Integration of resistivity, neutron, and density logs for detecting, identifying, and calculating of groundwater over-pressuring phenomenon at Siwa Oasis Depression, Egypt

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Abstract
Along with Siwa Oasis depression, there are several ponds, lakes, and Sabkhas features resulted from the current flows through the springs due to the over-pressure of deep sandstone aquifer. The Nubia Sandstone aquifer (NSA) and Carbonate aquifer are the main two water-bearing units. They are separated by a huge thickness of shale and controlled by complicated structural faults. There are ten wells including gamma-ray, short and long resistivity, caliper, neutron, and density logs. These logs were used in identifying the lithology, calculating the porosities, water saturation percentages, and effective permeability. The long resistivity, neutron, and density logs were used to detect, identify, and calculate this over-pressure and its zones. The shale resistivity, porosity, and density of the Nubia Sandstone formation were used in determining the expected normal compaction trend. The top of over-pressuring, over-pressuring forewarning, over-pressuring transition, and over-pressuring zones were detected. The formation pressure and its gradient were calculated at the first depth in the over-pressuring zone. The piezometric heads and pressures were calculated and mapped. The depths to the top of over-pressures, formation pressures, and their gradient maps were constructed. The statistical analyses between the two pressures were carried out. Accordingly, the thickness and type of shale, the effective porosity, the compaction of the deep aquifer, the huge thickness of the overlaid formation and its porosities, and the complicated structural conditions are considered the main factors in generating the over-pressuring phenomenon at Siwa Oasis. Therefore, this study considers that the used logs are compatible powerful tools in studying this phenomenon.

Keywords Resistivity, neutron, and density logs · Groundwater over-pressuring phenomenon · Resistivity, porosity, and density of shale · Formation and piezometric pressures · Over-pressure zones

Introduction
Over-pressure (OP) phenomena forecasting of the deep formations is difficult and it is an interesting key for several factors like drilling engineering, designing of wells, and planning for drilling for avoiding and overcoming the appearance of environmental troubles from appearing of lake and ponds. There are a number of pressures within the lithological formations such as the pore pressure (formation pressure), the pressure of rock grain, and the total overburden pressure which is backup by the former two pressures, where the formation pressure (Fp) is a part of the overburden pressure (Ammar 2005). The overburden pressure resulted from the united between the rock matrix weight and the fluid (groundwater) into the pores and it depends upon the compaction which is resulted in the pore space reduction. So, if the compaction increases with depth, the overburden pressure gradient will increase until a particular limit. The pressure is not equal in all directions when the sediment is heterogeneous. The normal and subnormal pressures are the main two types of Fp as well as the abnormal pressure (over-pressure) which occurs due to the pore pressure greater than the hydrostatic pressure at a certain depth. This study will focus on the last type of pressures and it differs due to the pressure origin and because of increasing the compaction with depth, the effective porosity will reduce, and the groundwater will trap and

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become under pressure. When the water flow is presented by the impermeable bed (shale) that isolated the porous sandstone, or the appropriate placement of such tectonic events (faulting), the Fp will create in the rock beds.

For a hydro-pressured system in the selected area (Fig. 1A panel), the porous and permeable aquifers like sandstone exist between impermeable shale and tight to fractured limestone and shaly limestone. So, because of the huge thickness of limestone and shale overlain, the aquifer and the ratio of shale are greater than the ratio of sandstone at different depths as well as the structural faults, the over-pressure will create. All the former cases are presented in the selected area. Accordingly, due to the squeezing of groundwater into the sandstone and its movement horizontally to other locations and vertically via the faults plan between over-pressured sandstone formation and an upper normally pressured limestone formation. Also, it is expected that the over-pressure at the sandstone was created due to the pressure of the weight of overburden, or overlying limestone rock.

If the groundwater within the sediments is captured into the pores, compaction is retarded, and the groundwater pressure becomes high and ultimately approaches the pressure that overlying rocks and contained groundwater exert. Normal formation pressure (NFP) at any determined depth is defined as being equal to the hydrostatic pressure (HP) exerted by a column of water of a height equal to the depth in question. The hydrostatic pressure exists, due to the height and weight of groundwater column. The fluid column size and shape have no effect on the hydrostatic pressure which can be determined by the following equation (Hottman and Johnson 1965):

\[ P_h = \delta_f D_v \]  

where \( P_h \) is the hydrostatic pressure in pounds per square inch (psi), \( \delta_f \) is the density of fluid, and \( D_v \) is the vertical depth.

Singha and Chatterjee (2014) used repeat formation tester (RFT) and gamma-ray, density, and sonic logs data for detecting the abnormally high pressures in the Miocene shale and Early Cretaceous shale. Kumar (2015) reported that the over-pressure mechanism is based on disequilibrium compaction. The log derived shale porosities shown the signature of under compaction at greater depths where at some intervals of depth, the thickness of shale is as seal for creating the over-pressure in several wells as well as fluid expansion and vertical pressure transfer are the other mechanisms which are associated with post-depositional events. Dickinson (1953) stated that over-pressures occur in

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Fig. 1 General location map (A), a topographic map with elevations in m (B), and a Landsat map to show lakes, ponds, marshes, limestone and cultivated areas (C) of the Siwa Oasis study area.
isolated porous reservoir beds in thick shale sections developed under the main beds or chain of sand. This assumption already exists in the selected study area of Siwa Oasis (Fig. 1A, panel), where there are sheets of sandstone, as isolated porous reservoir beds, into thicknesses of shale. The inter-relation among these parameters controls the compaction of the sedimentary rocks.

Generally, in the NSA in the selected area, huge thickness of shale intervals is frequently encountered. Many of these intervals are shales containing isolated Nubia Sandstone beds. As stated formally, the porosity is an interesting parameter for measuring the compaction degree of shale. Therefore, estimating the porosity of shale as a function of depth will reveal the degree of pressure or compaction. An interval is under compaction regarding to a specific burial depth, will be an interval whose groundwater pressure is high for the burial depth. The data recorded by different well logs can be used to infer the degree of compression or pressure. High permeable sandstone sediments act as venues of groundwater escaping. These sandstone deposits can be considered as pipelines. The almost complete absence of sandstone deposits in thick shale decreases the groundwater rate removal from it compared to thinner shale rocks sandwiched between sandstone deposits. All these conditions are detected and considered in the NSA at the selected study area. Fractures and non-sealing faults can also act as venues of groundwater escape. These conditions exist in the carbonate aquifer overlies the NSA. Because of detecting the overpressuring of the NSA, the sandstone sediments are considered to be important as venues. In such shale intervals, the permeability is small and groundwater removal is restricted; thus, the groundwater pressure of shale will be high for a specific burial depth. Accordingly, the resistivity, neutron, and density logs will be used in this study for detecting, identifying, and calculating the overpressuring phenomenon in the selected Siwa Oasis study area. This oasis lies in the North Western Desert, at about 300 km south of the Mediterranean Sea Coast (Matrouh City) and extended in an E-W direction, occupying an area of about 980 km². It is bounded by longitudes 25° 13′ and 26° 08’ E and latitudes 29° 04’ and 29° 24’ N (Fig. 1A, panel).

