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# Petrophysical Modelling For the Bahariya Formation, Egypt

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**Abstract**

Lithologic laminations have great consequences on the Bahariya sandstone, which are distinguished by the calculated reservoir statistical parameters. The non-laminated Bahariya studied samples have the lowest mean bulk density and specific internal surface values, while they have the highest mean porosity, permeability and Spor values. On the other hand, the laminated samples exhibit high values. The non-laminated Bahariya samples have the lowest mean permeability anisotropy, due to its relative pore-framework homogeneity. Contrary, the laminated Bahariya samples have the highest mean permeability anisotropy. By the same behaviour, the non-laminated Bahariya samples have the highest mean electrical resistivity value, due to the lack of conductive minerals, while the laminated Bahariya samples have the highest mean electrical resistivity.
The non-laminated Bahariya samples show the lowest mean magnetic susceptibility value, while the laminated samples reveal high values. Sonic wave velocities (Vp and Vs) are statistically treated, while the velocity anisotropy is calculated for all samples. Laminated samples display higher velocity in comparable to the non-laminated ones. Thin sections and SEM-micrographs were made for some selected samples in order to recognize the Bahariya sandstone forming minerals. Glauconite, micas, zircon, rutile and pyrite minerals are composing the laminas in the laminated samples, while some glauconitic sandstone are predominant in the non-laminated ones.
A number of linear regression models were performed among some measured petrophysical parameters, in order to differentiate between the laminated and the non-laminated sandstones, and to obtain reliable relationships permitting reservoir characterization.

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*Keywords:* Bahariya Formation; electrical resistivity; porosity; acoustic wave velocity; permeability.

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## 1. Introduction

The Bahariya Formation type locality is the Bahariya Oasis, which lies about 280 km south-west of Cairo town. The Bahariya Formation covers the floor and parts of the slope surrounding the depression with a maximal outcropped thickness of 170 m. Subsurface geology in the Western Desert of Egypt has posed many questions of how stratigraphy is related to the history of the Upper Cretaceous earth movements (Franks, 1982). The stratigraphic succession (EGPC, 1995) in the northern part of the Western Desert (Fig.1) shows that, the Bahariya Formation is laying at the lower most part of the Upper Cretaceous and belonging to the Early Cenomanian in age. It is overlain by Abu Rawash Formation and underlain by the Kharita Formation .The prospective part of the sedimentary section (Fig.2) , where the source ,reservoir and sealing rocks are most likely to be present ranges from Paleozoic (Silurian-Devonian) to the Lower Tertiary.

