CHAPTER (II)

SCALAR PARAMETERS

CHAPTER 2
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Petrophysical properties are of great importance in reservoir rock studies. The present study is carried out using more than 80 core samples from a depth below 3500 m from an exploration drilling in Abu Gharadig Basin. The samples were obtained from the Bahariya Formation about 100 km north of Bahariya Oasis. These samples have been investigated by numerous laboratory petrophysical measurements. Regarding the parameters determined, we differentiate between the so called scalar properties, which yield a single quantity for each sample, and the directional parameters which depend on the spatial orientation of the specimen and measurement. The determined values of scalar parameters like porosity, density, specific internal surface or magnetic susceptibility should be close to each other for a pair of horizontal and vertical samples. The minima, maxima, average values and standard deviations of all measured parameters are calculated. The investigated scalar properties and the applied methods and devices are compiled in Table 1.

Table 1: Investigated scalar properties and applied methods and devices used for Bahariya Formation samples.

Applied petrophysical methods			
Applied methods / devices	Parameter and symbol	Physical unit	Number of Samples
Archimedic weighing	grain density: d_g	g/cm^3	95
	porosity: Φ	%	96
	bulk density: d_b	g/cm^3	95
Nitrogen adsorption - BET	specifc internal sample surface: S_{por}	μm^{-1}	75
Magnetic properties- Kappabridge KLY 2	volumetric magnetic susceptibility: κ	10^{-6} SI	95

Before performing petrophysical measurements, samples were prepared as cylinders of 2.55 cm (1 inch) diameter and different lengths (2 to 4 cm) using a diamond drilling machine. The studied samples have been cleaned by solvent, the particular solvent to be used should be selected in order not to attack, alter, or destroy the structure of the sample. Samples were dried to remove pore water and cleaning solvent. Once the

extraction of fluids from the samples had been completed, the samples were dried in an oven to constant weight at 115 C^0 **(API, 1960)**. Samples are considered to be at constant weight, when before and after a subsequent 4 hours drying period, are repeatable weight (+/- 1%) could be determined. After constant weights had been achieved, all the samples were cooled to room temperature in moisture-free desiccators.

2-1. Rock density

Density and porosity are sometimes measured as one package. The investigation of density variation and the study of the relationships between them and the rock petrophysical properties are of great significance. It is usually used for lithological discrimination, identification and consequently for reservoir zonation **(El Sayed 1995)** the density of a rock is controlled by many factors such as mineral composition, porosity of the rock and saturating fluid. The density can be classified into: a) bulk density and b) grain density.

2-1.a Bulk density d_b

The bulk density is defined as the mass of unit volume of a rock in its natural state. The bulk density depends on solid phase (grains and cement), voids or spaces (porosity) and types of fluids saturating of the rock spaces. The bulk density is expressed as:

$$d_b = \frac{m}{V}. \qquad (1)$$

with

d_b bulk density in g/cm³,

m mass of the sample in g,

V volume of the samples in cm³.

2-1.1a Statistical analysis of dry bulk density

The obtained dry bulk density of the Bahariya Formation varies from 2.16 g/cm³ to 2.57 g/cm³ with a mean value of 2.33 g/cm³ and a standard deviation of 0.10 g/cm³. The data of dry bulk density of the studied samples is listed in Tables 2-1, 2, 3 of appendix 1 and presented in Figs. 2-1, 2. For laminated samples, bulk density ranges from 2.17 g/cm³ to 2.57 g/cm³ with a mean value of 2.37 g/cm³ and a standard deviation of 0.10 g/cm³. The dry bulk density of the non-laminated samples ranges from 2.16 g/cm³ to 2.38 g/cm³ with a lower mean value of 2.26 g/cm³ and the standard deviation equals 0.06 g/cm³.
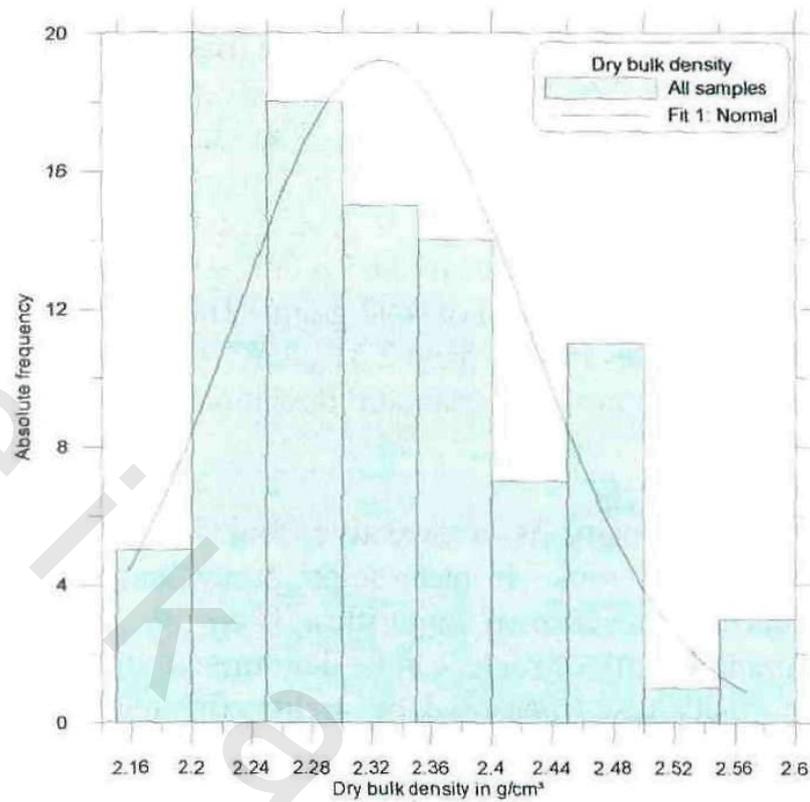
Fig. 2-1 Histogram of dry bulk density for all samples of the Bahariya Formation. 94 data points are used.
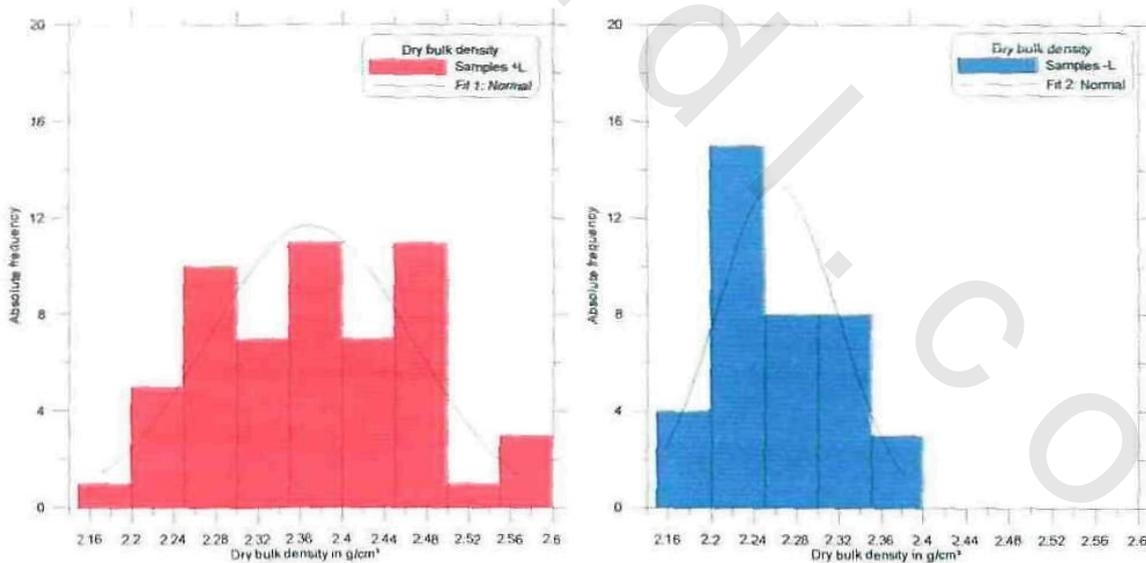