**Geology and hydrogeology**

Generally, the Siwa Oasis has an irregular elongated shape, narrowing westward (Fig. 1B, panel). It is bordered from the north by the steep escarpment of the Miocene Marmarica Limestone plateau. The elevation of this plateau is ranged from ~ 68 to 220 m with average ~ 144 m, but the sand dunes mostly cover the southern scarp. The general elevation of the study area is ranged from ~ − 39 to ~ 220 m. As a result of the poor agricultural drainage system, there are four lakes (Fig. 1C, panel). The isolated hills, which are located northwest and north of the Siwa Oasis, are confined to a well-defined belt. This belt is believed to represent a tectonically detached block of the Marmarica limestone plateau (Abd El-Rahman et. al. 1977). These lands consist of several isolated hills and tablelands of different sizes. There are high periphery areas having high topographic elevations (Fig. 1B, panel). The water drainage of these areas is around the lakes and they are bounded by sand dunes from the south, southwest, and west, in which most of them are cultivated (El-Hossary 1999). When the sand is mixed with salts, the Sabkha deposits will be built. These deposits existed in low-lying areas and appear in large parts along Siwa Oasis (Fig. 1C, panel).

Recent active oil exploration work revealed that the presence of subsurface stratigraphic column ranges from Paleozoic age to Recent age. According to the main surface geological sediments are continental to shallow marine clastics shale and sandy shale, silt, clay and evaporates, fossiliferous shallow marine platform limestone with marly intercalations, marine to continental clastic sequence, limestone, and sand dunes. Ammar (2005) used the surface resistivity method, thirty (30) vertical electrical soundings (VESs) (C1C2/2 is 400–700 m) using the Schlumberger array, in studying the shallow section of the carbonate aquifer. Also, well logging data of ten (10) deep drilled wells had used for studying the carbonate aquifer at the upper depths and NSA at the lower great depths as shown in geological and hydrogeoelectrical profile (Fig. 2). All the previous data were used in describing the local subsurface geological conditions in the selected area. The reported lithologies of the subsurface layers (Fig. 2) are the Quaternary deposits and Eocene to upper Cretaceous carbonate rocks, which are composed of two zones separated by thin shale bed, shale then deep sandstone rocks. Also, Ammar (2005) constructed and modified thirteen (13) shallow hydro-geoelectrical profiles were calibrated with well logs. Along these profiles, there are Quaternary deposits, Moghra Formation (Tertiary deposits), and Upper Cretaceous carbonate rocks. There is a thin layer of shale included in the carbonate section and subdivide its rocks into two main zones. The upper layer of Bahariya Formation (Early Cenomanian age) consists of Nubia Sandstone separated from the lower 2nd zone of carbonate rocks by the Late Cretaceous confined shale layer, which is interbedded by sandstone intercalations.

Structurally, the North Western Desert structures where the selected study area are dominated by faults. The majorities of these faults are step normal faults (Hantar in Said 1990). The Siwa Oasis groundwater basin belongs to the Northern up-thrown block and its axis trend is E-W (Ezzat 1974). Ammar (2005) reported that there are two faults directed NE–SW and have a Syrian Arc trend and there are two other faults directed NW–SE and have a Red Sea trend.
(Fig. 7). Rabeh (2012) stated from land magnetic survey, aeromagnetic data, and gravity data that there are tectonic forces affected the area in the E-W trend. In Fig. 3, the interface between the carbonate and NSA was determined from the correlation among the logs of gamma-ray, SN resistivity, and LN resistivity along the geological and hydro-geoelectric profile (Fig. 2).

Ammar (2005) detected that the resistivity values of the second shallow geoelectric layer decrease from the central parts to the eastern and western along Siwa Oasis. The resistivity values of the fourth shallow geoelectric layer are characterized by low to medium values at the central parts. But all the very high resistivity values of the base of the fourth shallow geoelectric layer are detected and concentrated only under the dissected hilly area at the eastern part. So, under this hilly area, he believed that the vertical flow of the groundwater will be transformed to the eastern and western directions, as well as increasing the pressure of the groundwater under these parts. Also, he reported that the depth of carbonate aquifer decreases generally from the central parts toward the eastern and western directions and increases also toward the northern and southern directions. The thickness of shale layer between the two main aquifers increases toward the eastern and western directions and decreases from the southern direction toward the central
part and also from the northern part toward the central part. But, the depth to the top of the NSA decreases toward the northern direction. At the western parts, it increases from the center toward the northern and southern directions along Siwa Oasis.

**Methodology**

**Lithological identification and determination of petrophysical parameters**

In this study, it will be focused on how to identify the lithology in each well at form of matrix (limestone and sandstone) and shale. These volumes affected the rock characteristics such as rock porosity, rock permeability, fluid saturation, rock productivity, and so on. Also, they cause erroneous determinations for the different rock matrices. So, to calculate the shale volumes, the following methods will be used:

The gamma-ray index (IGR) is determined by using the following equation:

\[
IGR = \frac{GR_{max} - GR_{min}}{GR_{max} - GR_{min}}
\]  

(2)

where \(GR_{log}\): the GR reading for each zone, \(GR_{min}\): the min GR value of pure carbonate or sandstone, and \(GR_{max}\): the max GR value of shale.

By using the following formulae (Dresser Atlas 1979), the shale volume is calculated from the gamma-ray index.