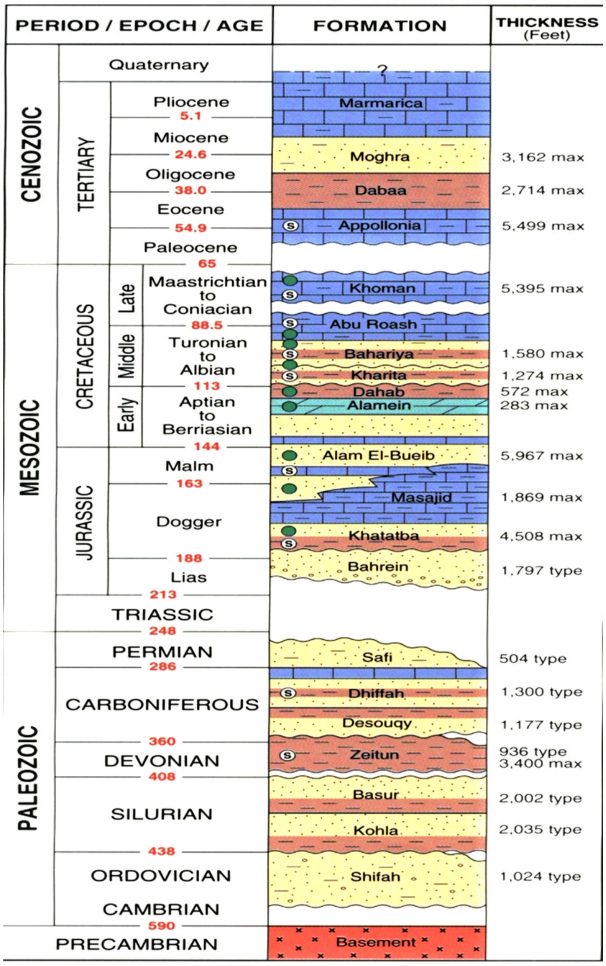

Fig.1: Stratigraphic Column of Western Desert (EGPC, 1995).

The geology of the Bahariya Oasis is almost well known, with a number of studies going back, as far as Ball and Beadnell (1903). Paleontological, petrophysics and reservoir evaluation studies were made by Stromer (1914), Said and Issawi (1964); Soliman et al (1970); El Sayed (1991and 2011); El Sayed et al. (1993 and 1999) ; Athmer (2006), Athmer et al. (2007) and Matthias et al (2009). El Sayed et al. (1993) concluded that, the Bahariya Formation encountered in both Salam-Khalda oil and gas fields consists mainly of sand layers occupying the upper most part of the formation, while the stacking sandy shale layers are common in the lower part. In the Bahariya sandstones, the pyrite is fine-grained, which leads to a dark to black coloring of the flaser bedding. The flaser bedding is wavy, as it mostly traces the morphology of ripples, but partly the wavy bedding was developed as a result of bioturbation. Very pronounced and curved flaser bedding refers to slumping in unconsolidated sediment. Oxidation of pyrite after diagenesis leads to the brown to auburn colour of the particles and of parts of the flaser bedding. Pyrite contains iron, which reacts with oxygen from the air or water circulating through the sediment over different oxidation states to iron hydroxides like limonite. In all the investigated samples, a high content of glauconite, zircon and rutile was found. The heavy minerals zircon and rutile are mostly well rounded and probably originated from beach placer deposits or older, weathered rocks, which were transported by rivers into the estuary. Green glauconite forms on the continental shelf in only little moving water with maximal depths of 200 m. In some samples, the glauconite is of brown colour, due to the partial oxidation-taking place in areas close to the cost. It indicates a relocation of the mineral grains. All the studied samples show features, which give indications of deep burial and increased pressure. Concave-convex contacts visible at the quartz grains are developed at a depth of two to three kilometres (Athmer, 2006). Moreover, the very close contacts of the plane kaolinite minerals resulted from an increase in pressure caused by the sedimentary load. In addition, solution occurring at quartz grains develops under high pressure and leads to new formation of quartz cement. Twisted mica and deformed particles in the studied Bahariya samples indicate a deep burial, too. Carbonate cement, that displaces quartz grains, can be generated by circulation of surface water containing carbonate, alteration of clay minerals and solution of carbonate minerals or calcareous skeletons. The detected clay minerals associations, using well logging analysis, were montmorillonite, kaolinite and Glauconite. El Sayed et al. (1993) concluded that, the Bahariya rock genetic types detected by their work were mainly: stream mouth bar, barrier bar, point bar and distributary channel sand bodies, which are usually repeated in time and space. The different rock genesis characterizing the Bahariya Formation should be rises as differences in their physical properties, either in its vertical or horizontal distribution (porosity, permeability, sonic wave velocity and electrical resistivity).

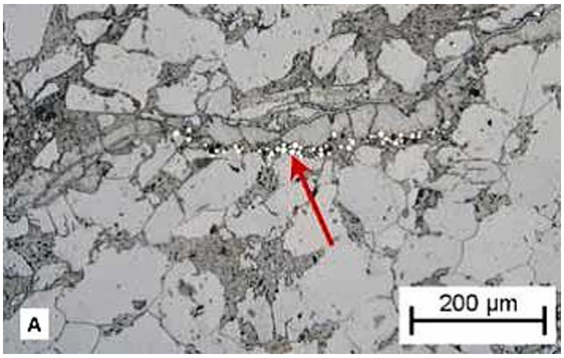


Fig. 2a Microscopic image of sample 43H under reflected light, showing feldspathic arenite with high reflective framboidal pyrites (red arrow), which are aligned like a pearl necklace within a flaser lamina.


