which formed the Gulf of Suez. The Gulf of Suez is located in northwestward from 27°30'N to 30°00'N, its width ranges from 50 km at the North end reaches to 90 km at South part, and divided into blocks due to the complex structural faulting (Abd El-Naby et al. 2009).

Regions of the high rate of sedimentation such as the Gulf of the United Mexican States are expected to be characterized by quickly compacted sediments that creating abnormal pressure zones. On the other hand, there are some studies that predicted the reverse under the special conditions from lithology, fluid type, and petrophysical properties (Thomas et al. 2001).

The Kareem Formation is composed of intercalation of sandstone with shale in Halal Field, that observed in the A5, A3B, and A9A wells (Rine 1985). Wherein the Kareem Formation was divided into three major lithologies: sandstone, shaley sand, and silty shale, based on log analysis. Also, the data from RFT are used to detect pressure differences in the Kareem Formation due to lithology variations in the south of El-Morgan Field at the central part of the Gulf of Suez (Bentley and Biller 1990). Therefore, the Kareem sediments are classified by Tewfik et al. (1992) into five depositional lithofacies as follows: alluvial fan, sabkha/lagoon (anhydrite), platform carbonates, submarine fan/fan delta, and basinal pelagic.

At the southern of the Gulf of Suez, Kareem Formation consists mainly from intercalation of sandstone and shale. Its reservoir quality is graded from good to poor, depending on the sedimentation and geological agents, and subdivided into seven hydraulic flow units (El Sharawy 2013). Also, the Kareem reservoir was divided into six distinctive electrofacies by El Sharawy and Nabawy (2016) which interpreted as mudstone, limestone, dolomite, anhydrite, prospective sandstone, and non-prospective sandstone.

The quality of the reservoir depends on the dolomite content; the lithology of Kareem Formation from rock cuttings,

Fig. 2 The generalized stratigraphic column of the Gulf of Suez basin (Darwish and El-Araby 1993)

in many wells at south section of the Gulf of Suez, is sandstone characterized by off-white to white to light brown, medium to very fine-grained, subangular to subrounded, occasionally rounded, semi-friable, with non-calcareous to slightly calcareous cement and poorly sorted. Also, the sandstones are characterized by high gamma-ray readings due to the presence of K-feldspars (Nabawy and El Sharawy 2018).

Abnormal pressure concept

The abnormal pressure occurs due to quick deposition of sand sediments surrounded by shale and increasing compaction process that causes fluid in the pores to become incapable to escape (Harkins and Baugher 1969). The topographic relief that creates an artesian head in the presence of pressured sandstone, which correspond to the process of the rapid filling during geological Tertiary periods for basins, these geological features cause to create abnormal pressure zones (Kaiser and Swartz 1988). Also, after formed the reservoir, the presence of thick gas cap at the boundaries between water and gas is another factor of the overpressure zone (Sanyal et al. 1993).

The pressure of the formation is normal when corresponds with the pore pressure, but it will be abnormal if the formation pressure deviates from hydrostatic pressure. The reason for the formation of the zones of abnormal pressure is the compaction disequilibrium of sediments, and this led to the changes in porosity and geological features, and this occurs mostly during intercalation of shale with sandstone (Bowers 2002). The gross pressure at any depth is coming from the rock column weight overhead the formation occupied by the pore fluids (water, oil, and gas or combination of them). This is called the overburden pressure which increases gradually with depth in the sedimentary basins (Hagoort 1974; Jacquard and Segurier 1962).

The recent researches are showing that an overpressure generation mechanism can be classified into two classes: the loading mechanisms which they are interpreted as rock stress and the mechanisms of fluids swell (Swarbrick et al. 2000). Also, the hydrocarbon buoyancy effect is another source of overpressure generation due to the accumulation of hydrocarbon fluids in the reservoir.

Creating the low-pressure zones are during the high permeable or fractured formations, and based on fluid type in these zones, there are many signs to detect these zones are loss of drilling fluids which is associated with increasing in ROP. As well, wire-line logging measurements such as caliper log, density log, and resistivity log under proper conditions are very effective in locating fractured zones. Also, dip-meter data are another tool for determining the fracture intervals. Furthermore, the pressure tests such as modular dynamic test (MDT), repeat formation test (RFT), and drill

stem test (DST) are used to measure the fluid gradient inside the reservoir, detect the type of the fluid inside the reservoir, detect the fluid contacts (OWC, OGC, and GOC), and measure the initial/average reservoir pressure at a certain depth (Neda et al. 2017).

Estimating the overburden pressure at the drilling site quickly is by integrating the density log and the lithology from rock cutting analysis. As well, pore pressure is acquired from water pressure gradient, variations in PVT, mud gradients, bottom hole pressure (BHP), and historical pressure records. The drilling trajectory and pressure safety are the typical work output of geologist, interpreter geophysicist, petrophysicist, and structural geologist. The resulting report is used to develop the plan of drilling, the hydraulic program (include mud design and properties), and control of the drilling well (Hakiki and Shidqi 2018).