1) Paleozoic and Mesozoic consolidated rocks:

\[
V_{sh} = 0.33[2^{(2.4 \cdot IGR)} - 1.0] = \chi
\]

(3)

2) Unconsolidated rocks of Tertiary:

\[
V_{sh} = 0.083[2^{(3.7 \cdot IGR)} - 1.0)] = \chi
\]

(4)

In case of high shale content and low values of effective porosities, the neutron log can be used for determining the shale volume, by using the following formula:

\[
V_{sh} \leq (\phi_N)_{log}/(\phi_N)_{sh} = \chi
\]

(5)

where \((\phi_N)_{log}\): the reading of neutron log for each zone, \((\phi_N)_{sh}\): the reading of neutron log in shale zone.

In case of high shale content and low true resistivity values \((R_t)\), the following formula can use the resistivity log to determine the volume of shale:

\[
V_{sh} \leq (R_{sh}/R_{tlog}) = \chi
\]

(6)

When this ratio is \(> 0.5\) (i.e., \(0.5 \leq V_{sh} \leq 1\)), then:

\[
V_{sh} \leq (R_{sh}/R_{tlog}) = \chi
\]

(7)

When this ratio is \(< 0.5\) (i.e., \(V_{sh} \leq 0.5\)), then:

\[
V_{sh} \leq \left[ \frac{R_{sh} - R_{tlog}}{R_{cl} - R_{sh}} \right]^{1/B} = \chi
\]

(8)

where \(R_{sh}\): the reading of resistivity log (RL) of a shale zone, \(R_{cl}\): the reading of resistivity log (RL) of a shale zone, \(R_{tlog}\): the reading of resistivity log (RL) for each zone, and \(B\): a constant from 1 to 2.

Therefore, min shale volumes must be chosen because most errors for any method tend to increase the apparent volume of shale. According to the matrix and shale volumes calculations for the carbonate and Nubia Sandstone along the study area, the matrix volume increases generally toward the northern direction, while the shale volume increases toward the southern direction. The shale volume increases in the NSA and decreases in the carbonate aquifer. Also, the qualitative interpretation of Dia–porosity cross plots reflects the occurrence of dispersed shale, and structural shale, that are dominating in the carbonate formation. The dispersed shale increases toward the eastern direction, while the structural shale increases toward the western direction from Um El–Heous (He) well. In the Nubia Sandstone section, the dispersed shale and silt are predominant, especially at the eastern parts. This shale is more concentrated in El–Awaff (Aw) well.

Because there are several factors like the matrix of the lithology, the fluid type, and the porosity type have large influence on density and neutron logs, these logs will be used in measuring the total porosity \((\phi_t)\) and effective porosity \((\phi_e)\) as well as the resistivity logs.

The density log is considered the best log in calculating the porosity because it is less affected by the argillaceous matter. So, it will estimate the porosity from this tool in clean and shaly zones. The following formula (Mencher 1964) had been used to derive the porosities from the density log in clean zones:

\[
\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}
\]

(9)

where \(\rho_b\): the formation bulk density, \(\rho_f\): the density of fluid (saline mud = 1.1), and \(\rho_{ma}\): the density of matrix, which will be calculated from the following formula:

\[
\rho_{ma} = \frac{\rho_{silic} + \rho_{carb}}{2}
\]

(10)

where \(\rho_{silic}\): the sandstone zone density, and \(\rho_{carb}\): the carbonate zone density.

In shaly zones, this porosity was calculated by the following formula (Dresser Atlas 1979):

\[
\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}
\]

(9)
\[
\varphi_D = \left[ \frac{\rho_{ma} - \rho_{sh}}{\rho_{ma} - \rho_f} \right] - V_{sh} \left[ \frac{\rho_{ma} - \rho_{sh}}{\rho_{ma} - \rho_f} \right]
\]

where \( \rho_{sh} \) is the density of shaly zone.

The neutron log measures the porosity values (\( \varphi_{CNL} \)) in the clean zone directly while the neutron porosity in shaly zone will be corrected due to the shale effect. Allen’s equation (Allen et al. 1965) is used for manipulating this corrected porosity as follows:

\[
\varphi_{NC} = \varphi_{Nlog} - V_{sh} \cdot \varphi_{Nsh}
\]

where \( \varphi_{NC} \): the corrected neutron porosity, \( \varphi_{Nlog} \): the log neutron porosity, and \( \varphi_{Nsh} \): the shale zone neutron porosity.

If the porosity logs are absent, the resistivity log is used in porosity calculation. Accordingly, the \( F \) (formation factor) will be calculated by applying the Archie’s formula for a saturated rock (Archie 1942):

\[
R_i = F R_w
\]

The following formula will be used in calculating the porosity for consolidated formations and carbonates:

\[
F = 1 \varphi^{-2}
\]

Generally, there are two ways for calculating the effective porosities:

1) \( \varphi_{e1} \) = \( \phi_i \) \( (1 - V_{sh}) \)

2) \( \varphi_{e2} \) = \( \frac{2\phi_{NC} + 7\phi_{DC}}{9} \)

where \( \phi_{NC} \) is the corrected neutron porosity, \( \phi_{DC} \) is the corrected density porosity.

The following equations (Schlumberger 1972) were used in calculating the corrected neutron and density porosities:

\[
\varphi_{NC} = \varphi_n - \left[ \frac{\varphi_{Nsh}}{0.45} \right] \times 0.30 \times V_{sh}
\]

\[
\varphi_{DC} = \varphi_D - \left[ \frac{\varphi_{Dsh}}{0.45} \right] \times 0.13 \times V_{sh}
\]

where \( \varphi_{Nsh} \) is the shale zone neutron porosity, and \( \varphi_{Dsh} \) is the shale zone density porosity.

From calculating the total and effective porosities of the carbonate aquifer, they were decreased toward the eastern direction and increased toward the western direction. The min value of the effective porosity was 6.8%, as reported in El–Awaff (Aw) well, because the formation is less fissured and fractured. The max value was 22%, as reported in El–Shahayem (Sh) well, because the formation was more fissured and fractured, while the total and effective porosities of the NSA increased toward the western direction and decreased toward the eastern direction. The min value of the effective porosity was 5.3%, as calculated in Tamera (Ta) well, while the max value was 15.5%, as determined in El–Shahayem well.

From the logs of resistivity, especially in pure formations with homogeneous porosity (intergranular porosity), the water saturation (\( S_w \)) calculation is based on the following formula of Archie (1942):

\[
S_w = \left[ \left( \frac{a \varphi_n}{R_t} \right) \left( \frac{R_w}{R_i} \right) \right]^{\frac{1}{2}}
\]

where \( a \): the factor of tortuosity (1.0), \( m \): the exponent of cementation (2.0), \( n \): the exponent of saturation (2.0), \( R_w \): the resistivity of water (\( \Omega \cdot m \)), and \( R_i \): the formation true resistivity the (\( \Omega \cdot m \)).