Fig.2b Samples from the Bahariya Formation (left) side laminated and non-laminated (right).

The Bahariya genetic sandstone bodies, laminations (vertical, inclined and horizontal) and facies changes, which are interpreted in the subsurface to the north, as have been described by El Sayed et al. (1993) in Salam-Khalda oil and gas fields and recently described by Athmer, et al. (2007), giving many reasons for obtaining reservoir anisotropy. The aim of this study is to building some multi-regression line models more relevant to such cases. This study is done through a joint project, which is partially funded by the German DFG- establishment.

## 2. Methodology

Sample porosity and permeability were measured by helium porosimeter and nitrogen gas permeameter respectively. While the ultrasonic wave velocities ($V_P$ and $V_s$) are measured by use of OYO-sonic viewer for dry and saturated samples using techniques adopted by El Sayed (2011). The permeability and acoustic wave velocity anisotropy were calculated as;

$$A_{v_p} = \frac{v_\perp}{v_\parallel} = \frac{v_V}{v_H} \qquad (1)$$

$$A_K = \frac{K_{\max}}{K_{\min}} \qquad (2)$$

where: $A_k$ is the permeability anisotropy, and $A_{vo}$ is the velocity anisotropy.
Some selected core samples of the Bahariya Formation were petrographically studied and most of them are described as feldspathic arenite (Fig. 3a, b) laminated in some intervals. The petrophysical measurements carried out were: rock porosity, permeability, electrical resistivity, surface area, magnetic susceptibility, sonic wave velocity for dry and some saturated samples, and the petrography for some selected samples.

## 3. Results and discussions

### *3.1. Rock Density and Porosity*

The measured non-oriented petrophysical parameters like, rock density and porosity have no anisotropy values, because they reveal 3D-dimensional rock properties. The measured bulk density of the Bahariya samples ranges from 2.16 to 2.57 $g.cm^{-3}$. The mean value is found to be 2.37 and 2.27 $g.cm^{-3}$ for laminated and non-laminated samples, respectively (Fig.3a and b).The effect of lithologic lamination is marked on the density mean value. The non-laminated samples have the lowest mean bulk density value. On the other hand, the measured Helium porosity ranges from 0.97% up to 20.11% with mean values of 8.97% and 12.44% for laminated and non-laminated samples, respectively (Figs. 1 a and b). The effect of lithologic lamination is obvious on the rock porosity mean value. The non-laminated samples have the highest mean porosity value.

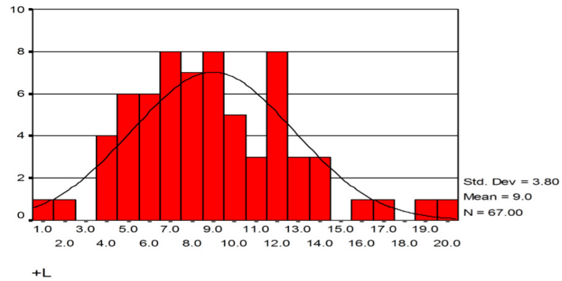

Fig.3a: Porosities (ø, %) for the laminated samples.

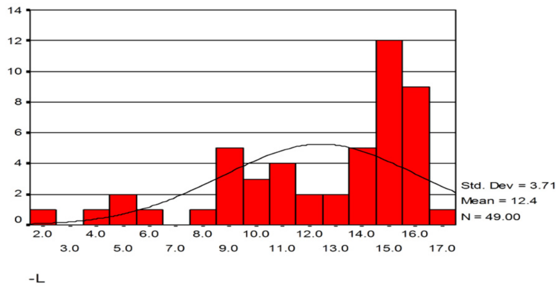

Fig.3b: Porosities (ø, %) for the non-laminated samples.