Fig. 2-2 Histogram of dry bulk density for laminated and non-laminated samples of the Bahariya Formation. 56 data points are used for laminated samples and 38 data points are used for non-laminated samples.

2-1.2a Statistical analysis of wet bulk density

The obtained wet bulk density of the Bahariya Formation varies from 2.30 g/cm³ to 2.65 g/cm³ with a mean value of 2.44 g/cm³. The standard deviation equals 0.07 g/cm³. The data of wet bulk density determination of the studied samples is listed in Tables 2-1, 2, 3 of appendix 1 and presented in Figs. 2-3, 4. For laminated samples, bulk density ranges from 2.30 g/cm³ to 2.65 g/cm³ with a mean value of 2.46 g/cm³ and a standard deviation of 0.07 g/cm³. The wet bulk density of the non-laminated samples ranges from 2.31 g/cm³ to 2.48 g/cm³ with a lower mean value of 2.40 g/cm³. The standard deviation equals 0.04 g/cm³.

2-1.b Grain density d_g

The grain density is a sensitive tool to indicate the mineral composition of the rock. It also helps in evaluation of the cement materials and the presence of impurities. There are several methods by which the grain density of rocks can be determined. It has been calculated from the porosity test (measured by archimedic method) by using the following equation:

$$d_g = \frac{m_d}{V_g} . \qquad (2)$$

with

d_g grain density in g/cm³,

m_d dry mass of sample in g,

V_g volume of grains in cm³.