The overpressure zones in the X-field onshore Niger Delta are associated with hydrocarbon and serve as a tool for prospective evaluation of productive zones; they are must be controlled during drilling to save hydrocarbon fluids (Sylvester and Cyril 2014).

During the design of well, it is very important to investigate the mud pressure (hydrostatic pressure during drilling); when the mud pressure is higher or lower than the pressure of pores, this may cause the underbalance of the drilling operation, cause to collapse the walls of the wellbore, and the formation fluids (oil and gas) flow into the well leading to occur the kick. The kick must be organized to prevent blowout of the well. As well, the formation damage occurs due to the pressure effect of drilling fluid (mud) when it exceeds the formation pressure (called the over-balance well). On the other hand, the under-pressure causes the drill pipe to stick with the under-pressure formation and losses of the formation fluids (Asquith and Krygowski 2004).

There are different important empirical methods for abnormal pore pressure prediction from well logs such as Eaton's resistivity and sonic methods, which adapted by using dependent normal compaction relationships to detect pore pressure in subsurface formations (Zhang 2011; Kalidhasan et al. 2019). The well logs measurements such as gamma ray, density, and sonic are used to estimate and predict overpressure zones, which calibrated with a repeat formation tester (RFT), so these techniques are contributed to form model is applied for Krishna-Godavari Basin, India, on 10 wells, where the proposed regression model uses to detect the overpressure zones in this basin (Singha and Chatterjee 2014).

In this study, the integration of mud logging records analysis with wire-line logging is established, which is useful in estimating the petrophysical properties at real time by using drilling parameters and rock cutting lithology from mud logging for calibrating them with the petrophysical properties determined from the wire-line logging.

Methodology

Analysis of mud records

Mud logging data for the three wells are shown in Table 1, where the recorded data are real time during the drilling operation of the Kareem Formation. These data are SPP (standpipe pressure), WOB (weight on Bit), TRQ (torque), HKL (hook load), RPM (revolutions per minute), BS (bit size), SPM (stroke per minute), MW (mud weight), and ROP (the rate of penetration). Also, the geological features of the drilled sections are the rock cuttings, the lithology interpretation, the hydrocarbon gases, and the total gas; the analysis of these data is carried out as follows:

Drilling exponent (*D*-exponent) evaluation

Drilling exponent (*D*) is the normalization of the rate of penetration (ROP) by eliminating the effects of the drilling parameters. Hence, the ROP increases with increasing weight on bit as a result of several factors such as the drill string, the bottom hole assembly, the driller experience, and the rotary speed RPM (revolutions per minute). The general formula of the drilling parameters is shown in Eq. (1) by Bingham (1965).

$$\frac{ROP}{RPM} = a \left(\frac{WOB}{BS} \right)^D \quad (1)$$

where ROP is the rate of penetration, ft/min; RPM is the rotary speed, rpm; *a* is the matrix strength constant; *D* is the drilling exponent, dimensionless; WOB is the weight on bit, lbs; BS is the bit size, inch.

The drillability of rocks is called the *D*-exponent determined by removing the effects of external drilling parameters on the ROP values. This exponent increases with advancing of drilling during the normally pressured formations and is directly proportional to the rock strength. On the other hand, when drilling into abnormally pressured shale, the exponent will decrease with increasing of the depth. During the drilling of the uncompacted geological sections, the density decreases so this led to more drillable formations with the drilling parameters stay unchanged. The abnormal pressure zones are accurately detected by using the non-worn bit than the worn-down bit, where the non-worn bit gives the *D*-exponent values as an effective indicator of pore pressure and abnormally pressured zones (Rabia 2002; Ablard et al. 2012).

From the previous formula, the “*D*” value can be derived at each depth by inserting constants for oilfield units and “log” mathematic function. Also, let “*a*” in Eq. (1) equal to unity to simplify Eq. (1) as shown in Eq. (2) by Jorden and Shirley (1966).

Table 1 Wire-line logging and mud logging records in the three studied wells

Well name	Wire-line logging records			Mud logging records
	Top (ft)	Bottom (ft)	Resistivity, caliper, photoelectric effect, neutron porosity, thermal neutron porosity, formation density, gamma ray	
ASHRAFI_H_IX_ST2	5832.00	6345.00		Rate of penetration, torque, hook load, stand pipe pressure, mud weight, bit size, revaluation per minute, weight n bit, stroke per minute, cutting lithology, lithology interpretation, oil shows, total gas, hydrocarbon gases, mgco ₃ %, caco ₃ %, lithology description
ASHRAFI_I_IX_ST	6580.00	6875.00		
ASHRAFI_K_IX	7655.00	8005.00		

$$D = \frac{\text{Log}\left(\frac{\text{ROP}}{60 \times \text{RPM}}\right)}{\text{Log}\left(\frac{12 \times \text{WOB}}{1000 \times \text{BS}}\right)} \quad (2)$$

where ROP is the rate of penetration, ft/h; RPM is the rotary speed, rpm; WOB is the weight on bit, klbs; BS is the bit size, inch

Normalization of methane gas (C_1)