Simandoux (1963) suggested that the following relation (Simandoux 1963) can express the resistivity:

\[
\frac{1}{R_i} = \frac{a R_w (1 - V_{sh})}{2 R_{sh}} + \frac{V_{sh} S_w}{2 R_{sh}}
\]

In using this equation, \( R_{sh} \) equal to the resistivity of adjacent shale beds and \( V_{sh} \) is the shale fraction. Therefore, the Eq. (23) is used for evaluating the water saturation of the shaly sands (\( S_w \)) in case of total shale (\( V_{sh} \)) model, as follows:

\[
S_w = \frac{\frac{-V_{sh}}{R_{sh}} + \sqrt{\left[ \frac{V_{sh}}{R_{sh}} \right]^2 + \left[ \frac{4 \varphi_n^2}{a R_w (1 - V_{sh})} \right]}}{rac{2 \varphi_n^2}{a R_w (1 - V_{sh})}}
\]

The reducible and irreducible water saturation are the two main types of the water saturation. The reducible water can be obtained from the reservoir rocks but irreducible water is an indication of the combined effect of capillary pore forces and the wettability of rocks to liquids, as reported by Neasham (1977). By using the following equation, it can be calculated the irreducible water saturation by using the equation (Crain 1986)

\[
S_{wirr} = \frac{S_w}{\varphi_e}
\]

Then, the reducible water saturation by using the equation

\[
S_{wt} = S_w - S_{wirr}
\]

where \( S_{wirr} \): the saturation of irreducible water, \( S_w \): the saturation of reducible water.

Accordingly, it was found that, the eastern parts had lower saturation percentages of the irreducible (0.2% in Tamera well) and reducible (6.6% in El–Awaff well) waters than the western parts, 12.4% in El–Shahayem well and 12%
in El–Teptah well, respectively, of the carbonate aquifer. This is because the western parts are more fractured and connected horizontally and vertically with the NSA than the other one. The irreducible water saturation of the NSA increases principally toward the central parts and eventually toward the northern direction, where the min value (0.3%) is defined in El–Gerba well and the max value (6.9%) is estimated in Um El–Heous well. The reducible water saturation of this aquifer increases toward the southwest and decreases toward the northeast, where the max value (12.5%) is reached in Bahi El–Din well and the min value (3.2%) is attained in Tamera well. Generally, the considerable amounts of groundwater of the NSA increases toward the western direction, and these amounts increase toward the same direction in the carbonate aquifer. This confirms the presence of hydraulic connection between two aquifers.

The effective permeability depends on the rock and the percentages of water present in the pores; that are, their saturations. The following equation (Crain 1986) can be used in calculating the relative permeability of the water ($K_{rw}$):

$$K_{rw} = \frac{(S_w - S_{wirr})}{(1 - S_{wirr})}$$

(24)

where $K_{rw}$: the water relative permeability

Because $S_{wirr}$ is high in low permeability rocks, where the capillaries are fine. So, by using log calculated data for porosity ($\phi$) and $S_{wirr}$, Timur (1968) suggested a relationship between $\phi$ and $S_{wirr}$ for calculating the $K_{abs}$ (absolute permeability), as follows:

$$K_{abs} = 0.136\phi^{4.4}/(S_{wirr})^2$$

(25)

Then, from Eqs. (26) and (27), the $K_{eff}$ (effective permeability) will be calculated from the ratio between the $K_{rw}$ and $K_{abs}$ as follows:

$$K_{eff} = K_{rw}/K_{abs}$$

(26)

Accordingly, the effective permeability of the carbonate aquifer increases and decreases toward analogous directions, as in case of the absolute permeability, where the max value (114 mD) is shown in El–Gerba well and the min value (23 mD) is exhibited in El–Awaff well. The abundance, distribution, and connection of the fractures control the increasing or decreasing trends of the carbonate aquifer permeability. The effective permeability of the NSA was 163 mD as max value and it is occurred in El–Gerba well and the min value (10 mD) is located in El–Awaff well. Consequently, the western parts are more permeable than the eastern parts. So, the pressure is expected to increase eastward.

According to the previous results and using the neutron and density cross plots, the carbonate aquifer is denser at the eastern parts. The NSA is generally more dense, cemented, compacted, and has less connected pores directed from the western to the eastern directions. Also, the volume of matrix of the carbonate aquifer from the litho–saturation cross plots is the major volume, then the reducible water volume, then the irreducible water saturation, then the shale volume. The shale volume, sometimes, is higher than the water saturation, where the carbonate formation is hard and less in fissures and fractures. This phenomenon is more obvious at the eastern parts, especially in Tamera and El–Awaff wells or at the areas of expected high in pressure (under pressure), while the volume of matrix of the NSA is the major volume, then the shale volume, then the reducible and irreducible water saturations. The volumes of shale and cementation materials increase with increasing the irreducible water saturations, where the effective zones are bounded by them. Moreover, the volumes of shale and cementation materials increase with decreasing the effective pores. So, the occurrence of groundwater decreases. This case is clearer at the eastern parts parallel to Um El–Heous well. The thickness of the formation increases from the parts parallel to Um El–Heous well to the eastern parts. Under this thickness, the irreducible water saturation are larger than those of reducible water saturation. This increases the Fp and becomes more effective on the groundwater movement to the other parts, especially to the western and far-eastern parts, where ponds, lakes, and Sabkhas are considered the main natural outputs from this over-pressuring as shown in Landsat map (Fig. 1C panel).