2-1.1b Statistical analysis of grain density

The obtained grain density values of Bahariya samples vary from 2.55 g/cm³ to 2.84 g/cm³ with a mean value of 2.64 g/cm³ and a standard deviation of 0.04 g/cm³. Grain density data of the studied samples is listed in Tables 2-1, 2, 3 of appendix 1 and presented in Figs. 2-5, 6. The grain density values for laminated samples ranges from 2.55 g/cm³ to 2.84 g/cm³ with a mean value of 2.64 g/cm³ and a standard deviation of 0.04 g/cm³. For the non-laminated samples, the values range from 2.59 g/cm³ to 2.69 g/cm³ with a mean value of 2.64 g/cm³. The standard deviation equals 0.02 g/cm³.
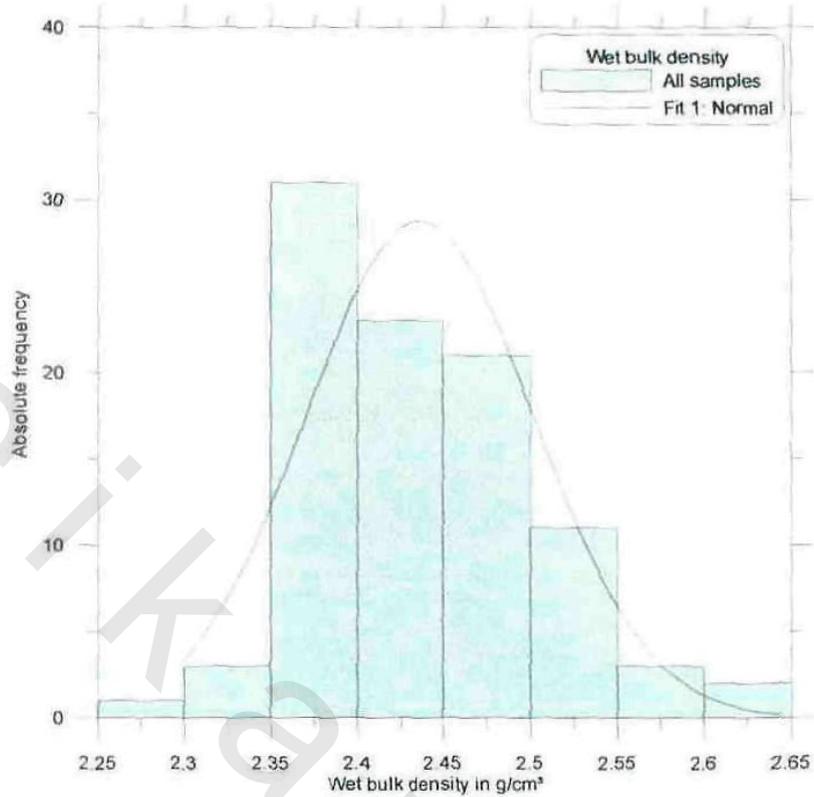
Fig. 2-3 Histogram of wet bulk density for all samples of the Bahariya Formation. 95 data points are used.
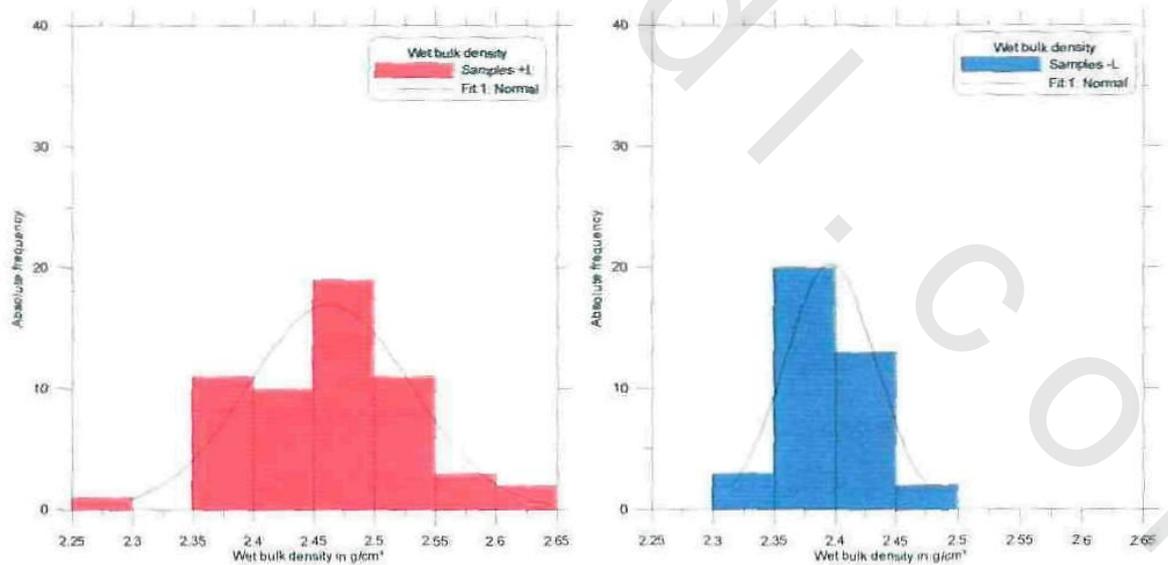