The normalization of methane gas is a mathematical rectification of the drilling parameters which affect gas shows, where the increase in the flow rate causes extracting more gases to the surface. Also, the gases are inversely proportional with ROP, where the low ROP allows extract more gases at this depth of the adjacent layers. The bit size and the wellbore size are directly proportional to the lagging time of the gas sample so that the gases reach the surface quickly. Clearly, Eq. (3) is capable to correct methane gas (the major component of hydrocarbon gases) from the different drilling phases (Kandel et al. 2000). Normalizing of methane gas is expressed in the following Eq. (3):

$$C_{1\text{Norm}} = \frac{11.6 \times C_1 \times \text{FLOW}}{\text{ROP} \times (\text{BS})^2} \quad (3)$$

where $C_{1\text{Norm}}$ is the normalization of the methane gas, ppm; C_1 is the methane gas, ppm; Flow is the mudflow in the borehole, l/min; ROP is the rate of penetration, m/min; BS is the bit size (diameter), m

Perforability index (PI)

The porosity (ϕ) and water saturation (S_w) of the formation during the drilling of the borehole (real-time) are very important parameters. They are calculated by the perforability index (PI) (as an inversion of the D -exponent values) and by using the unit's conversion; then, Eq. (2) is reformulated to Eq. (4) (Giulia and Devendra 2011).

This index directly expresses the profit intervals since the increase in the (PI) values matches with the high porosity and low bulk density of the formation. The decrease in the D -exponent may be interpreted as due to the drilling in sandstone intervals which is characterized by quick drilling, whereas the shale intervals are associated with the decrease in the rate of penetration due to the reduction in bit capability to drill (shale cuttings fill gaps between bit teethes). Clearly, the perforability index (PI) is calculated by Eq. (4).

$$\text{PI} = 1 / \left[\frac{\text{Log}\left(\frac{\text{ROP}}{\text{RPM}}\right)}{\text{Log}\left(\frac{3 \times \text{WOB}}{14 \times \text{BS}}\right)} \right] \quad (4)$$

where PI is the perforability index, dimensionless; ROP is the rate of penetration, ft/min; RPM is the rotary speed, rpm; WOB is the weight on bit, 1000 kg; BS is the bit size (diameter), m

Water saturation (S_{w_Gas})

The water saturation (S_w) is estimated by integrating the perforability index (PI) and the normalized methane gas to detect the benefit intervals (PI and the hydrocarbon gases increase at the water saturation which is less than 100%). The formation fluids (water and hydrocarbons) have different behavior in mobility and filling kinetics, where these depend on values of surface tension, contact angle, and viscosity of the bulk liquid. The theory of forming formation fluids in reservoirs is due to capillary filling kinetic in a microchannel, where fluid interfaces, geometry, and rock wettability (from oil-wet to water-wet) are among the effective parameters in filling analysis of reservoirs (Mozaffari et al. 2017; Keshmiri et al. 2016). As well, the shale or tight formations are associated with the lower values of the PI, the hydrocarbon gases content, and the water saturation. This method is carried out by the (G_w) baseline, which separates the two clusters of points by plotting of $C_{1\text{norm}}$ and (PI) on the Y- and X-axis, respectively. Therefore, the points below the (G_w) baseline represents water saturation of 100% and the other points above this line have low values of the water saturation (SW) less than 100%. The baseline is drawn and the equation of this line extracted which used to estimate the water saturation from gas methane (S_{w_Gas}) by using Eq. (5) (Giulia and Devendra 2011).

$$S_{w_Gas} = \sqrt{\frac{G_w}{C_{1\text{Norm}}}} \quad (5)$$

where S_{w_Gas} is the water saturation from methane gas, fraction; G_w is the baseline at water saturation 100%, (extracted from the equation of a line between two cluster zones); $C_{1\text{Norm}}$ is the normalization of the methane gas, ppm

The estimation of water saturation from gas methane is based on assumptions that the water saturation is less than 100% in the formation which has methane gas, and the G_w line represents 100% water saturation. The G_w line is determined by normalizing the methane gas ($C_{1\text{norm}}$, ppm) which is plotted on the Y-axis versus the perforability index (PI) on the X-axis (log–log cross-plot), used to remove effect the drilling parameters on methane gases values from formation.

Porosity (ϕ_{ML})

The porosity is estimated from mud logging by representing (PI) values versus depth and by tracing the zero baselines of

(PI_{0line}) at the low (PI) values. Tracing of this line is by trial and error until reach to acceptable results; this line indicates the tight intervals or the shale layers. The equation of this line is used to calculate zero PI at each value of PI as a function of depth. By solving Eq. (6), the porosity is determined at every depth (Giulia and Devendra 2011), where the porosity values depend on the location of the points from the PI_{0line} , and the porosity is estimated by Eq. (6):

$$\phi_{ML} = \left\{ \left\{ \frac{PI - PI_{0line}}{PI_{0line}} \right\} + K \right\} M \quad (6)$$

where ϕ_{ML} is the porosity from mud logging technique, fraction; PI_{0line} is the PI baseline in shale zone at 0% effective porosity (shale baseline), dimensionless; K and M are the constants based on the lithology and the type of basin, $0.2 < K < 1$ and $0.05 < M < 0.5$.