**Measuring formation pressure methods**

The resistivity, neutron, and density logs will be used in this study for detecting and estimating the over-pressure of the formation and are considered some of several tools for measuring the shale porosity of the formation. In the over-pressured shales, the short normal curve of the resistivity log shows a departure from the normal shale resistivity gradient, indicating high water content and increasing porosity in these shales (Hottman 1965; Ham 1966). Also, Fig. 3 represents an example about the short- and long-normal resistivity logs, as well as the gamma-ray logs, for five deep wells along the study area. These logs will be used in calculating the over-pressure values using the shale resistivity and in determining the NCT, as seen in Fig. 4, left panel. Therefore, the shale resistivity ($R_{sh}$) trend in $\Omega$·m vs. depth in ft for hydrostatic shales is established for each well. These trends reflect the NCT as a function of depth, for example, as seen in Figs. 4, left panel, and 6 (upper right and left panels). If the over-pressured aquifers occurred, the resistivity values of shale points suddenly diverge from NT toward lower resistivity values, due to the exceptionally high values of
porosity. Hence, the degree of divergence of a given point from the selected NCT was attributed to the pressure gradient observed in adjacent reservoir formations (Hottman and Johnson 1965). To detect, identify, and calculate the over-pressure of reservoirs from the adjacent values of shale resistivity ($R_{sh}$), there are necessary steps were modified after Hottman and Johnson (1965) as follows:

i. The NCT for each available well in the study area was generated from plotting the logarithm of shale resistivity ($R_{sh}$) values from the long resistivity (NLR) log vs. depth, as shown in Figs. 4, left panel, and 6 (upper right and left panels).

ii. The peak of over-pressured formations is determined by noting the depth, where the plotted values diverge from the NT line.

iii. The pressure gradient at any depth is determined as follows:

1. The divergence of the adjacent shale was determined from the NT line.
2. The water pressure gradient (WPG) corresponding to the ($R_{sh}(no) - R_{sh}(ob)$) value is found.

iv. The pressure of reservoir is calculated by multiplying WPG by depth (Table 1).

Results and discussion

Determination of formation pressure, piezometric heads, and piezometric pressure

Accordingly, to illustrate the techniques of calculating the formation pressures from the petrophysical characteristics of shale by using the resistivity, neutron, and density methods in the available drilled wells in the study area, the shale resistivity ($\Omega \cdot m$), porosity ($\%$), and density ($kg/m^3$) are plotted vs. depth (ft) on a semi-log grid. Then, after choosing the considerable shale thickness of the formation under study, the NCT, which is fitted to the given data, is shown, the top of over-pressure, forewarning of the over-pressure, and the transition zone must be determined accurately. The identification of such zones will give an indication about the prediction and intensity of over-pressure of the formation under concern. The deviation of the observed resistivity, neutron, and density curves from the established NCT, under

| Well name | Shale thickness (m) | Shale resistivity ($\Omega \cdot m$) ($R_{sh}(no) - R_{sh}(ob)$) | WPG (psi/ft) | First depth (ft) at the zone of over-pressuring | Formation pressure (psi) |
|-----------|---------------------|-------------------------------------------------|------------|-----------------------------------------------|-------------------------|
| El-Gerba  | 34                  | 7                                               | 0.50       | 2391                                          | 1195.5                  |
| El-Zitoun | 120                 | 5.8                                             | 0.41       | 2138.5                                        | 886                     |
| Tamera    | 269                 | 11.5                                            | 0.82       | 2619                                          | 1924                    |
| El-Khashby| 200                 | 12.9                                            | 0.92       | 2683                                          | 2472                    |
| Bahi El-Din| 191                | 7.4                                             | 0.53       | 2619                                          | 1384                    |
| Um El-Heous| 155                | 11.6                                            | 0.83       | 2463                                          | 2041                    |
| El-Meghaz | 32                  | 6                                               | 0.43       | 4175                                          | 1789                    |
| El-Shahayem| 110                | 5.8                                             | 0.41       | 3126                                          | 1295                    |
| El-Teptah | 138                 | 13.5                                            | 0.96       | 2263                                          | 2182                    |
| El-Awaff  | 70                  | 14                                              | 1.00       | 2676.5                                        | 2676.5                  |
| Average   | 9.55                | 0.68                                            |            | 2688                                          | 1785                    |
hydrostatic pressure conditions, measures the pore pressure in shale and in adjacent to the permeable sediments. During the determination of the NCT for all wells, the resistivity, porosity, and density values of the clean sandstone, which is occurred as a thin layer compared to the major thickness of shale, generally, do not consider.

From the resistivity method, especially in El-Gerba well, the top of over-pressure of the NSA is occurred at approximately 2378 ft, forewarning of over-pressure is extended from depth 2378 to ~2389.5 ft, the transition zone is also extended from depth 2389.5 to 2391 ft, where the last depth (2391 ft) is considered the start of the zone of overpressuring. Hence, the over-pressure in this well is determined at depth 2391 ft with shale resistivity separation ~7 Ω·m, referring to the Fp and WPGs are constant with depth (Table 1). Accordingly, in El-Awaff well; the max separation value between the NCT and the observed data of shale resistivity calculated at this well (Fig. 5, upper right panel) is ~14 Ω·m as estimated at the first depth (2676.5 ft) of the zone of over-pressuring. The max values of WPG and Fp are

**Fig. 5** Examples of plots for the shale resistivity (Rtsh) versus depth (ft) of the Nubia Sandstone section with NCT in El-Gerba well and El-Awaff well (right and left upper panels), for the shale porosity (fish) versus depth (ft) of the Nubia Sandstone section with NCT in El-Gerba well and El-Awaff well (right and left middle panels) and for the shale density (rsh) versus depth (ft) of the Nubia Sandstone section with NCT in Tamara well and El-Awaff well (right and lower left panels).
expected in this well to be 1 psi/ft and 2676.5 psi, respectively. This value is assumed to be 1 (100% over-pressured). So, it will be assumed that this value is a constant over-pressure of 1 psi/ft for the Nubia Sandstone formation, which may approach this WPG. The pore water in this well is considered completely confined and non-movable, so the pore pressure attains a geostatic pressure of 1 psi/ft deep. The top of over-pressuring is detected at a depth of 2571.5 ft, forewarning of over-pressure is extended from 2571.5 to 2660 ft and the transition zone is extended from 2660 to 2676.5 ft. The WPGs in this well are expected to be higher with depth. From that, El-Gerba well has a WPG of ~0.50 psi/ft and a Fp of ~1195.5 psi (Fig. 5, upper left panel). This pressure and its gradient in this well are considered constant with depth that may result from the presence of deep structure and deep sandstone development.