Fig. 2-4 Histogram of wet bulk density for laminated and non-laminated samples of the Bahariya Formation. 57 data points are used for laminated samples and 38 data points are used for non-laminated samples.
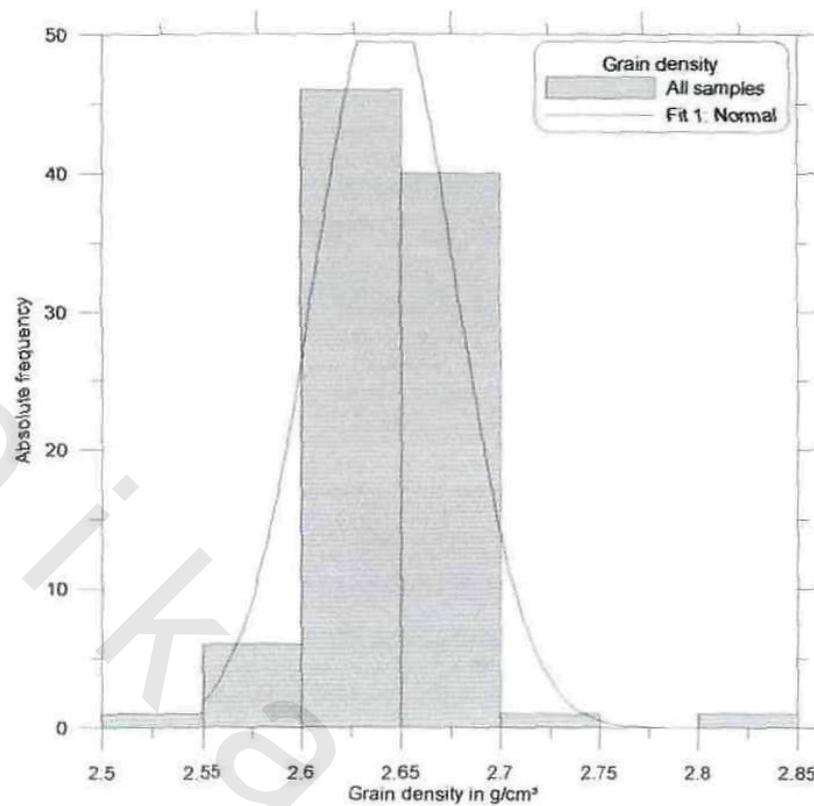
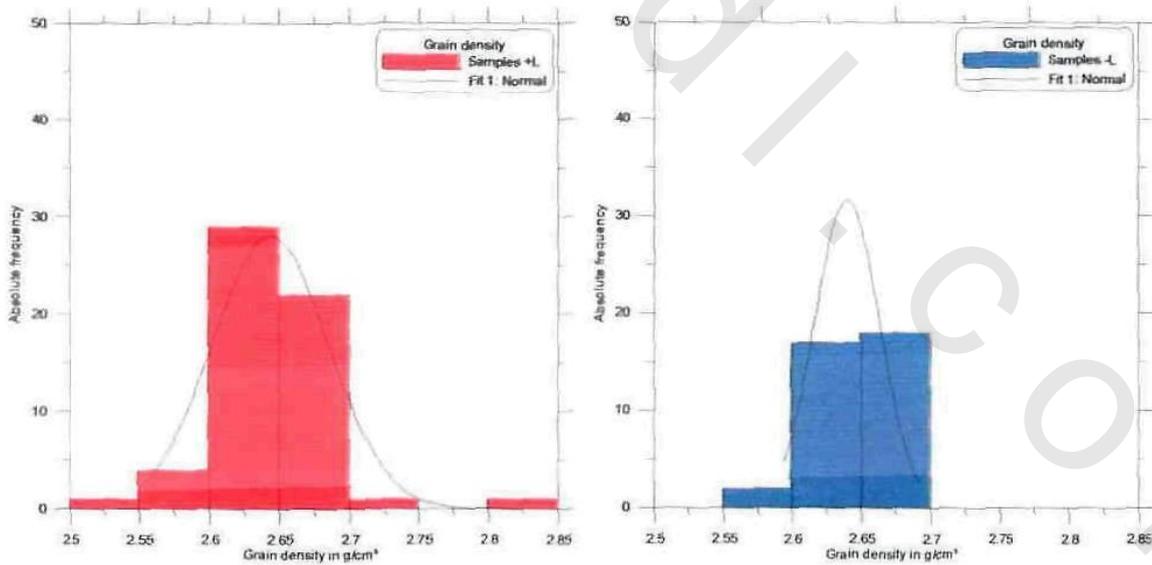Fig. 2-5 Histogram of grain density for all samples of the Bahariya Formation. 95 data points are used.

Fig. 2-6 Histogram of grain density for laminated and non-laminated samples of the Bahariya Formation. 58 data points are used for laminated samples and 37 data points are used for non-laminated samples.

2-2. Porosity

The porosity Φ of a reservoir rock is defined as that fraction of bulk volume of the reservoir that is not occupied by the solid framework of the reservoir **(Tiab and Donaldson, 2004)**. This can be expressed in mathematical form as:

$$\Phi = \frac{V_b - V_g}{V_b} = \frac{V_p}{V_b}. \qquad (3)$$

with

V_g grain volume in cm³,

V_b bulk volume in cm³,

V_p volume of pore space in cm³,

Φ porosity.

The porosity of a rock is one of the most important reservoir properties. It controls the storage capacity of a reservoir. In other words, it is responsible for quantity of fluids that the rock can store. The average depositional porosity ranges between 40 and 58% **(Atkins and McBride, 1992)** while the porosity of petroleum clastic reservoirs ranges from 10% up to 35%. The factors governing the magnitude of porosity in clastic sediments can be summarized as:

1- grain packing,
2- grain size and shape,
3- diagenesis, cementation,
4- compaction, fracturing and solution.

2-2.1 Classification of Porosity

Serra (1984) gives the following short definition: "Porosity is the fraction of the total volume of a rock that is not occupied by the solid constituents." This is a complete definition of "total porosity".

According to **Serra (1984)** the porosity can be classified into:

A.   Total porosity: is related to all void spaces (pores, channels, fissures, vugs) between the solid components.

B.   Interconnected porosity: is related only to those spaces which are connected. Pores are considered to be connected when electrical current and fluids can flow between them.

C.   Potential porosity: is that part of the interconnected porosity in which the diameter of the connecting channels is large enough to permit a fluid flow.

D.   Effective porosity: is the porosity that is available for free fluids; it excludes all non-connected porosity including the space occupied by the clay-bound water. Effective porosity is a term used specifically in log analysis.

The effective porosity can be calculated by the equation introduced by **El Sayed (1995)** as:

$$\Phi_{eff} = \Phi_t (1 - S_{wirr.}) . \qquad (4)$$

with

S_{wirr} fraction of irreducible water saturation,

Φ_{eff} effective porosity,

Φ_t total porosity.

A general classification of porosity, adopted by **Ellison (1958)** differentiates between primary and secondary porosity:

A. Primary porosity

Primary porosity has been developed during the deposition of the rock materials and is divided into:

a)   Intercrystalline voids between cleavage planes of crystals, voids between individual crystal, and voids in crystal lattices that are called "micro-porosity".

b)   Intergrannlar or interparticle voids between grains in all types of rocks.

c)   Bedding planes voids of many varieties are concentrated in parallel to the bedding plan.

d)   Miscellaneous sedimentary voids resulting from the accumulation of detrital fragments of fossils, voids created by living organisms at the time of deposition.