The porosity estimation from the empirical equation from mud logging data is very important to determine the porosity with depths. Therefore, these porosity values are real-time data during drilling, which may be helped to make a quick decision about these zones. The application of this equation in this study by using perforability index is a tool to confirm the overpressure zones by comparing the porosity values from mud logging with the porosity from wire-line logging.

Analysis of wire-line logging

The petrophysical parameters of the studied three wells are determined from the wire-line logging data; these data in Ashrafi field are presented in Table 1. By utilizing Interactive Petrophysics software, the zone of interest (Kareem Formation) is determined. Also, this software used for estimating the resistivity, the porosity, and the permeability is as follows:

Resistivity

The water resistivity (R_w) of the formation is mostly estimated from the formation resistivity or the deep resistivity (R_t), which is determined from latero-log or induction log (direct measurements during the wire-line records) (Paul 2011).

Porosity

The neutron and the density logs are utilized to discriminate between water-bearing zones than hydrocarbon intervals; this usually is performed by using the cross-plot between them. Also, the porosity is corrected and calculated by combining these logs as follows in Eq. (7) (Asquith and Gibson 1982):

$$\phi_{corr} = \sqrt{\frac{\phi_D^2 + \phi_N^2}{2}} \quad (7)$$

where ϕ_{corr} is the corrected porosity by density and neutron logs, fraction; ϕ_D is the porosity from density log, fraction; ϕ_N is the porosity from neutron log, fraction

Permeability

The permeability is calculated by using a Young–Laplace equation, and the general formula was introduced by Wyllie and Rose (1950). So, the modification of this equation is made by using the constants which is based on the formation characterization (grain-size, grain sorting, fluid saturation, and reservoir diagenesis) and the irreducible water saturation (S_{wi}) which is determined from core analysis of the samples. By using the corrected porosity (ϕ_{corr}) calculated from Eq. (7), the empirical equation of the permeability will become as follows in Eq. (8) (Coats and Dumanoir 1974):

$$k^{0.5} = 100 \times \frac{(1 - S_{wi}) \times \phi_{corr}^2}{S_{wi}} \quad (8)$$

where k is the permeability, mD; S_{wi} is the irreducible water saturation, fraction

Results and discussion

Cuttings analysis during mud logging

Rock cuttings provide information about formation lithology, which is required in the stratigraphic correlation. In addition, these may be used to determine the oil shows in rock samples and help to interpret some phenomena and problems which match with the lithology variation such as overpressure zones and losses of drilling fluids during under-pressure zones. Also, the rock cutting is a source for microfossils used in biostratigraphy of reservoirs.

The sampling operation is every 10 ft during the drilling to detect the lithology changes with drilling advancing. Figure 3a–c shows the percent of lithology variation in the Ash_H_1X_ST2, Ash_I_1X_ST, and Ash_K_1X wells, respectively. As well, the lithology type variations have effects on the petrophysical parameters and pore pressure, where the overpressure zones are detected at the intercalation of streaks sandstone and shale in the studied wells.

Drilling exponent (D-exponent)

The D -exponent increases with the depth and takes mathematical form as the power function that is inversely proportional to the rate of penetration (ROP) for the three wells (Ash_H_1X_ST2, Ash_I_1X_ST, and Ash_K_1X) as shown in Fig. 4. As well, these relationships give very good to excellent correlation coefficient values (0.88, 0.98,

Fig. 3 Lithology percent variation with depth. **a** Ashrafi_H_1X_ST, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. The red dashed lines represent the possible average overpressure depths

and 0.78, respectively). So, by averaging these relationship results, we can use a general empirical relationship for the Kareem Formation in Ashrafi field as follows in Eq. (9):

$$D\text{-exponent} = 2.1378 (\text{ROP})^{-0.1716} \quad (9)$$

where ROP is the rate of penetration, ft/h.

Fig. 4 *D*-exponent and rate of penetration (ROP, ft/h) relationship for the three studied wells

In Fig. 4, the *D*-exponents for the three wells have high values with ROP values range from 0 to 5 ft/h, which may be attributed to the shale intervals. Also, the green relationship for the Ash_I_1X_ST well shows that most of the density values are in range from 0 to 5 ft/h, where the shale is the main lithology in this well. As well, the ROP values above 5 ft/h refer to the intercalation of shale and sandstone; thus, the very high values of ROP with low values of the *D*-exponent may refer to sandstone as the main lithology.

Comparing the *D*-exponent values in the three studied wells clarified that the *D*-exponent values in Ash_K_1X well are greater than the other two wells. Thus, this may be attributed to the formation fluid content as well as the dominant sandstone lithology.

The integration of both *D*-exponent and the resistivity from wire-line logging for the three wells is considered as a tool to detect the overpressure zones as shown in Fig. 5. Therefore, the overpressure zone in the Ash_H_1X_ST2 well is detected at depth interval ranges from 6010 to 6050 ft (Fig. 5a), which is marked by a change in the trends of *D*-exponent and the resistivity with lithology, where the lithology changes from marl of low *D*-exponent and low resistivity values to sandstone intercalated with anhydrite and marl of high *D*-exponent and high resistivity values.

