PERMEABILITY ANISOTROPY DISTRIBUTIONS IN AN UPPER JURASSIC CARBONATE RESERVOIR, EASTERN SAUDI ARABIA

A. Sahin[1,2], A. Z. Ali[1], S. Saner[1] and H. Menouar [1]

Most classical reservoir engineering concepts are based on homogeneous reservoirs despite the fact that homogeneous reservoirs are the exception rather than the rule. This is especially true of carbonate reservoirs in the Middle East which are known to be highly heterogeneous. The realistic petrophysical characterization of these kinds of reservoirs is not an easy task and must include the study of directional variations of permeability. Such variation can be incorporated into engineering calculations as the square root of the ratio of horizontal to vertical permeability, a parameter known as the anisotropy ratio.

This paper addresses the distribution of anisotropy ratio values in an Upper Jurassic carbonate reservoir in the Eastern Province of Saudi Arabia. Based on whole core data from a number of vertical wells, statistical distributions of horizontal and vertical permeability measurements as well as anisotropy ratios were determined. The distributions of both permeability measurements and anisotropy ratios have similar patterns characterized by considerable positive skewness. The coefficients of variation for these distributions are relatively high, indicating their very heterogeneous nature.

Comparison of plots of anisotropy ratios against depth for the wells and the corresponding core permeability values indicate that reservoir intervals with lower vertical permeability yield consistently higher ratios with considerable fluctuations. These intervals are represented by lower porosity mud-rich and/or mud-rich/granular facies. Granular facies, on the other hand, yielded considerably lower ratios without significant fluctuations.

INTRODUCTION

Permeability values in most reservoir rocks are dependent on the direction in which the measurements are made. Very often, measurements made in the horizontal plane are not significantly different from one another, but considerable differences may exist between measurements made in horizontal and vertical directions. These differences in permeability distributions may significantly affect the reservoir during depletion, and should be taken into account in reservoir engineering calculations, including well productivity, formation of water and gas coning, secondary recovery methods and well test analyses. Therefore, it is essential to determine permeability variations in different directions, particularly in vertical and horizontal directions within the reservoir. Such variation can be incorporated into engineering applications as the square root of the ratio of the horizontal to vertical permeability (Muskat, 1937; Henley *et al*., 1961; Forrest, 1971; Wilhite, 1986; Farouq *et al*., 1988; Joshi and Ding, 1996; Menouar and Hakim, 1995). This ratio is commonly referred to as the anisotropy ratio.

Due to zonation and layering in a reservoir, the anisotropy ratio may vary from one zone to another and even from one layer to another. Significant variations in this ratio within a particular zone or layer can also be observed. The pattern of variation of this ratio provides valuable information about flow

[1]King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

[2]KFUPM Box 661, Dhahran 31261, Saudi Arabia.
email: asahin@kfupm.edu.sa

Key words: permeability, permeability anisotropy, anisotropy ratio, carbonate reservoir, Arab-D, Saudi Arabia.