B. Secondary porosity

Secondary porosity is the result of geological processes (diagenesis and catagenesis) after the deposition of sediment. Secondary (induced) porosity can be subdivided into:

a)   Solution porosity consists of channels due to the solution of certain minerals by circulation of water or hot solutions.

b)   Dolomitization is a process by which limestone is transformed into dolomite with a higher mineral density.

c)   Fracture porosity created by structural failure of the reservoir rocks under tension caused by tectonic activities such as folding and faulting.

2-2.2 Porosity measurements

Several methods have been proposed and explained in different literature for rock porosity determination. In the laboratory, measurement of rock porosity require the determination of only two of the three volume parameters: they are pore volume (Vp), grain volume (Vg) and bulk volume (Vb) with the latter being the sum of the previous two parameters. In the present study, the rock porosity and grain density was determined by Archimedic method with weighting the sample three time: in dry state, in fully saturated state and finally in a water basin.

2-2.3 Statistical analysis of porosity

The rock porosity of the Bahariya samples varies from 3.6 % to 17.0 % with a mean value of 10.8% and a standard deviation of 3.5%. Porosity data of the studied samples is listed in Tables 2-1, 2, 3 of appendix 1 and presented Figs. 2-7, 8. The porosity values for laminated samples spread over a relatively wide interval ranging from 3.6% to 15.3% with a mean value of 9.0% and a standard deviation of 3.0%. The porosity of the non-laminated samples interval becomes narrower ranging from 9.0% to 17.0% with a mean value of 13.5% and a lower standard deviation of 2.2%.
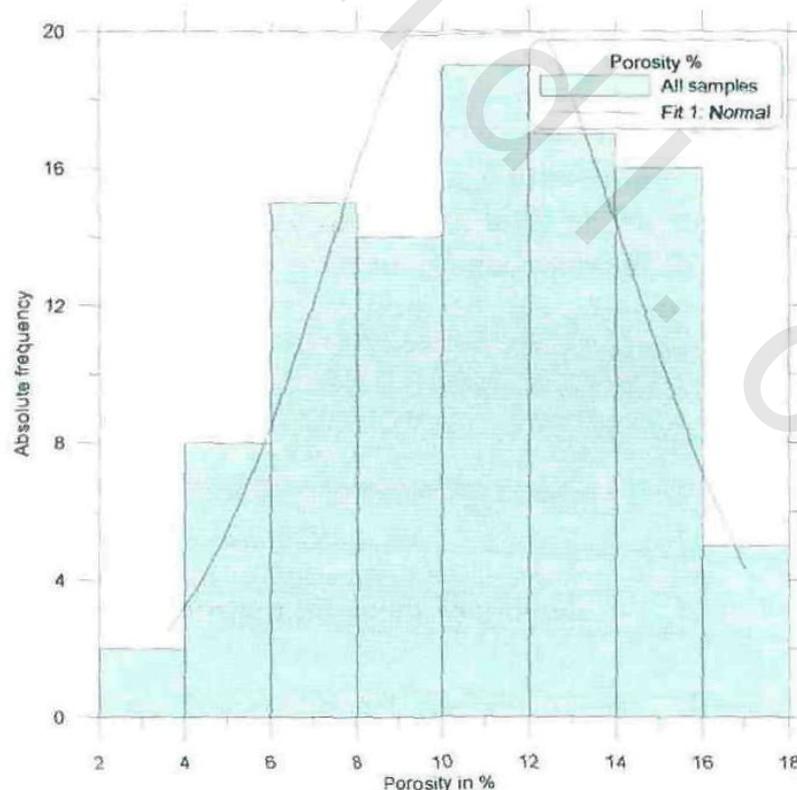

Fig. 2-7 Histogram of porosity for all samples of the Bahariya Formation. 96 data points are used.
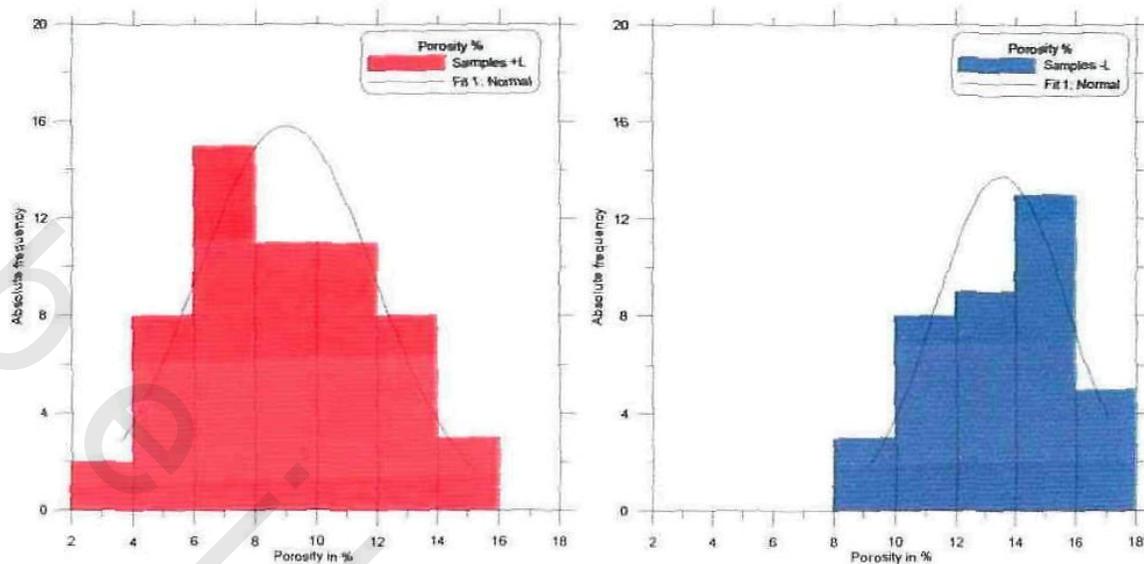
Fig. 2-8 Histogram of porosity for laminated samples of the Bahariya Formation. 58 data points are used for laminated samples and 38 data points are used for non-laminated samples.