In Fig. 5b, the top of the overpressure zone in the Ash_I_1X_ST well is detected at the top of Kareem Formation, and the bottom at 6690 ft, this may be attributed to sandy shale of low *D*-exponent and high resistivity values which overlies the shale layer. In the Ash_K_1X well (Fig. 5c), the lithology of the overpressure zone is shaly

sandstone and detected at depth interval ranging from 7710 to 7830 ft with low *D*-exponent and high resistivity values. This interval overlies the sandstone interval that reflects a decrease in *D*-exponent and resistivity values.

Correlating the *D*-exponent with porosity from wire-line logging for the three wells Ash_H_1X_ST2, Ash_I_1X_ST, and Ash_K_1X is another tool to detect and confirm the overpressure zones as shown in Fig. 6. Therefore, the overpressure zone in the Ash_H_1X_ST2 well is detected at depth interval ranging from 6010 to 6120 ft. The overpressure zone is detected in the Ash_I_1X_ST well at the top of Kareem Formation, and the bottom at depth 6725 ft, which marked by sandy shale. Also, the overpressure zone is detected in the Ash_K_1X well at depth ranging from 7710 ft to 7850 ft and matched with the shaly sandstone lithology.

Plotting the permeability from wire-line logging with the *D*-exponent for the studied wells used to determine overpressure zones as shown in Fig. 7a–c. Therefore, the depth interval of the zone in the Ash_H_1X_ST2 well is ranging from 6025 to 6140 ft, the zone depths in the Ash_I_1X_ST well are at the top of Kareem Formation and the bottom at 6710 ft, whereas the depth interval in the Ash_K_1X well is ranging from 7710 to 7850 ft.

Water saturation from methane gas (S_{w_Gas})

Representing the normalized methane gas (C_{Inorm}) on the Y-axis versus the perforability index (PI) on the X-axis (log–log cross-plot) is used to derive the (G_w) baseline which representing the 100% water saturation. Therefore, the

Fig. 5 D-exponent and resistivity log with depth relationship. **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. The red dashed lines represent the possible overpressure depths

Fig. 6 D-exponent and porosity log with depth relationship. **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. The red dashed lines represent the possible overpressure depths

Fig. 7 D-exponent and permeability log with depth relationship. **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. The red dashed lines represent the possible overpressure depths

Fig. 8 Perforability index (PI) and normalized methane (ppm) relationships. **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. Gw is the gas–water baseline

relationship illustrates two cluster of points (Fig. 8a–c) for the three Ash_H_1X_ST2, Ash_I_1X_ST, and Ash_K_1X wells, respectively. The cluster 2 represents the lower values of CI (water-bearing and shale formation), whereas cluster 1 represents the high values of CI (hydrocarbon zones) with different values of water saturation.

The G_w line passes between the two clusters of points, where the points below this line represent the 100% water saturation. On the other hand, the points above this line indicate the water saturation less than 100%, depending upon the point location from this line and the values of hydrocarbon gas.

After determining the two sets of points, the line is drawn between them by using a trial and error method, and then the equation of the baseline G_w is extracted. The water saturation from gas methane can be calculated by using Eq. (5) and the following Eqs. (10), (11), and (12) for the G_w line;

$$G_w = 2.500E + 11PI^{-9.560} \text{ "Ash_H_1X_ST2"} \quad (10)$$

$$G_w = 1.909E + 12PI^{-1.234} \text{ "Ash_I_1X_ST"} \quad (11)$$

$$G_w = 2.1100E + 11PI^{-9.312} \text{ "Ash_K_1X"} \quad (12)$$

where G_w is the value of C_{Inorm} at baseline (G_w baseline), where the water saturation is 100% (ppm); PI is the perforability index (dimensionless).

The water saturation is plotted versus depth accompanied with the resistivity from wire logging as shown in Fig. 9a–c for the three wells Ash_H_1X_ST2, Ash_I_1X_ST, and Ash_K_1X, respectively. The hydrocarbon zone is characterized by the high values of resistivity and the water saturation which is less than 100%. The zone depths in the Ash_H_1X_ST2 well are ranging from 6010 to 6050 ft, whereas the zone is detected in the Ash_I_1X_ST well at the top of Kareem Formation, and the bottom at depth 6700 ft. Also, the zone depths in the Ash_K_1X well are ranging from 7710 to 7840 ft.

The permeability from wire-line logging versus the methane gas (mud logging) is plotted with the depth as shown in Fig. 10a–c for the studied wells. The zones of overpressure are marked by the zones that have hydrocarbon indicator. So, these zones are detected at top depth of 6040 ft and bottom depth of 6080 ft in the Ash_H_1X_ST2 well, whereas in the Ash_I_1X_ST well, the zone is detected at the top of Kareem Formation and at bottom depth of 6710 ft. As well as, the top and bottom depths are at 7730 ft and 7810 ft, respectively, in the Ash_K_1X well.