From the neutron method; generally, the NL measures the hydrogen density within the sediments. Therefore, the increased porosity and corresponding water within the abnormal pressure zones allows the application of this tool to detect these zones. Accordingly, as in the resistivity method but by using the shale porosity ($\phi_{sh}$) instead of the shale resistivity at this method, the same steps are necessary to estimate the Fp of reservoirs (Figs. 4, middle panel, and 5, middle left and right panels). Hence, the reservoir pressure is obtained by multiplying the WPG, which is corresponding to the ($\phi_{sh}$(no) − $\phi_{sh}$(ob)) value, by the depth (Table 2). In general, the neutron log is used for measuring the formation porosity at eight wells. In this study, the great thickness of shale of the Nubia Sandstone formation. Because the porosity is considered as a useful measure of the compaction degree of shale and it at a specific burial depth depends on the groundwater pressure, if the groundwater pressure is high, the porosity will be high for the given burial depth (Hottman and Johnson 1965). The NCT (Fig. 4, middle panel) determination from the shale porosity by the neutron method is not easy and taken passing through a large number of porosity values with expelling the porosity values at the clean sandstone.

In El-Gerba well (Fig. 5, middle left panel), the identification of depths to the top of over-pressuring, forewarning of over-pressure extension, transition zone extension, and over-pressuring zone are the same as determined by the resistivity method in the same well. The max separation value between the NCT and the observed data of shale porosity is detected only in El-Awaff well (Fig. 5, middle right panel). This value is ~16% and considered the standard separation value, which refers to the presence of max Fp along the study area. Therefore, the separation value in this well is ~7% and from that, the WPG is ~0.44 psi/ft and the Fp is ~1046 psi, as calculated at the first depth in the zone of over-pressuring (~2391 ft). Also, in this well, the pressure and its gradient are expected to be constant with depth that may be the result of presence of deep structure and deep sandstone development. Because this well is outside the limits of the depression, the similarity of the final results, which are determined by the two previous methods, is excellent.

From the density method, such measurements can be carried out in site by means of the density logging (Ham 1966) or at the surface from the shale cuttings (Boatman 1967). Also, by the same way, as in the previous two methods but by using the shale density ($\rho_{sh}$) for six wells. The Fp of reservoirs is also estimated by applying the same steps (Fig. 5, lower left and right panels), and it is obtained by multiplying the WPG, which is corresponding to the ($\rho_{sh}$(no) − $\rho_{sh}$(ob)) value by the depth (Table 3). The compaction trend is shown in Fig. 4, right panel. Generally, the densities of the shales are different according to their degree of compaction, porosity, mineral composition, matrices, and saturation. If the shales are porous and saturated by groundwater, their densities will be reduced. Also, if the shales are occurred in permeable formation and this formation is subjected to any

| Well name     | Shale porosity (%) | WPG (psi/ft) | First depth (ft) at the zone of over-pressuring | Formation pressure (psi) |
|---------------|--------------------|--------------|-----------------------------------------------|--------------------------|
| El-Gerba      | 7                  | 0.44         | 2391                                          | 1046                     |
| El-Zitoun     | 7                  | 0.44         | 2148.5                                        | 940                      |
| Tamera        | 13.6               | 0.85         | 2583                                          | 2196                     |
| El-Khashby    | —                  | —            | —                                             | —                        |
| Bahi El-Din   | 8.2                | 0.51         | 2657                                          | 1362                     |
| Um El-Heous   | 12.9               | 0.81         | 2493                                          | 2010                     |
| El-Meghaz     | 7                  | 0.44         | 4202                                          | 1838                     |
| El-Shahayem   | 6.6                | 0.41         | 3116                                          | 1285                     |
| El-Teptah     | —                  | —            | —                                             | —                        |
| El-Awaff      | 16                 | 1.00         | 2732                                          | 2732                     |
| Average       | 9.79               | 0.61         | 2790                                          | 1676                     |
pressure, then the shales densities will be reduced and this reduction appears in the form abrupt or sharp decreasing deviation of densities. Therefore, in this study, it will depend upon the detection of the previous deviation and its depth of start. At this depth, the top of over-pressure is considered the key to define the zone of over-pressure occurring in the formation under study. This method can be considered more easier in the expectation and determination of the zones of over-pressuring than the previous methods.

In Tamera well, the deviation of the observed data (Fig. 5, lower left panel) is begun from depth 2129 ft (this depth is the top of over-pressure). Extension of forewarning of over-pressure is expected from 2129 to ~2152 ft. The transition zone is extended from depth 2152 to 2381 ft. The zone of over-pressuring is expected to start from depth 2381 ft, where the calculated separation at this depth is ~9.5 kg/m$^3$. The calculated Fp and its water gradient at the end depth are 1933 psi and 0.81 psi/ft, respectively. In El-Awaff well, the sharp and large deviation of the observed data from the NCT of the shale density is more obvious (Fig. 5, lower right panel). This reflects that the formation is over-pressured and the value of the pressure is abnormally higher than the expected values of the other pressures at any well. This deviation shows that the calculated separation between the normal trend and the observed data is ~11.7 kg/m$^3$. The WPG is calculated to be 1 psi/ft. The top of over-pressure is determined at depth ~2391 ft. Forewarning of over-pressure is extended from depth 2391 to 2545.5 ft and the transition zone is extended from 2545.5 to 2571.5 ft. The calculated Nubia Sandstone pressure is ~2575 psi at a depth of ~2575 ft.

The determination of piezometric heads is of considerable interest to know the Pp. Generally, the piezometric heads of the NSA (Fig. 6, left panel) decrease to the western direction along Siwa Oasis. This decreasing reflects the general flow direction of groundwater is to the west. Also, from the comparison between piezometric heads and the reducible water saturation ($S_{wr}$), the general increasing of $S_{wr}$ to the west and the general decrease of the piezometric heads that will reflect the pressure of groundwater at this aquifer is reduced to the same direction. The contour lines of $S_{wr}$ are perpendicular to the contour lines of the piezometric heads that will confirm the flow direction of groundwater (reducible groundwater).