2-3 Specifc surface area

Porosity describes the volume of the voids (pores, cracks, fissures, fractures etc.) in relation to the considered rock volume. The specific internal surface describes the surface area of these voids in relation to either:

· the total rock volume with S_{tot} in μm^{-1},
· the pore volume with S_{por} in μm^{-1},
· the volume of the solid matrix with S_m in μm^{-1},
· the mass of the dry rock S_{ma} in m^2/g.

The following equations can be used to make a transformation between the quantities:

$$S_{tot} = \Phi.S_{por} = (1-\Phi).S_m. \tag{5}$$

$$S_{ma} = \frac{S_m}{d_m}. \tag{6}$$

with

d_m density of the solid matrix material.

The specific internal surface depends mainly on: the shape and size of pores, and the microstructure and morphology of the matrix - pore interface. The specific internal surface varies over a wide range. The "micromorphology" of the pore surface has a strong influence on the value of the specific internal surface. As a general tendency, the specific

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internal surface increases with the decrease of the mean pore or grain size. The presence of clay particles, and the growth of various types of surface structures in the pore space increases the internal surface (**Schön, 1996**).

2-3.1 Statistical analysis of Specific surface area

The measured specifc surface area has been normalized to the volume of pore space (S_{por}). The specifc surface area of the Bahariya samples varies from 1.35 μm^{-1} to 113 μm^{-1} with a mean value 17.24 μm^{-1} and a standard deviation 20.77μm^{-1}. Data of specifc surface area (S_{por}) of the studied samples is listed in Tables 2-1, 2, 3 of appendix 1 and presented in Figs. 2-9, 10. Specifc surface area values for laminated samples ranges from 1.48 μm^{-1} to 113 μm^{-1} with a mean value of 25.61 μm^{-1} and a standard deviation of 23.30 μm^{-1}. For non-laminated samples, the specifc surface area ranges from 1.35 μm^{-1} to 10.87 μm^{-1} with a lower mean value of 4.69 μm^{-1} and a standard deviation of 2.30 μm^{-1}. Though the average values indicate a remarkable difference, the surface ranges broadly overlap. In general, the laminated samples are characterized by a higher internal surface.
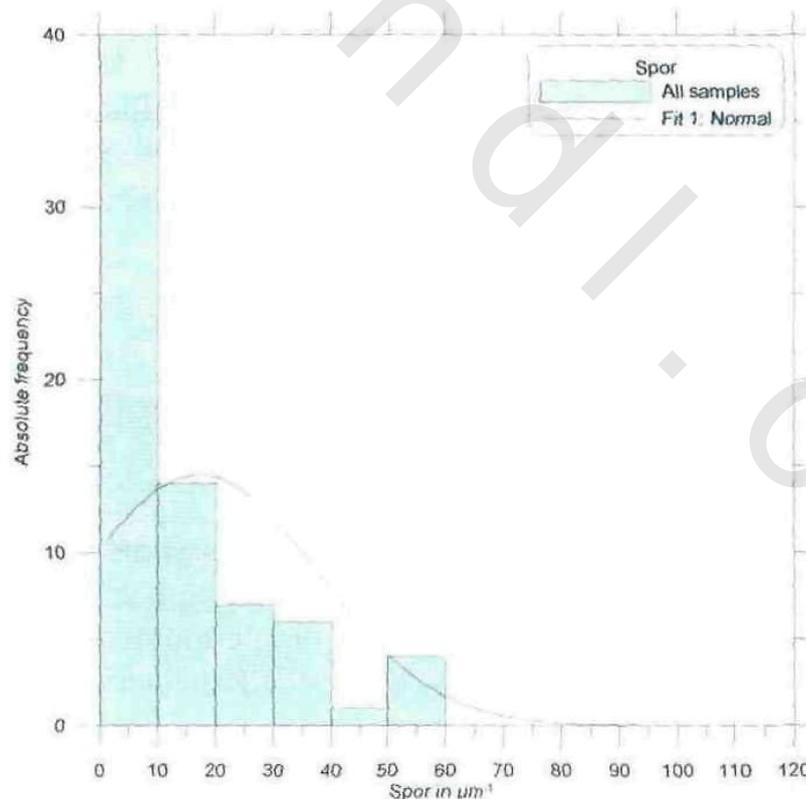