Porosity from mud logging

The mud logging porosity can be calculated by using Eq. (6), where the perforability index of the shale zones have zero effective porosity and determined from the equations (PI0line) at each depth. These equations are obtained from the cross-plots between depth and perforability index (PI) by tracing the line at low values of the perforability index and extracting the equation of this line. This line represents the shale baseline or poor zones of the hydrocarbon content as shown in Fig. 11a–c for the studied wells. Moreover, the general increase of PI values in the Ash_K_1X well with depth may be due to the predominant sandstone lithology in this well.

By comparing the porosity results from the mud logging with the porosity of the wire-line logging in Fig. 12a–c, which represent a good matching in the studied wells, the top and the bottom of the overpressure zones are detected at 6040 ft and 6120 ft, respectively, in the Ash_H_1X_ST2 well, at the top of Kareem Formation and bottom depth 6690 ft in the Ash_I_1X_ST well, and at 7740 ft and 7820 ft, respectively, in the Ash_K_1X well.

The previous integrations and results are summarized in Table 2, as well as, the average depths for each overpressure zone for the Kareem Formation in the three Ash_H_1X_ST2, Ash_I_1X_ST, and Ash_K_1X wells.

Finally, the concept of detecting the overpressure zones by integrating D -exponent with the different petrophysical parameters such as porosity, permeability, and resistivity is based on finding out the marked changes between these curves, in addition to the change in lithological content for the studied wells that effect on the thickness of overpressure zones. Most of the overpressure zones were detected and accompanied with the intervals of sandstone and shale intercalation in the studied wells.

Once more to confirm the above results, these intervals are mostly marked by a decrease in porosity and permeability as well as an increase in resistivity and D -exponent. The high resistivity values in these intervals may be attributed to the high hydrocarbon content. The high values of the D -exponent are probably due to the low rate of penetration in the shale zones. Also, the thickness of the overpressure zone in the Ash_H_1X_ST2 well is influenced by the marl content that reaches up to 80%.

Fig. 9 Water saturation (S_w , fraction) from mud logging and resistivity (R , ohm m) from wire-line logging with depth relationships **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. The green dashed lines represent the possible overpressure depths

Fig. 10 The relationships between methane gas (ppm) and permeability (K , mD) with depth **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. The red dashed lines represent the possible overpressure depths

Fig. 11 Perforability index (PI) and depth relationships **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X

Fig. 12 Comparison between mud logging porosity (fraction) and wire-line logging porosity (fraction) with depth **a** Ashrafi_H_1X_ST2, **b** Ashrafi_I_1X_ST, and **c** Ashrafi_K_1X. The red dashed lines represent the possible overpressure depths

Table 2 The summarized relationships to detect overpressure depths

Relationships	Ashrafi_H_1X_ST2 Depth, ft		Ashrafi_I_1X_ST Depth, ft	Ashrafi_K_1X Depth, ft	
	Top (ft)	Bottom (ft)	Bottom (ft)	Top (ft)	Bottom (ft)
D -exp. and R_t log	6010.00	6050.00	6690.00	7710.00	7830.00
D -exp. and ϕ log	6010.00	6120.00	6725.00	7710.00	7850.00
D -exp. and k log	6025.00	6140.00	6710.00	7710.00	7850.00
Sw-gas mud and R_t log	6010.00	6050.00	6700.00	7710.00	7840.00
Methane gas mud and k log	6040.00	6080.00	6710.00	7730.00	7810.00
ϕ mud and ϕ log	6040.00	6120.00	6690.00	7740.00	7820.00
The average depth of overpressure zones	6022.50	6093.30	6704.20	7718.33	7833.33

The top of overpressure zone in Ashrafi_I_1X_ST well is at Kareem Formation top is 6580.00 ft

Summary and conclusion

The main goal of this study is based on using the change in the D -exponent trends that arise from the variations of the fluids and the lithology of the Kareem Formation. Therefore, these trends are integrated with the petrophysical parameters such as resistivity, porosity, and permeability from wire-line logging to detect the overpressure zones.

Perforability index (PI) is an inversion of the D -exponent, utilized to directly express the promise intervals within the formation, where the drilling becomes fast through the sandstone layers. Also, it is used to estimate the water saturation and porosity from mud logging technique.

The plotting of normalizing methane gas and (PI) are used to separate between the promise intervals and water-bearing or shale intervals by using the baseline (G_w). So, the water saturation is estimated by utilizing this baseline and integration with the resistivity from wire-line logging to confirm the overpressure zones.

The porosity is estimated from mud logging by using the (PI) (inversion of the D -exponent), and is plotted and compared with the porosity of wire-line logging as another tool to emphasize the overpressure zones.

In the three structurally blocks H, K, and I, the thickness of the abnormal pressure zone is influenced by the lithological variations. Clearly, the dominant marl content that reaches up to 80% in the well Ash_H_1X_ST2, which has low porosity, and the lithology changes to the intercalation of tight sand with anhydrite and marl. On the other hand, the sandstone and the shale lithology in the Ash_I_1X_ST and Ash_K_1X wells cause the creation of the overpressure zones, which are affected by the hydrocarbon content in the streaks of sandstones.

