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Prediction of vertical permeability and reservoir anisotropy using coring data

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Abstract

Most reservoirs have different degrees of permeability anisotropy. Optimization of recovery is crucially dependent on the reservoir quality and anisotropy. The ratio of vertical and horizontal permeability is important when reservoir anisotropy (K_v/K_h) and heterogeneity cannot be neglected. Therefore, an accurate knowledge of vertical and lateral permeability distribution is essential for better reservoir characterization. This work uses routine core data for analysis to develop new correlations and characterization of a sandstone reservoir under development. The two main goals of this study are to use core data to (1) develop correlations capable of predicting vertical permeability from horizontal permeability or mean hydraulic radius and (2) develop another correlation capable of predicting the permeability anisotropy ratio (K_v/K_h) using effective porosity data. To accomplish the objectives of this project, various petrophysical properties were experimentally measured for 112 core samples extracted from an actual sandstone reservoir. The measurements included vertical permeability, horizontal permeability, effective porosity and saturations of oil and water. Applications of the developed results of this study help enhancing the prediction of vertical permeability, improving reservoir characterization and providing better simulation studies.

Keywords Vertical permeability · Anisotropic reservoir · Core data · Sandstones

Nomenclature

A_1, B_1	Curve fitting constants
F_s	Shape factor
K	Absolute permeability, md
K_h	Horizontal permeability, md
K_v	Vertical permeability, md
RQI	Reservoir quality index, µm, micron
RCA	Routine core analysis
SCAL	Special core analysis
S_{gv}	Surface area per unit grain volume, μm^{-1}
S_w	Water saturation, fraction
φ_e	Effective porosity, fraction
τ	Tortuosity

Subscripts

e	Effective
gr	Grain
w	Water
irr	Irreducible

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Introduction and literature review

In early studies of reservoir engineering, the reservoirs are assumed to be homogeneous, isotropic and uniform. Absolute rock permeability (K) is defined as the ability of the rock to transmit fluid(s). Horizontal permeability (K_h) is parallel to bedding plan and is generally greater than vertical (K_v). Low vertical permeability creates a larger pressure drop near the wellbore and directly affects the skin factor.

Vertical permeability is essential in reservoir management and development such as, the optimal well locations and production rate, horizontal well applications, completion optimization and perforation design, and planning EOR injectors/producers (Clark 1969; Zahaf and Tiab 2002).

The ratio of vertical to horizontal permeability (K_v/K_h) represents the contrast in permeability between the vertical and horizontal planes within a formation (called anisotropic permeability). This ratio is important in reservoir simulation studies, because it is applicable in vertical wells and more important in partially penetrated or horizontal wells. In layered reservoirs, the vertical permeability of each layer is quite different from the surrounding layers. Therefore, these type of reservoirs are divided into layers based on the (K_v/K_h) relationships.

Clark (1969) indicated that the horizontal permeability (K_h) would be higher than the vertical one for large and flat rock grains. He concluded that generally, vertical permeability is lower than horizontal permeability, especially, if the sand grains are small and have irregular shape. Majority of petroleum reservoirs are in this category.

Prediction of permeability accurately enough from core and well logs have been achieved by several authors (Tiab 1993; Amaefule et al. 1993; Elkewidy 1996; Shedid Elgaghah 1997). They proposed methods for integrating core and log data for formation evaluation in term of flow units. To have a better reservoir description, we should consider the vertical variation of hydraulic properties. Osisanya et al. (1998) developed new permeability porosity correlations but without consideration of anisotropic conditions of the reservoirs.

Iheanacho et al. (2012) developed several correlations of vertical and horizontal permeability for sandstone and shaly sandstones reservoirs and made a general conclusion that vertical permeability decreases with depth. Fazelalav (2013) developed several correlations for prediction of vertical permeability for Arbuckle formation as shown in Table 1. However, these correlations suffer from poor correlating coefficients.