### *3.2. Specific Internal Surface Distribution*

The specific surface area is determined by BET method (Brunauer et al., 1938). It is normalized by the total sample volume, the pore volume or the mass and is defined as;

$$S_{total} = \text{surface area of the pores / total volume} \quad (3)$$

$$S_{por} = \text{surface area of the pores/pore volume} \quad (4)$$

$$S_{mass} = \text{Surface area of the pores/total mass} \quad (5)$$

The measured mass ($S_m$), pore ($S_{por}$) and total ($S_t$) specific area are ranged from 07 to 2.01(103cm2/Kg), 1.35 to 68.53(10^6* 1/m) and 1.08to 43.95($m^2$/kg), respectively for all the studied Bahariya samples. The mean values of $S_m$ are found to be 0.52 and 0.45 ($10^3$ $cm^2$/Kg) for laminated and non-laminated samples respectively. The high range and discrepancy in it is due to the high anisotropy in the laminated samples (std. Dev. = 0.41), while it is very small in the non-laminated ones (std.Dev = 0.29).
The mean values of pore specific surface ($S_{por}$) are found to be 14.43 and 15.75 (10^6* 1/m) for laminated and non-laminated samples, respectively. The mean values of S are found to be 15.5 and 16.2 ($m^2$/kg) for laminated and non-laminated samples respectively.

### *3.3. Permeability Distribution*

The rock permeability is non-scalar parameter and is defined as the ability of a rock to conduct fluids under certain pressure gradient. It represents the communication lines between pore spaces and subsequently it depends on the pore throat radius and rock properties such as grain shapes, packing, angularity and cementing materials, and irreducible water. Liquids flow faster in the centre of the pore than along the sides. This differential fluid flow is known as Klinkenberg effect. Thus, a small grain size (high specific surface area) has the effect of lowering the permeability. Permeability is measured using the Darcy formula:

$$Q/A= (K/\mu). (\Delta P/L) \quad (6)$$

where: Q = flow rate, cc/sec, A = cross sectional area, $cm^2$, L = length, cm, μ = viscosity of flowing fluids, cp, ΔP = pressure differential across sample, atm pressure = 101 325 Pa, K = permeability by Darcy, while, one Darcy equals 0.9869$\mu m^2$. The Nitrogen permeability of the Bahariya samples is measured by Raska Gas permeameter. It is ranged from 0.01 mD up to 62.94 mD with mean permeability values of 3.18 mD, and 8.43 mD for laminated and non-laminated samples respectively. The non-laminated samples have the highest mean permeability value (0.32 mD) due to the of permeability barriers (laminas).

The permeability anisotropy of the Bahariya samples has been calculated using equation (1). It ranges from 1.0

up to 174.4. The mean values of the permeability anisotropy are found to be equal 7.52, 10.56 and 3.55 for all, laminated, and non-laminated samples respectively.

### *3.4. Electrical Resistivity Distribution*

The electrical resistivity (non- scalar) of all samples has been derived from the measurements of the induced polarization spectra (Borner and Schon, 1995) in a frequency range from 750 kHz to 1 m Hz. Only the resistivity amplitudes at a frequency of 1.4 Hz have been used in this study. The measurements were performed under ambient conditions at a constant temperature of about 20°C. The samples were fully saturated with a sodium-chloride solution of 0.56 g/l resulting in a water conductivity of 0.1 S/m. ranges from 35 Ω.m to 2022 Ω.m with mean values of 336.297 Ω.m and 699.852 Ω.m for laminated and non-laminated samples respectively. Figures 4a) and 4b) show histograms of electrical resistivity distribution of laminated and non-laminated samples.