### Table 3

| Well name      | Shale density (kg/m$^3$) | WPG (psi/ft) | First depth (ft) at the zone of over-pressuring | Formation pressure (psi) |
|----------------|--------------------------|--------------|-----------------------------------------------|--------------------------|
| El-Gerba       | —                        | —            | —                                             | —                        |
| El-Zitoun      | 5.2                      | 0.44         | 2165                                          | 962                      |
| Tamera         | 9.5                      | 0.81         | 2381                                          | 1933                     |
| El-Khashby     | —                        | —            | —                                             | —                        |
| Bahi El-Din    | 6                        | 0.51         | 2657                                          | 1363                     |
| Um El-Heous    | 9.5                      | 0.81         | 2453.5                                        | 1992                     |
| El-Meghaz      | 5                        | 0.43         | 4175.5                                        | 178                      |
| El-Shahayem    | —                        | —            | —                                             | —                        |
| El-Teptah      | —                        | —            | —                                             | —                        |
| El-Awaff       | 11.7                     | 1.00         | 2575                                          | 2575                     |
| Average        | 7.82                     | 0.67         | 2734.5                                        | 1768                     |

**Fig. 6** Piezometric heads distribution map (left panel) and piezometric heads and reducible water saturation distribution map (right panel) of the NSA

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perpendicular to the piezometric heads of the groundwater of the aquifer (Fig. 6, right panel). This comparison, also, illustrates the high values of the piezometric heads are depending not only upon the $S_w$ but also on main several factors, such as the effective porosity ($\phi_{eff}$), irreducible water saturation ($S_{wirr}$), compaction factor (CF), and effective permeability ($K_{eff}$). Consequently, these factors are considered the main factors that effect on the Fp of the groundwater of the aquifer. By using the measured piezometric heads as reported in Table 4 and as shown in the diagram (Fig. 7), the piezometric pressures (Pps) can be calculated by using the following equation:

$$h_b = \frac{P_p}{|g|}$$  \hspace{1cm} (27)

where $h_b$ is the piezometric pressure head (m); $P_p$ is the piezometric pressure (psi); and $|g|$ is the gravity acceleration (9.817 m/s$^2$).

| Well name    | Piezometric heads (m) | Piezometric pressure (psi) |
|--------------|------------------------|----------------------------|
| El-Gerba     | 86                     | 844                        |
| El-Ghazalat  | 60                     | 589                        |
| Tamera       | 108                    | 1060                       |
| El-Khashby   | 115                    | 1128.5                     |
| Bahi El-Din  | 82                     | 805                        |
| Um El-Heous  | 104                    | 1021                       |
| El-Meghaz    | 82                     | 805                        |
| El-Shahayem  | 90                     | 883                        |
| El-Teptah    | 115                    | 1129                       |
| El-Awaff     | 120                    | 1178                       |
| Average      | 96                     | 944                        |

After calculating the Pps from the previous equation, the piezometric pressure gradients (PPGs) are calculated by using the following relation:

$$PPG = \frac{P_p}{Depth}$$  \hspace{1cm} (28)

The PPG was calculated from the previous relation in each well and the Pps and their gradients were mapped, as shown in Fig. 8, left panel and right panel, respectively. Generally, as seen in Fig. 8, the Pps decrease to the western direction and the max value is calculated in El-Awaff well (~1177.5 psi), but the min value was calculated in El-Ghazalat well (~589 psi). Also, the PPGs decrease to the western direction, where the min value was calculated in El-Meghaz well (~0.575 psi/m), but the max value was calculated in El-Awaff well (~1.3 psi/m). Hence, it can be said that the part bounded between 25°36′ and 26°E has high piezometric heads, Pps, and PPGs. This reflects that the other parts are more influenced by the high pressure occurred at the previous part. This pressure assists in moving the groundwater to the east and west parts of this area. This duplicates the water amounts at these parts and will be more productive than achieved from increasing the lakes, ponds, and Sabkhas, as distributed and shown in Fig. 1C panel.

### Relationship between the formation pressure and piezometric pressure

For estimating the formation pressure (Fp) from the piezometric pressure (Pp), the statistical analyses were carried out between both with focusing on using the calculated Fp from resistivity, porosity, and density of the shale by the MINITAB (1998) statistical software package. The main outputs of the statistical analysis include the descriptive

![Fig. 7 Diagram in 3-D for showing the piezometric heads in m (left panel) and piezometric pressures in psi (right panel) from east to west along Siwa Oasis](Image)
statistics, statistical hypothesis testing, parameter estimation, and the basic linear regression, ANOVA table, and model fit validation.

Therefore, the statistical analyses between \( P_p \) and \( F_p \) from shale resistivity were carried out for inferring the relation between both and for deducing the effect of \( F_p \) on \( P_p \) and the effect of shale on \( P_p \). In general, the increasing of \( F_p \) will be due to increase of \( P_p \) (\( F_p \propto P_p \)). By judging this relation, the distribution was normal and congruent, the trend of the data was linear and their model fit. Therefore, the \( P \)-probability value was lowered to 0.002 due to the \( T \)-ratio and \( F \)-statistic values are high. Also, the evidence and correlation are strong and high (\(-0.879; P \text{ value } = 0.002\)), respectively (Fig. 9D panel). Because this relation was linear, it means that the measured \( P_p \) of the NSA differ significantly for different \( F_p \) of the same aquifer. \( R^2 \) of the two variables is \(-77.3\% \) that refers to \( P_p \) cannot interpret more than 77.3\% of \( F_p \) or \(-22.7\% \) of \( F_p \) cannot be interpreted by \( P_p \). This may be due to the shale distribution effect, shale types, connection of pores, and percentages of water saturation and

![Fig. 8 Piezometric pressure distribution map (left panel) and piezometric pressure gradient map (right panel) of the NSA](image)

![Fig. 9 Relationship between piezometric pressure and formation pressure from resistivity logs (D), from neutron logs (E), and from density logs (F), as well as relationship between the piezometric pressure and average formation pressure (G)](image)
its types, the pores distribution and its density. Hence, the following linear regression can be used for calculating \( F_p \) from \( P_p \):

\[
F_p (R) = -1116 + 3.05P_p \quad (R^2 = 77.3\% \text{ and } R^2(\text{adj}) = 74.1\%)
\]  

(29)

In addition, from the relation between the same two previous variables \( F_p \) and \( P_p \) but in case of using the calculated values of \( F_p \) from the neutron log depending on the shale porosity (Fig. 9E panel), the \( F_p \) increases with increasing \( P_p \) (\( F_p \propto P_p \)) and vice versa. This relation is characterized by normal and identical in distribution and its general trend is linear as well as its model fit is valid. The \( P \) value decreases to 0.014 due to the \( T \) and \( F \) values are high. Also, the correlation is high (0.857; \( P \) value=0.014) (Fig. 9E panel). So, the evidence is strong and it reflects that \( P_p \) differ significantly for different \( F_p \).

\[
F_p (N) = -1512.6 + 3.5P_p \quad (R^2 = 73.5\% \text{ and } R^2(\text{adj}) = 68.1\%)
\]

(30)