Correlations listed in Table 1 below indicates that vertical permeability may increase or decrease, but it does not have a general trend. Majority of other studies had confirmed a general conclusion that vertical permeability decreases with depth (Clark 1969; Osisanya et al, 1998; Zahaf and Tiab 2002; Iheanacho et al. 2012).

The main objective of this work is to develop semi-empirical correlations between vertical permeability and horizontal permeability for sandstone reservoirs. Actual core data are gathered and analyzed from an Egyptian sandstone reservoir to achieve this goal.

Development of vertical–horizontal permeability relationship using core data

The factors affecting rock permeability have been recognized to include the size, form, and shape of grains constituting the reservoir rocks. Therefore, it is important to develop a relationship between microscopic level attributes and microscopic core data based on the concept of hydraulic mean radius. This is because the hydraulic mean radius considers variations in permeability and porosity as it is defined to be equal to $\sqrt{K/\varphi}$.

Recalling the modified Kozeny–Carman equation, Eq. (1) that is shown below:

$$K = \left(\frac{\varphi_e^3}{(1-\varphi_e)^2}\right) \times \left[\frac{1}{F_s \tau^2 S_{gr}^2}\right] \quad (1)$$

It is possible to build a relationship between microscopic level attributes and microscopic core data. Dividing both sides of Eq. (1) by effective porosity (φ_e) and taking the square root of both sides results in:

$$\sqrt{\frac{K}{\varphi_e}} = \left(\frac{\varphi_e}{(1-\varphi_e)}\right) \times \left[\frac{1}{\sqrt{F_s}\tau S_{gr}}\right] \quad (2)$$

Amaefule et al. (1993) introduced the concept of reservoir quality index (RQI) considering the pore throat, pore and grain distributions and other macroscopic parameters to come up with an equation of the reservoir quality index (RQI) as follows:

$$\text{RQI}\ (\mu\text{m}) = 0.0324\left(\sqrt{\frac{K}{\varphi_e}}\right) \quad (3)$$

where RQI is the reservoir quality index (micron, μm), K is permeability (md) and ϕ is the effective porosity (fraction).

Zahaf and Tiab (2002) replaced absolute permeability (K) by the horizontal one (K_h) in the RQI model, Eq. (3), and developed a general vertical permeability model as a function of hydraulic mean radius, as given below:

$$K_v = A_1 \times \left(\sqrt{\frac{K_h}{\varphi}}\right)^{B_1} \quad (4)$$

where A_1 and B_1 are coefficients to be determined for a specific field case. K_v and K_h are vertical and horizontal permeability (md), respectively, and ϕ is the effective porosity (fraction).

Table 1 Developed vertical permeability correlations for Arbuckle formation (Fazelalav 2013)

#	Correlation	Correlating coefficient	# Of cores	Application condition and core observation
1	$K_v = 0.1871\ K_h$	$R^2 = 0.5367$	216	Rock without fractures
2	$K_v = 0.1871\ K_x$	$R^2 = 0.5367$	97	For K_v is less than K_h
3	$K_v = 2.4484\ K_h$	$R^2 = 0.6916$	60	For K_v is bigger than K_h
4	$K_v = 82.624\ K_h$	$R^2 = 0.9906$	18	For K_v is much bigger than K_h due to extremely vertical fractures

Field case study: Gulf of Suez, Egypt

An oil field is located in the Gulf of Suez, Egypt. The field was discovered in the early 2000s with potential pay in the HL-R formation. This formation is characterized as a sandstone reservoir with multiple thin intervals of average thickness of 5′ ft. Geological analysis of the HL-R sandstone rock showed that it contains glauconite, which usually occurs as green, amorphous grains seldom larger than fine sand size.

Reservoir characterization studies showed that the formation was a transgressive succession punctuated by surfaces of erosion and mainly dominated by estuarine and restricted marine deposits. The reservoir fluid in the HL-R reservoir is described as a volatile oil that may grade into black oil in the deeper portion of the reservoir. Data from vertical appraisal wells confirmed low production rates and low estimate ultimate recovery. This represented a challenge for the economic development to capture the reservoir heterogeneity in this formation.