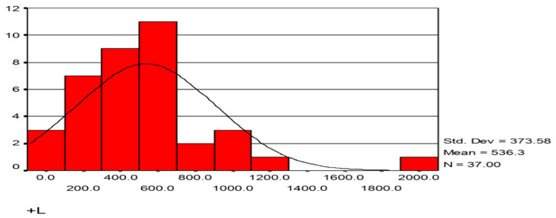

Fig. 4a: Electrical resistivity (Ωm) for laminated samples.

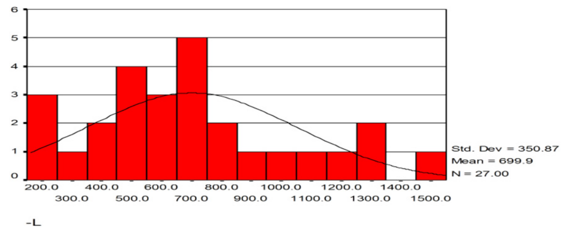

Fig. 4b: Electrical resistivity (Ωm) for non- laminated samples.

The non-laminated samples have the highest mean electrical resistivity value due to its relative homogeneity and lack of conductive minerals composing the laminas.
The electrical resistivity anisotropy (Aρ) was calculated from:

$$A_\rho = \sqrt{\frac{\rho_\perp}{\rho_\parallel}} = \sqrt{\frac{\rho_V}{\rho_H}} \quad (7)$$

where: $\rho_V$ = Electrical resistivity of vertical sample, Ω.m,
$\rho_H$ = Electrical resistivity of horizontal sample, Ω.m,
The calculated electrical anisotropy ranges from 0.59 to 3.16 with mean values of 1.41, 1.68, and 1.14 for all, laminated and non-laminated samples respectively.

### *3.5. Magnetic Susceptibility Distribution*

The volume magnetic susceptibility (χ) is related to the magnetic permeability (μ) and considered as victor parameter (Rzheysky and Novik, 1971):

$$\chi = (\mu - 1) \quad (8)$$

where: $\mu > 1.0$ for paramagnetic rocks and $\mu < 1.0$ for diamagnetic rocks.
The ratio of magnetic susceptibility to density of the rock is known as specific magnetic susceptibility. As the differences in magnetic permeability of rocks are not large, it is therefore often more convenient to use the parameter of magnetic susceptibility (χ) which can be written in a reduced form as $\chi.10^{-6}$.The measured magnetic susceptibility (10^ - 6 SI) for the Bahariya samples ranges from 23.17 to 594.92(10^ - 6 SI) with mean values of 147.36 and 66.85(10^ - 6 SI) for laminated and non-laminated samples respectively. It indicates the effect of iron rich minerals, existing in laminas and characterizing the laminated samples. The non-laminated samples have the lowest mean susceptibility value.
The magnetic susceptibility anisotropy ($A_\kappa$) was calculated as:

$$A_\kappa = \kappa_{max}/\kappa_{min} \quad (9)$$

It is vary from 1.0 up to 2.75 for all studied samples of the Bahariya Formation. The mean anisotropy values were found to be 1.33 for all, for laminated 1.32, and non-laminated samples 1.33 respectively.

## 4. Petrophysical Modelling

Several linear regression and multi-regression models were performed using the SPSS-software among some measured and/or calculated petrophysical parameters in order to inter-correlate and obtain robust relationships permitting to calculate an important reservoir parameter from others, which can be outlined by routine laboratory measurements. The practical application of any model depends on its consistency.

### *4.1. Permeability Prediction*

The permeability prediction is a very important subject in reservoir evaluation. However, it is not a simple job if there are no core samples from the reservoir under investigation. This is a fact due to the difficulties and uncertainty facing petrophysicists and reservoir engineers during permeability calculations from most sophisticated well logs. Therefore, if there are some advances in permeability modelling, it should be helpful in both cost and time reduction. The following models deal with the permeability prediction for non-laminated (homogeneous), laminated and all studied samples.