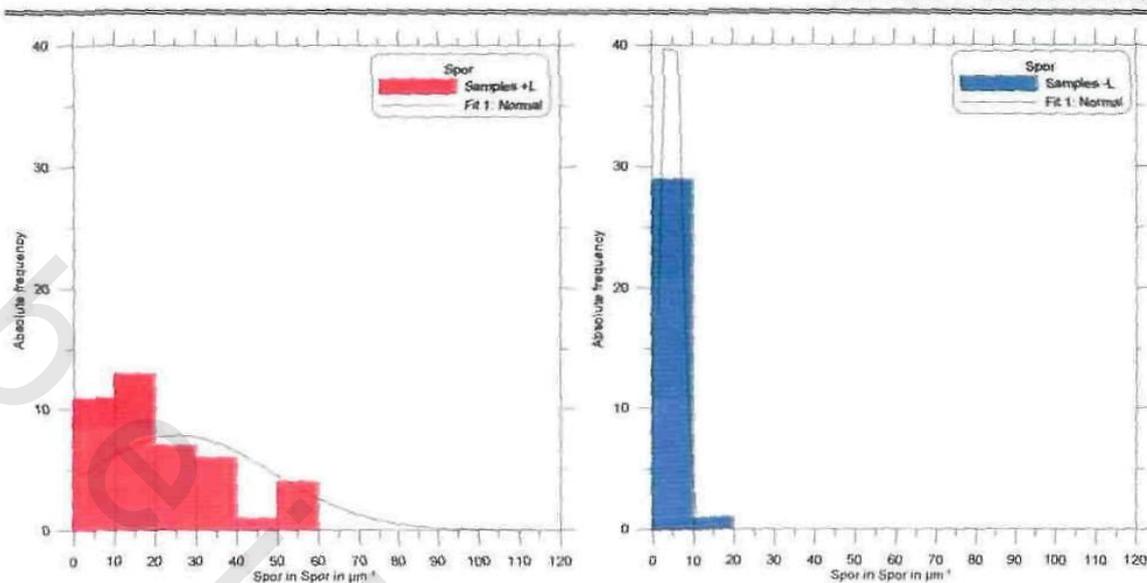Fig. 2-9 Histogram of specifc surface area for all samples of the Bahariya Formation. 75 data points are used.

Fig. 2-10 Histogram of specifc surface area for laminated samples of the Bahariya Formation. 45 data points are used for laminated samples and 30 data points are used for non-laminated samples.

2-4 Magnetic susceptibility

The magnetic properties of rocks are controlled by those mineral constituents which have a magnetic effect. The fraction of these minerals with respect to the total rock volume may be small. Magnetic properties describe the behavior of any substance under the influence of a magnetic field. Magnetic phenomena arise from the motion of electrically charged particles within the substance. **Schön (1996)** describes three main groups of materials with regard to the magnetic properties:

1. Diamagnetic behaviour: The electron shells of the atoms are complete.
2. Paramagnetic behaviour: The electron shells of the atoms are incomplete.

Diamagnetic and paramagnetic substances show only weak effects in the presence of an applied magnetic field. In both cases, the strength of the induced magnetization M (magnetic dipole moment per unit volume) is directly related to the strength of the applied magnetic field H:

$$M = \kappa.H. \tag{7}$$

with the factor of proportionality κ being the magnetic susceptibility.

In general, the susceptibility is a tensor of rank two. If not otherwise mentioned, the symbol κ means a "mean, quasi isotropic" susceptibility.

3. Ferro-, antiferro-, and ferrimagnetic behaviour: This type of magnetism occurs in substances in which the electron spins have been spontaneously coupled (spontaneous magnetization) in a way that alines the individual spin magnetizations even in the absence of an externally applied magnetic field. The magnetic behavior is described by the existence and properties of magnetic volume elements termed "magnetic domains" (single-domain, multi-domain). The phenomenon of ferro-, antiferro-, and ferrimagnetism can also be discussed as that of a material which contains ions with an intrinsic magnetic moment.

Diamagnetic substances are characterized by negative susceptibilities. The magnitude for common rock-forming minerals is often in the region of -10^{-5} (SI). Paramagnetic substances show positive susceptibilities that extend over a range between 10^{-4} and 10^{-2} (SI) for the common rock-forming minerals **(Tarling and Hrouda, 1993).** Diamagnetic susceptibility is independent of temperature. The temperature dependence of paramagnetic susceptibility is given by the Curie law or the Curie-Weiss law.