The vertical well HL-R6 was selected as a part of an appraisal program for a coring study. This coring task provided 112 preserved cores, which were used for measuring vertical permeability, horizontal permeability, porosity, density and saturations of oil and irreducible water. The core samples were extracted from the producing formation and the average rock density of core was measured to be 2.66 g/cm^3. The laboratory measurements were conducted at COREX lab in Cairo, Egypt. The porosity was measured volumetrically, while permeability was measured with a conventional air permeameter, and the irreducible water saturation was determined by the porous plate method.

Table 2 presents data of only 30 samples for every 5 ft of the cored zone, but the well was sampled every 1 ft and 112 core data are selected and used in plots of this project.

The attained data of vertical permeability is plotted versus depth in Fig. 1 It shows a wide range of variation and a general decrease mode in vertical permeability with depth. Figure 1 reveals that vertical permeability at depths

Table 2 Routine core analysis (RCA) data for 30 core samples as an example of 112 core data used

Core #	Depth (ft)	Perm-H [K_h (md)]	PermV [K_v (md)]	(K_v/K_h)	Porosity, ϕ (%)	Sw (%)
1	8700	99.70	56.10	0.057	13.20	06.50
3	8705	42.10	31.00	0.736	12.80	07.50
4	8710	12.80	12.30	0.961	11.10	03.70
5	8715	1480.00	13.30	0.001	08.90	04.80
6	8720	21.60	10.11	0.468	11.60	05.20
7	8725	40.70	23.20	0.570	11.70	05.10
8	8730	187.0	97.70	0.522	14.40	06.70
9	8735	2274.0	2189.00	0.962	21.60	03.30
10	8740	1967.0	378.00	0.192	17.20	05.20
11	8745	1457.0	401.00	0.275	14.70	04.00
12	8750	01.25	0.82	0.656	02.12	17.87
13	8755	0.05	0.05	1.00	09.60	13.00
14	8760	1634.00	0.04	0.00	21.40	03.00
15	8765	0.05	0.05	1.00	19.10	04.00
16	8770	1490.00	1080.00	0.725	21.40	10.03
17	8775	0.08	0.06	0.750	18.80	02.00
18	8780	0.05	0.04	0.800	01.70	05.00
19	8785	184.00	0.00	0.000	19.10	10.50
20	8790	151.00	0.04	0.001	18.10	05.00
21	8795	176.00	120.00	0.682	15.40	04.00
22	8800	368.00	332.00	0.902	18.80	09.00
23	8805	12.40	2.94	0.237	01.40	05.00
24	8810	192.00	88.80	0.462	13.70	04.40
25	8815	427.00	11.00	0.258	13.40	13.20
26	8820	61.10	47.70	0.780	14.30	03.50
27	8825	150.00	114.00	0.760	17.50	07.00
28	8830	86.00	0.05	0.000	18.30	04.00
29	8835	2.48	1.09	0.439	02.40	03.00
30	8840	563.00	668.00	1.186	20.20	02.00