- Non – laminated samples - An attempt was made to relate permeability to rock porosity, $S_{por}$, and $S_m$ using the stepwise linear regression method. The obtained regression equation was:

$$Log\ K = -1.102 + 0.127Ø - 1.768\ S_m + 5.63x10^{-3}S_{por} \quad (10)$$

  where: Ø, %, $S_m.10^3$ m$^2$/kg, and $S_{por}.10^6$*1/m.
  This equation is characterizing by a reliable and robust coefficient of correlation (r = 0.89).
- Laminated samples - by the same manner, the permeability as a dependant variable is calculated from the porosity, $S_{por}$, and $S_m$ using the calculated regression equation as:

$$Log\ K = -0.787 + 8.679x10^{-2}\ Ø + 0.118S_m - 5.5x10^{-2}\ S_{por} \quad (11)$$

  The calculated coefficient of correlation from the eq.11 was r = 0.701, while the relation between the measured and predicted permeability exhibits more scattered data points than that obtained for non-laminated Bahariya samples.
- All Samples - the obtained regression line equation for predicted permeability of all studied Bahariya samples is,

$$Log\ K = -1.61 + 0.154\ Ø - 1.644\ S_m \quad (r = 0.753) \quad (12)$$

  The calculated permeability model for the laminated samples has the lowest coefficient of correlation.

### *4.2. Magnetic Susceptibility Prediction*

Magnetic susceptibility as a dependant variable is related to rock porosity, bulk density, electrical resistivity and $S_m$ as independent variables, while the most reliable model should
be selected according the stepwise technique done by the SPSS-software. In each calculation step, some parameters are excluded due to its lower coefficient of correlations.

- Non – laminated samples - the regression model for calculating magnetic susceptibility of non-laminated samples is represented by:

$$\chi = 139.181 - 6.911Ø + 56.48\ S_m \quad (r = 0.733) \quad (13)$$

  where: $\chi = \chi.10^{-6}$ (magnetic susceptibility), Ø= porosity, %, $S_m.10^3$ m$^2$/kg.
- Laminated samples - the regression model calculated for laminated Bahariya samples was represented by:

$$\chi = -298.357 - 1.47Ø + 56.48\ S_m + 171.24\ \rho_b \quad (r = 0.521) \quad (14)$$

- All samples - the regression model calculated for all Bahariya samples was:

$$\chi = -939.951 + 469.971\ \rho_b - 6.39x10^{-2}\ R; \quad (r = 0.61) \quad (15)$$

  where: $\rho_b$ =bulk density,cm$^3$ and R = electrical resistivity, Ω.m.

### *4.3. Specific pore surface area ($S_{por}$) prediction*

Inner surface ($S_{por}$) as a dependant variable is related to rock porosity (Ø), mass specific surface ($S_m$ ) and total specific surface ($S_t$ ) as independent variables, while the most reliable model should be selected according to the stepwise technique done by the SPSS-software. In each calculation step, some parameters are excluded due to its lower coefficient of correlations (r):

- Non-laminated samples - the regression model calculated, by stepwise technique, for non-laminated Bahariya samples was represented by:

$$S_{por} = 21.893 - 1.614Ø + 17.972\,S_m, \qquad (r = 0.941) \qquad (16)$$

- Laminated samples - the regression model calculated, by stepwise technique, for laminated Bahariya samples was:

$$S_{por} = -0.341 + 28.412\,S_m, \qquad (r = 0.90) \qquad (17)$$

- All samples - the regression model calculated, by stepwise technique, for all Bahariya samples was represented by eq.

$$S_{por} = 7.894 + 26.862\,S_m - 0.759Ø, \quad (r=0.903) \qquad (18)$$

### *4.4. Seismic Velocity Distribution*

The sonic wave velocity is measured using OYO-170 Sonic Viewer with transducer of 33 kHz for the P-wave and 63 kHz for the S-wave measurements. The statistics of measured sonic velocity of the Bahariya samples indicates that shear wave velocity data is closer around the mean value than that of the compressional wave velocity for all samples. The mean value of the measured compressional and shear wave velocity for all samples are 3099.01 m/s, and 2212.47m/s respectively. It is found to be 3078.695m/s and 2188.261m/s for the $\mathbf{V_p}$ and the $\mathbf{V_s}$ belonging to laminated samples. The non-laminated samples have the highest mean seismic velocity relative to other categories. The laminated samples data has the highest standard deviation among the studied three categories. The obtained results are going in a wright way compatible with the acoustic wave behaviour as non-scalar parameter.