Also, from the relation between the same two previous variables \( F_p \) and \( P_p \) but in case of using the calculated values of \( F_p \) from the density log depending on the shale density, the correlation is high (0.881; \( P \) value=0.049) (Fig. 9F panel). Also, the evidence is strong and \( R^2 \) is \( \sim 77.6\% \) that refer to \( P_p \) of the NSA cannot interpret more than \( 77.6\% \) of \( F_p \) of the same aquifer or \( \sim 22.4\% \) of \( F_p \) of this aquifer cannot be defined by \( P_p \) of the same aquifer, due to the shale content effect, shale types, connection of pores, and water saturation, and shale porosity. Therefore, the \( F_p \) is more affected by the shale porosity, which is varied with varying the shale content. Accordingly, the following linear regression can be used for calculating the \( F_p \) from the \( P_p \):

\[
F_p (N) = -354 + 2.35P_p \quad (R^2 = 77.6\% \text{ and } R^2(\text{adj}) = 70.1\%)
\]

(31)

By the same way, the following resulted linear regression is from carrying out the relationship between the average \( F_p \) and \( P_p \) (Fig. 9G panel) as following:

\[
F_p (\text{av}) = -1948 + 3.82P_p \quad (R^2 = 92.6\% \text{ and } R^2(\text{adj}) = 91.3\%)
\]

(32)

Accordingly, the correlation is high (0.962; \( P \) value=0.000). So, it can be used for calculating the \( F_p \) of the NSA, as deep aquifer, with considering the depth to the aquifer, thickness of the overlain formation, formation type, the content, porosity, density, and type of the shale as well as the vertical hydraulic connection between the deep and shallow aquifer.

**Over-pressure maps**

The depths to the top of over-pressuring map (Fig. 10, left panel) were generated by taking the averages of depths defined to the top of over-pressuring in each well using the three method along the study area as reported in Tables 1, 2, and 3, respectively. The deeper over-pressuring top was defined in El-Meghaz well (~1264 m) while the shallower over-pressuring top was determined in El-Zitoun well (~644.5 m). So, it is expected that the previous shallow depth in El-Zitoun well is resulted from the presence of fault. Generally, from the parts paralleled to the coordinate 25°30' E, the depths to the top of over-pressuring are decreased from 1264 to 644.5 m. Table 5 represents the average of the pressure gradient, the average to the top of the over-pressure (ft), the average to the top of the over-pressure (m), and the average of the \( F_p \) (psi) of the wells along the study area.

![Fig. 10 Depth to the top of over-pressuring (left panel) and pressure gradient distribution map of the NSA (right panel)](image-url)
Also, by using the fore-mentioned system in generating the previous map, over-pressure gradient map (Fig. 10, right panel) is generated, but by taking the averages of WPGs in each well. The max gradient value was calculated in El-Awaff (Aw) well in the eastern part (~1 psi/ft) but the min value was estimated in El-Shahayem (Sh) well in the western part (~0.41 psi/ft). Generally, along the Siwa Oasis, the WPGs are increased through the parts paralleled to the coordinate 25°30′E from 0.41 to 1 psi/ft. From these gradients, it can see the pressure gradients are within 0.05 psi/ft of the calculated gradients and the expected pressure separating value is ~0.05 psi/ft.

Accordingly, the averages of the calculated formation pressures in each well were mapped in 1D and 3D (overpressuring map), as shown in Fig. 11, left panel and right panel, respectively. The min value of the Fp is shown in El-Zitoun well (~92 psi) while the max value was exhibited in El-Awaff well (~2661 psi). Along Siwa depression, as shown in the generated map (Fig. 11), the Fp is increased, generally, to the east and decreased to the west.

### Table 5

| Well name         | Average of the pressure gradient | Average to the top of the over-pressure (ft) | Average to the top of the over-pressure (m) | Average of the formation pressure (psi) |
|-------------------|----------------------------------|---------------------------------------------|--------------------------------------------|----------------------------------------|
| El-Gerba          | 0.47                             | 2378                                        | 725                                        | 1121                                   |
| El-Zitoun         | 0.43                             | 2114                                        | 644.5                                      | 929                                    |
| Tamera            | 0.83                             | 2266                                        | 691                                        | 2017                                   |
| El-Khashby        | 0.92                             | 2585                                        | 788                                        | 2472                                   |
| Bahi El-Din       | 0.52                             | 2604                                        | 794                                        | 1369                                   |
| Um El-Heous       | 0.82                             | 2437                                        | 743                                        | 2014                                   |
| El-Meghaz         | 0.43                             | 4146                                        | 1264                                       | 1804                                   |
| El-Shahayem       | 0.41                             | 3076                                        | 938                                        | 1290                                   |
| El-Teptah         | 0.96                             | 2237                                        | 682                                        | 2182                                   |
| El-Awaff          | 1                                | 2515                                        | 767                                        | 2661                                   |
| Average           | 0.679                            | 2636                                        | 804                                        | 1786                                   |

**Conclusions**

The over-pressure phenomenon was appeared at some locations in the western desert of Egypt like in Siwa Oasis depression. The main aquifer is the NSA and it is overlaid by huge shale thickness and carbonate aquifer. The carbonate aquifer was divided into two zones and there is hydraulic connection between the two aquifers. There are ten wells with short and long resistivity, SP, GR, density, and neutron logs. These logs were corrected and used in determining the petrophysical parameters of the two aquifers. The resistivity, neutron, and density logs were applied for detecting, identifying, and calculating of the formation pressure (Fp). The expected NCT of the over-pressure was determined. The depths to the top, forewarning, transition zones of overpressuring, and the main zones of over-pressuring were determined, as well as the Fp value and its gradient were calculated. The piezometric heads of NSA determined the general flow direction of groundwater to the west. The Pps are decreased to the west but the Fp is increased to the east.

![Fig. 11 Over-pressuring distribution map of the NSA (left panel) and 3D over-pressuring distribution map of the NSA along Siwa Oasis (right panel)](image_url)
and decreased to the west. The general increase of the WPGs and Fps is to the east, but the general decrease is to the west. The Pp increases with increasing the Fp and the Fp increases with increasing the shale content.

Accordingly, the shale thickness and their types, the higher effective porosities of the formations under compaction, and their complicated geological structural conditions are the main factors in generating the Fp. Therefore, to solve the over-pressure problem in this area, it must be drilled number of deep-water wells at the eastern parts for decreasing their Fp and preventing the increasing of the water storage and its pressure at the other parts. Also, this study considers the used logs are compatible powerful tools in studying this phenomenon.

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Declarations

Conflict of interest The author declares no competing interests.

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