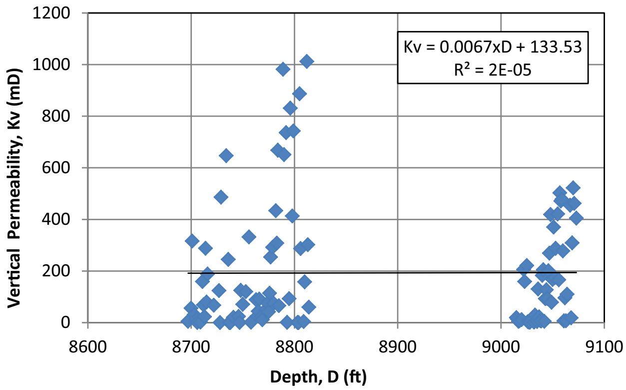

Fig. 1 Variation of vertical permeability with depth

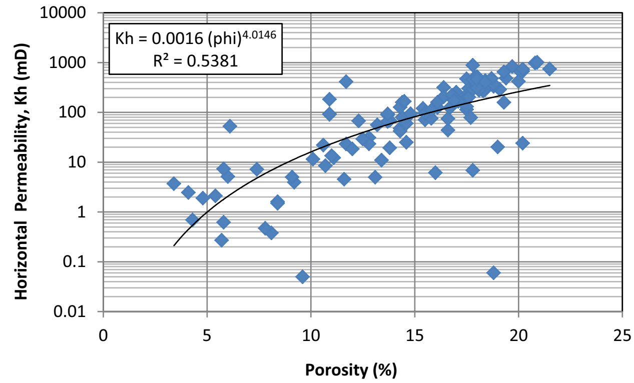

Fig. 3 Horizontal permeability and porosity relationship

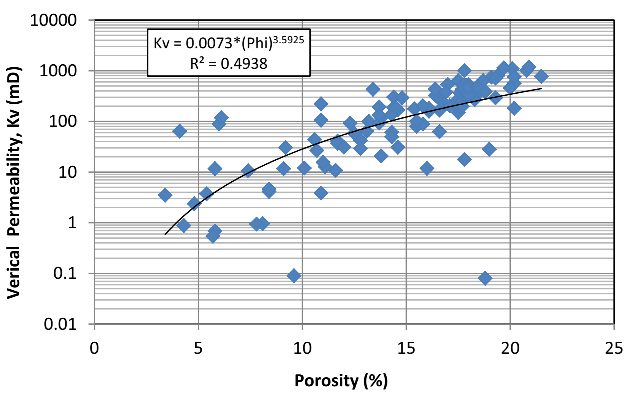

Fig. 2 Vertical permeability and porosity relationship

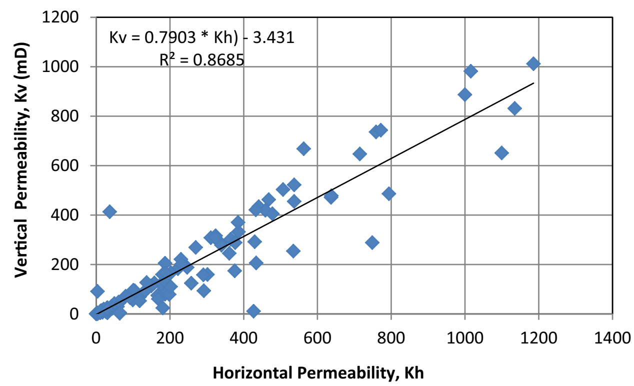

Fig. 4 Newly developed vertical–horizontal permeability relationship

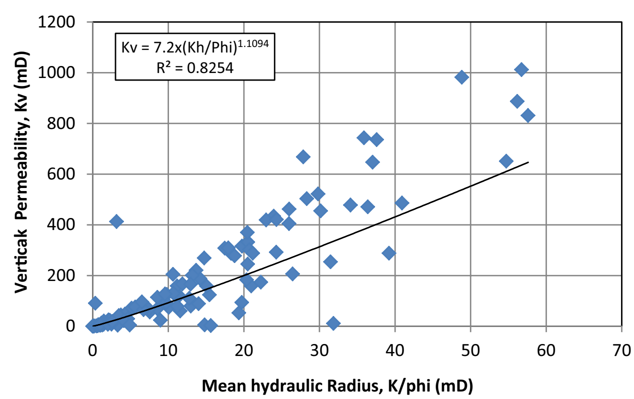

Fig. 5 A plot of vertical perm versus mean hydraulic radius

from 9000 to 9100 ft is lower than others at depths from 8700 to 8800 ft.