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References

- Abd El-Naby A, Abd El-Aal M, Kuss J, Boukhary M, Lashin A (2009) Structural and basin evolution in Miocene time, southwestern Gulf of Suez, Egypt. *Neues Jahrbuch für Geologie und Paläontologie—Abhandlungen* 251(3):331–353
- Abd El-Naby AIM, Ghanem H, Boukhary M, Abd El-Aal M, Lüning S, Kuss J (2010) Sequence stratigraphic interpretation of structurally controlled deposition: Middle Miocene Kareem Formation, southwestern Gulf of Suez, Egypt. *GeoArabia* 15(3):129–150
- Ablard P, Lawton L, Haines G, Herkommer MA, McCarthy K, Radakovic M, Umar L (2012) The expanding role of mud logging. *Oilfield Rev* 24(1):31–32
- Alsharhan AS, Salah MG (1994) Geology and hydrocarbon habitat in rift setting: Southern Gulf of Suez, Egypt. *Bull Can Pet Geol* 42:312–331
- Alsharhan AS, Salah MG (1995) Geology and hydrocarbon habitat in rift setting: Northern and central Gulf of Suez, Egypt. *Bull Can Pet Geol* 43(2):156–176
- Asquith GB, Gibson CR (1982) Basic wireline-logging analysis for geologists. Series on methods in exploration. The American of Association Petroleum Geologists, Tulsa, p 226
- Asquith G, Krygowski D (2004) Basic well log analysis, 2nd edn. AAPG, New York
- Bentley BB, Biller EJ (1990) Exploitation study and impact on the Kareem Formation, South El Morgan Field, Gulf of Suez, Egypt. In: Offshore technology conference, 7–10 May, Houston, TX, OTC-6270-MS
- Bingham MG (1965) A New approach to interpreting rock drillability. Petroleum Publishing Company, Tulsa, A technical manual reprinted from the Oil and gas journal, 93p
- Boatman WA (1967) Measuring and using shale density to aid in drilling wells in high-pressure areas. *Soc Petrol Eng* 19:1423–1429. <https://doi.org/10.2118/1799-PA>
- Bowers GL (2002) Detecting high overpressure, the leading edge. SEG Publication, Houston, pp 174–177
- Burke JA, Campbell RL, Schmidt AW (1969) The litho-porosity crossplot. The log analyst SPWLA. In: 10th Annual symposium transactions, November–December, Paper J
- Coats GR, Dumanoir JL (1974) A new approach to improved log-derived permeability. The log analyst, p 17