2-4.1 Statistical analysis of magnetic susceptibility

Volumetric magnetic susceptibility values of the Bahariya samples vary from $23*10^{-6}$ SI to $595*10^{-6}$ SI with a mean value of $112*10^{-6}$ SI and a standard deviation of $82*10^{-6}$ SI. Data of magnetic susceptibility determination of the studied samples is listed in Tables 2-1, 2, 3 of appendix 1 and presented in Figs. 2-11, 12. Magnetic susceptibility values for laminated samples range from $27*10^{-6}$ SI to $595*10^{-6}$ SI with a mean value of $147*10^{-6}$ SI and a standard deviation $86*10^{-6}$ SI. For non-laminated samples the magnetic susceptibility ranges from $23*10^{-6}$ SI to $164*10^{-6}$ SI with a lower mean value of $59*10^{-6}$ SI and a standard deviation of $36*10^{-6}$ SI. Though there is a broad overlapping interval between the susceptibility values of laminated and non-laminated samples, a clear distinction becomes apparent. A majority of the laminated samples shows susceptibility values larger than $60*10^{-6}$ SI, but only a small number of non-laminated samples exceed this limit. Though no difference in grain density has been observed, the changes in the mineral content of the strongly laminated samples obviously cause an increase in magnetic susceptibility which might be explained by the presence of iron minerals.
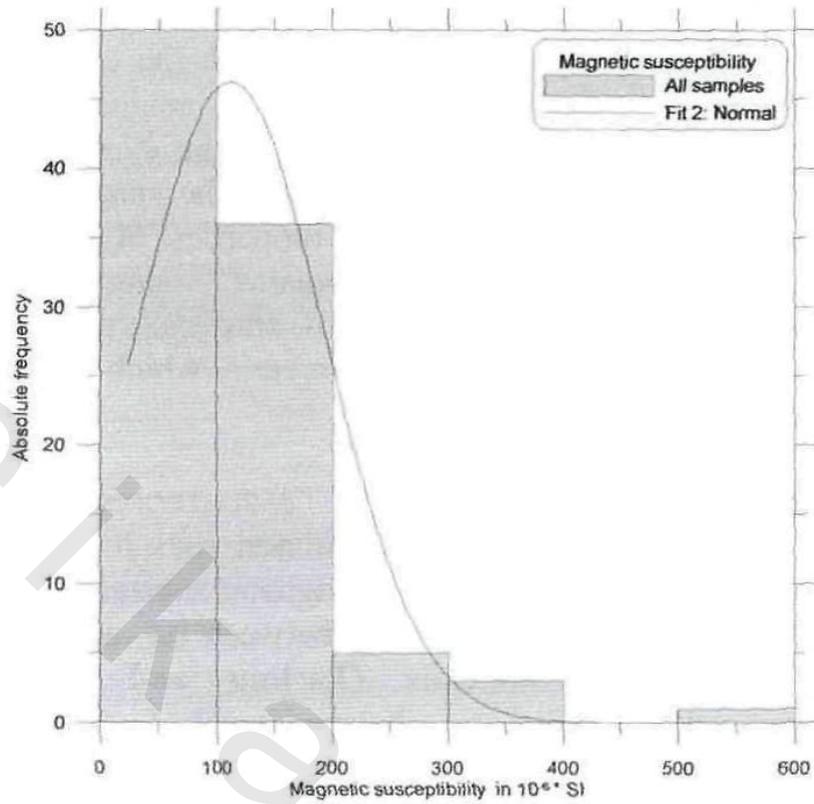
Fig. 2-11 Histogram of magnetic susceptibility for all samples of the Bahariya Formation. 95 data points are used.
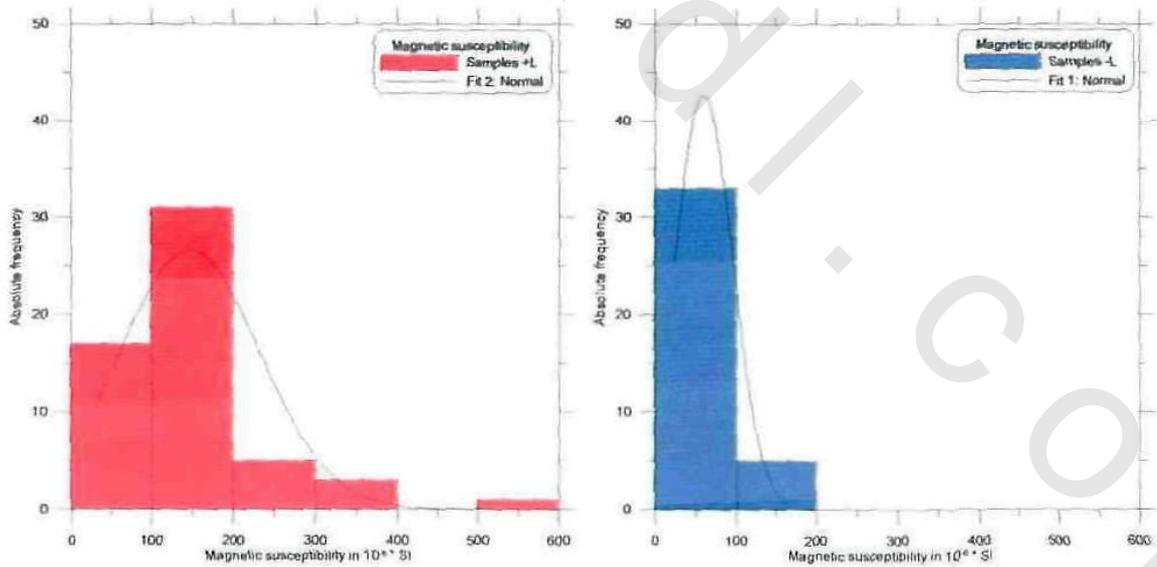

Fig. 2-12 Histogram of magnetic susceptibility for laminated samples of the Bahariya Formation. 57 data points are used for laminated samples and 38 data points are used for non-laminated samples.

The values calculated for scalar properties including minima, maxima, average and standard deviations for the investigated Bahariya Formation samples are compiled in Table 2.

Table 2: The minima, maxima, average and standard deviations values for scalar properties investigated for Bahariya Formation samples.

Scalar parameter	All				Laminated				Non-laminated			
	Min.	Max.	Mean	St. Dv.	Min.	Max.	Mean	St. Dv.	Min.	Max.	Mean	St. Dv.
Dry bulk density (g/cm³)	2.16	2.57	2.33	0.10	2.17	2.57	2.37	0.10	2.16	2.38	2.26	0.06
Wet bulk density (g/cm³)	2.30	2.65	2.44	0.07	2.30	2.65	2.46	0.07	2.31	2.48	2.40	0.04
Grain density (g/cm³)	2.55	2.84	2.64	0.04	2.55	2.84	2.64	0.04	2.59	2.69	2.64	0.02
Porosity (%)	3.56	17.03	10.79	3.48	3.56	15.33	9.00	2.95	9.04	17.03	13.51	2.24
S_{por} (μm^{-1})	1.35	113.02	17.24	20.77	1.48	113.02	25.61	23.30	1.35	10.87	4.69	2.30
Magnetic susceptibility (10^{-6} SI)	23.17	594.92	111.77	82.42	27.28	594.92	146.67	86.27	23.17	163.84	59.41	36.06