Using all data points of 112 cores and plotting of vertical permeability versus porosity is shown in Fig. 2. This core data is used to develop the following empirical correlation:

$$K_v = 0.0073 \times \Phi^{3.5925}, \quad R^2 = 0.4938 \tag{5}$$

Additionally, a plot of horizontal permeability versus porosity is presented in Fig. 3 and a correlation is developed using curve fitting as shown below,

$$K_h = 0.0016 \times \Phi^{4.0146}, \quad R^2 = 0.5381 \tag{6}$$

A plot of vertical permeability versus a horizontal one using 112 core data is shown in Fig. 4 and yields the following new Eq. (7) for predicting vertical permeability;

$$K_\mathrm{v} = 0.7903 \times K_\mathrm{h} - 3.431, \quad R^2 = 0.868 \tag{7}$$

Equation (7) represents a good tool for predicting vertical permeability with a good correlating coefficient (R^2=0.868).

For the purpose of correlating the vertical permeability to the hydraulic mean radius, the same data points were plotted in Fig. 5. Applying the curving fitting technique provides the following correlation below,

$$K_\mathrm{v} = 7.2 \times \left(\sqrt{\frac{K_\mathrm{h}}{\varphi}}\right)^{1.1094}, \quad R^2 = 0.868 \tag{8}$$

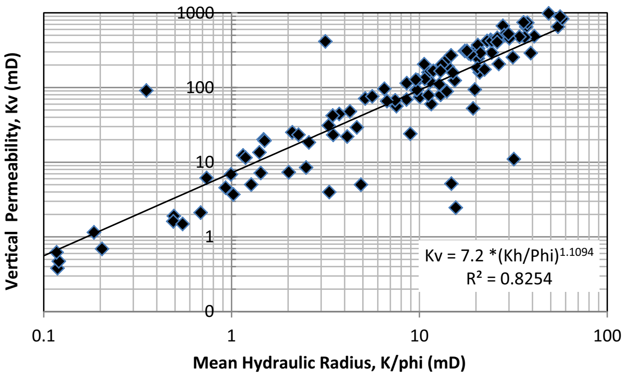

Fig. 6 Log–log plot of vertical permeability versus mean hydraulic radius

where K_v and K_h are vertical and horizontal permeability (md), respectively, and Φ is the effective porosity (fraction).

A log–log plot of vertical permeability versus mean hydraulic radius is presented in Fig. 6 with a good correlating coefficient of 0.82.

Rearranging Eq. (8) results in a correlation capable of predicting the anisotropic permeability ratio from porosity, as shown below,

$$\frac{K_v}{K_h^{1.1094}} = \left(\frac{7.2}{\sqrt{\phi^{1.1094}}}\right) = \left(\frac{7.2}{\phi^{0.5547}}\right), \quad R^2 = 0.825 \tag{9}$$

The above equation indicates that the anisotropy ratio of permeability decreases with porosity for this sandstone reservoir. Equation (9) is important for reservoir simulation studies and may be used to predict the anisotropic ratio for more realistic results than that one attained from defaulted values in commercial software.

Conclusions

This study was undertaken to develop correlations capable of predicting vertical permeability and permeability anisotropy ratio using routine core data. The main conclusions of the study are summarized as follows:

1. Routine core data were gathered and used for the analysis and correlation of vertical permeability with horizontal permeability and other petrophysical properties of sandstone reservoir.
2. The permeability anisotropy ratio varies over a wide range of depth in sandstone reservoir under investigation. The variation exhibits a general decrease with depth.
3. New correlations were developed as tools capable of predicting vertical permeability from porosity, horizontal permeability and/or from mean hydraulic radius.
4. A correlation between anisotropic permeability ratio and porosity is developed and can be used to predict the anisotropic ratio from porosity core data.
5. The developed correlations represent useful tools for better studying reservoir management such as optimal well location, simulation studies and a better description of the reservoir.

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