- Danenberger EP (1993) Outer continental shelf drilling blowouts. In: Offshore technology conference, Houston, OTC 7248
- Darwish M, El-Araby M (1993) Petrography and diagenetic aspects of some siliciclastic hydrocarbon reservoir in relation to rifting of the Gulf of Suez, Egypt. *J Geol* 1:155–189
- El-Araby A, Moneim AA, Darwish M (2009) Geological modeling of Kareem Formation in Amal oil field, south Gulf of Suez, Egypt. In: Proceedings of the 1st symposium on the geological resources in the Tethys Realm
- El Sharawy MS (2013) Reservoir characterization of Kareem Formation along the central trough of the Southern Gulf of Suez, Egypt. *J Appl Sci Res* 9(3):1798–1814
- El Sharawy MS, Nabawy BS (2016) Determination of electrofacies using wireline logs based on multivariate statistical analysis for the Kareem Formation, Gulf of Suez, Egypt. *Environ Earth Sci* 75(21):1394
- El-Werr A, Shebl A, El-Rawy A, Al-Gundor N (2017) Pre-drill pore pressure prediction using seismic velocities for prospect areas at Beni Suef Oil Field, Western Desert, Egypt. *J Petrol Explor Prod Technol* 7:1011–1021. <https://doi.org/10.1007/s13202-017-0359-6>
- Giulia B, Devendra T (2011) An innovative approach for estimating the sw and porosity using gas and mud logging data in real time. In: AAPG international conference and exhibition, October, Milan, Italy
- Hagoort J (1974) Displacement stability of water drives in water wet connate water bearing reservoirs. *Soc Petrol Eng J Trans.* <https://doi.org/10.2118/4268-PA>
- Hakiki F, Shidqi M (2018) Revisiting fracture gradient: comments on “A new approaching method to estimate fracture gradient by correcting Matthew–Kelly and Eaton’s stress ratio”. *Petroleum* 4(1):1–6
- Harkins KL, Baugher JW (1969) Geological significance of abnormal formation pressures. *J Petrol Technol* 21(08):961–966. <https://doi.org/10.2118/2228-pa>
- Hottmann CE, Johnson RK (1965) Estimation of formation pressures from log-derived shale properties. *Soc Petrol Eng.* <https://doi.org/10.2118/1110-PA>
- Jacquard P, Seguier P (1962) Movement de Deux Fluides en Contact dans un Milieu Poreux. *J de Mechanique*, pp 1–25
- Jorden JR, Shirley OJ (1966) Application of drilling performance data to overpressure detection. *Soc Petrol Eng.* <https://doi.org/10.2118/1407-PA>
- Kaiser WR, Swartz T E (1988) Hydrology of the Fruitland Formation and coalbed methane producibility. In: Ayers WB, Jr et al. (eds) *Geologic evaluation of critical production parameters for coalbed methane resources; Part 1. The University of Texas at Austin, Bureau of Economic Geology, San Juan Basin. Annual report prepared for the Gas Research Institute, GRI-88/ 0332.1*, pp 61–81
- Kalidhasan R, Kaushalendra BT, Mimonitu O (2019) A 2D geomechanical model of an offshore gas field in the Bredasdorp Basin, South Africa. *J Petrol Explor Prod Technol* 9:207–222
- Kandel D, Quagliaroli R, Segalini G, Barraud B (2000) Improved integrated reservoir interpretation using the gas while drilling (GWD) data. Society of petroleum engineers, SPE European petroleum conference, 24–25 October, Paris, France. <https://doi.org/10.2118/65176-ms>
- Keshmiri K, Mozaffari S, Tchoukov P, Huang H, Nazemifard N (2016) Using microfluidic device to study rheological properties of heavy oil. In: AIChE conference. [arXiv:1611.10163v1](https://arxiv.org/abs/1611.10163v1)
- Morris RL, Biggs WP (1967) Using logging derived values of water saturation and porosity. In: SPWLA symposium, Paper X
- Mouchet JP, Mitchell AF (1989) Abnormal pressures while drilling: origins, prediction, detection, Elf aquitaine edition. *Eval Tech* 2:225
- Mozaffari S, Tchoukov P, Mozaffari A, Atias J, Czarnecki J, Nazemifard N (2017) Capillary driven flow in nanochannels—application to heavy oil rheology studies. *Colloids Surf A Physicochem Eng Aspects* 513:178–187. <https://doi.org/10.1016/j.colsurfa.2016.10.038>
- Nabawy BS, El Sharawy MS (2018) Reservoir assessment and quality discrimination of Kareem Formation using integrated petrophysical data, Southern Gulf of Suez, Egypt. *Mar Petrol Geol* 93:230–246
- Neda N, Seyed RS, Abbas KM (2017) Determination of pore size distribution profile along wellbore: using repeat formation tester. *J Petrol Explor Prod Technol* 7:621–626. <https://doi.org/10.1007/s13202-016-0310-2>
- Paul FW (2011) The petrophysics of problematic reservoirs. SPE, Gaffney, Cline & Associates, Amsterdam
- Rabia H (2002) Entrac Consulting, Well Engineering & Construction, pp 26–29. ISBN: 0954108701. <http://faculty.ksu.edu.sa/shokir/PGE472/Textbook%20and%20References/RABIA%20-%20WELL%20ENGINEERING%20%20CONSTRUCTION.pdf>
- Rine JM (1985) Lithology and reservoir characteristics of Hilal -A5, Kareem Formation; interval 8065–8122 ft: Gupco Unpublished Internal Report
- Salah MG, Alsharhan AS (1997) The Miocene Kareem Formation in the southern Gulf of Suez, Egypt: a review on stratigraphy and petroleum geology. *J Petrol Geol* 20(3):327–346
- Sanyal SK, Robertson-Tait A, Kramer M, Buening N (1993) Some aspects of geopressed resources in California. *Geoth Resour Coun Trans* 17:175–180
- Singha DK, Chatterjee R (2014) Detection of overpressure zones and a statistical model for pore pressure estimation from well logs in the Krishna-Godavari Basin, India. *Geochem Geophys Geosyst* 15:1009–1020. <https://doi.org/10.1002/2013GC005162>
- Swarbrick RE, Osborne MJ, Grunberger D, Yardley G, Macleod G, Aplin A, Larter SR, Knight I, Auld H (2000) Integrated study of the Judy field (block 30/7a)—an over pressured central North Sea oil/gas field. *Mar Petrol Geol* 17(9):993–1010
- Sylvester AU, Cyril NN (2014) Integrated approach to geopressure detection in the X-field, Onshore Niger Delta. *J Petrol Explor Prod Technol* 4:215–231. <https://doi.org/10.1007/s13202-013-0088-4>
- Tewfik N, Harwood C, Deighton I (1992) The Miocene, Rudeis and Kareem Formations in the Gulf of Suez: aspects of sedimentology and geohistory. In: 11th EGPC exploration seminar, Cairo, vol 1, pp 84–113
- Thomas F, Mark Z, Peter F, Beth S (2001) Stress, pore pressure, and dynamically constrained hydrocarbon columns in the South Eugene Island 330 field, northern Gulf of Mexico. *AAPG Bull* 85(6):1007–1031
- Wyllie MRJ, Rose WD (1950) Some theoretical considerations related to the quantitative evaluation of the physical characterization of reservoir rock from electric log data. *Trans AIME* 189:105–118
- Xie X, Bethke CM, Li S, Liu X, Zheng H (2001) Overpressure and petroleum generation and accumulation in the Dongying depression of the Bohaiwan Basin, China. *Geofluids* 1:257–271
- Zhang JJ (2011) Pore pressure prediction from well logs: methods, modifications, and new approaches. *Earth Sci Rev* 108:50–63

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