- Compressional – Shear Wave Velocity. The high reliable coefficient of correlation (0.976) for the relation between compressional and shear wave velocity measured for the all Bahariya samples is represented by equation:

$$Vp = 175.578 + 1.321\,Vs \qquad (19)$$

where: both $V_p$ and $V_s$ in m/s.

- Sonic Velocity Anisotropy - It is defined as velocity measured in vertical direction to that measured in horizontal direction as:

$$A_{v_p} = \frac{v_\perp}{v_\parallel} = \frac{v_V}{v_H} \qquad (20)$$

where: $v_v$ = velocity of vertical sample, m/s and $v_H$ = the velocity of horizontal sample, m/s.

- Non-laminated samples - the mean anisotropy value for both of them is 0.87. The standard deviation equals 0.15 and 0.17 for compressional and shear wave anisotropy respectively. It indicates that data points are closer to the mean value in case of the compressional wave than that of the shear wave velocity anisotropy. The regression model calculated, by stepwise technique, for non-laminated Bahariya samples was represented by:

$$A_{Vp} = 9.158\,x10^{-2} + 0.893\,A_{Vs}; \qquad (r = 0.971) \qquad (21)$$

where: $A_{Vp}$ = compressional wave velocity anisotropy, $A_{Vs}$ = shear wave velocity anisotropy.

- Laminated samples - mean anisotropy value for $A_{Vp}$ is 0.77, while it is 0.76 for $A_{Vs}$ . The standard deviation equals 0.12 for both compressional and shears wave anisotropy. The regression model calculated, by stepwise technique, for laminated Bahariya samples was represented by:

$$AVp = 4.811\,x10^{-2} + 0.956\,AVs \quad (r = 0.937) \qquad (22)$$

where: $A_{Vp}$ = compressional wave velocity anisotropy, $A_{Vs}$ = shear wave velocity anisotropy.

- All samples - the mean anisotropy value for both longitudinal and shear wave velocity ($A_{Vp}$ and $A_{Vs}$) is 0.81. The standard deviation equals 0.14 and 0.15 for both compressional and shears wave anisotropy respectively. The regression model calculated by stepwise technique for laminated Bahariya samples was:

$$AVp = 8.888x10^{-2} + 0.9\ AVs \quad (r = 0.96) \tag{23}$$

where: $A_{Vp}$ = compressional wave velocity anisotropy, $A_{Vs}$ = shear wave velocity anisotropy.

## 5. Conclusions

Lithologic lamination has the major effect on the petrophysical modelling and anisotropy of reservoir rock parameters because the laminas themselves composed of pyrite, rutile, glauconite, micas and iron rich minerals. The non-laminated Bahariya samples have the lowest mean bulk density and $S_m$ values, while they have the highest mean porosity, S and $S_{por}$ values. In addition, it has the highest mean permeability value; lowest mean permeability anisotropy and highest mean electrical resistivity value due to its relative homogeneity. The laminated Bahariya samples have the highest permeability anisotropy and highest mean electrical resistivity anisotropy; also it has the highest mean electrical resistivity.

The non-laminated Bahariya samples have the lowest mean magnetic susceptibility value, while the differences among the calculated mean susceptibility anisotropy of all, laminated and non-laminated Bahariya samples are negligible. Robust regression petrophysical models are performed for Bahariya permeability, susceptibility, $S_{por}$ and seismic wave velocity prediction for both laminated and non-laminated sandstone reservoir facies. These important reservoir parameters and their anisotropy can be outlined from routine measurements using the calculated regression models.

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