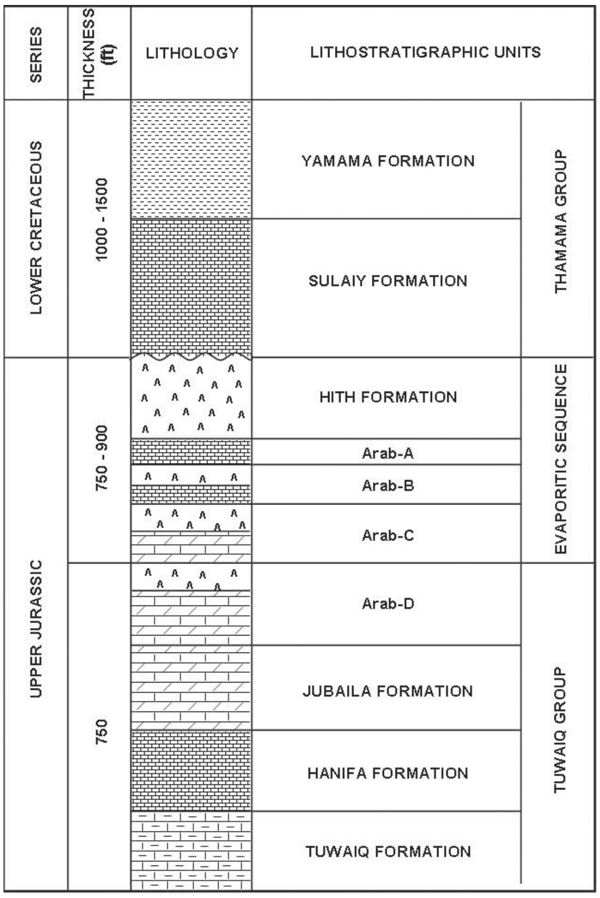


Fig. 1. Stratigraphic column for the Upper Jurassic-Lower Cretaceous succession in Eastern Saudi Arabia.

behavior within the reservoir, and should be determined prior to any engineering calculations. If significant variations do not exist within a particular zone, it is logical to use a single anisotropy ratio to represent this zone.

Because of the dependence of permeability anisotropy on lithology, it is also important to investigate variations in anisotropy ratio within each lithofacies in the reservoir. This will help to identify any facies which is prone to major variations in this ratio. General information related to these topics may already be available in geological reports in a descriptive format. However, results based on numerical data will greatly enhance our understanding and, at the same time, facilitate the transfer of information to reservoir engineers.

This study outlines patterns of distribution of the permeability anisotropy within the Upper Jurassic Arab-D carbonate reservoir in an active oilfield located in the Eastern Province of Saudi Arabia. Brief reviews of reservoir geology and of data sets available for the study are given in the following two sections. Then we present and discuss the distributions of horizontal and vertical permeability as well as permeability anisotropy. The final part of the paper is devoted to an analysis of anisotropy ratio - porosity relationships, and to specific conclusions which can be drawn from the study.

RESERVOIR GEOLOGY

The stratigraphic section through the Upper Jurassic-Lower Cretaceous succession in Eastern Saudi Arabia is illustrated in Fig. 1. The Upper Jurassic in the area consists mainly of shallow-marine carbonates and intervening evaporite units. Four carbonate cycles each having an evaporite seal have been distinguished in the final stages of the Upper Jurassic. The Arab-D reservoir, which is the subject of this study, represents the oldest of these cycles. It comprises an approximately 300 ft (91.5m) thick carbonate succession exhibiting an overall decrease in porosity and an increase in dolomite content with depth. Grainstones dominate the upper intervals, whereas wackestones and fine-crystalline dolomitic rocks dominate the lower units. Lithological and palaeontological evidence suggests that the reservoir rocks represents a shallowing-upward depositional sequence (Hughes, 1996).

Based on porosity-log characteristics, it is possible to distinguish six zones in the reservoir, referred to as Zones 1 to 6 (from top to bottom) in our study. Zones 2 and 3 are the most prolific hydrocarbon producing zones. The data used in this study originated from Zones 2 to 4, which are briefly described in the following paragraphs.

Zone 2 is a 54 ft (16.4 m) thick interval consisting mainly of grainstones which overlies Zone 3 with a sharp contact. Grains are mainly bioclasts, peloids and ooids. The most common bioclasts are miliolid and textulariid foraminifera and echinoid fragments. The average grain size is 0.5 mm, but some grains reach up to 1 cm in diameter. The average core-derived porosity for this zone is approximately 26%.

Zone 3 is an 82 ft (25 m) thick heterogeneous carbonate unit consisting of alternating bioclastic-intraclastic grainstones, packstones, wackestones, dolomite and dolomitic lime-mudstones. This is a transitional zone between the mud-rich Zone 4 below and the almost mud-free Zone 2 above. Therefore, mud-bearing rock types such as packstones, wackestones and mudstones are common in Zone 3. Grains are moderately to poorly sorted and range in diameter from 0.15 to 1 mm. Stromatoporoids, 1 to 7 cm across, were observed in the lower portion of the zone. The most common bioclasts are miliolid and textulariid foraminifera, and echinoids. Zone 3 has an average core-derived porosity of about 21%.

Zone 4 is a 53 ft (16.1 m) thick interval consisting mainly of fine-crystalline dolomite and dolomitic mudstones with thin bioclastic packstone/grainstone

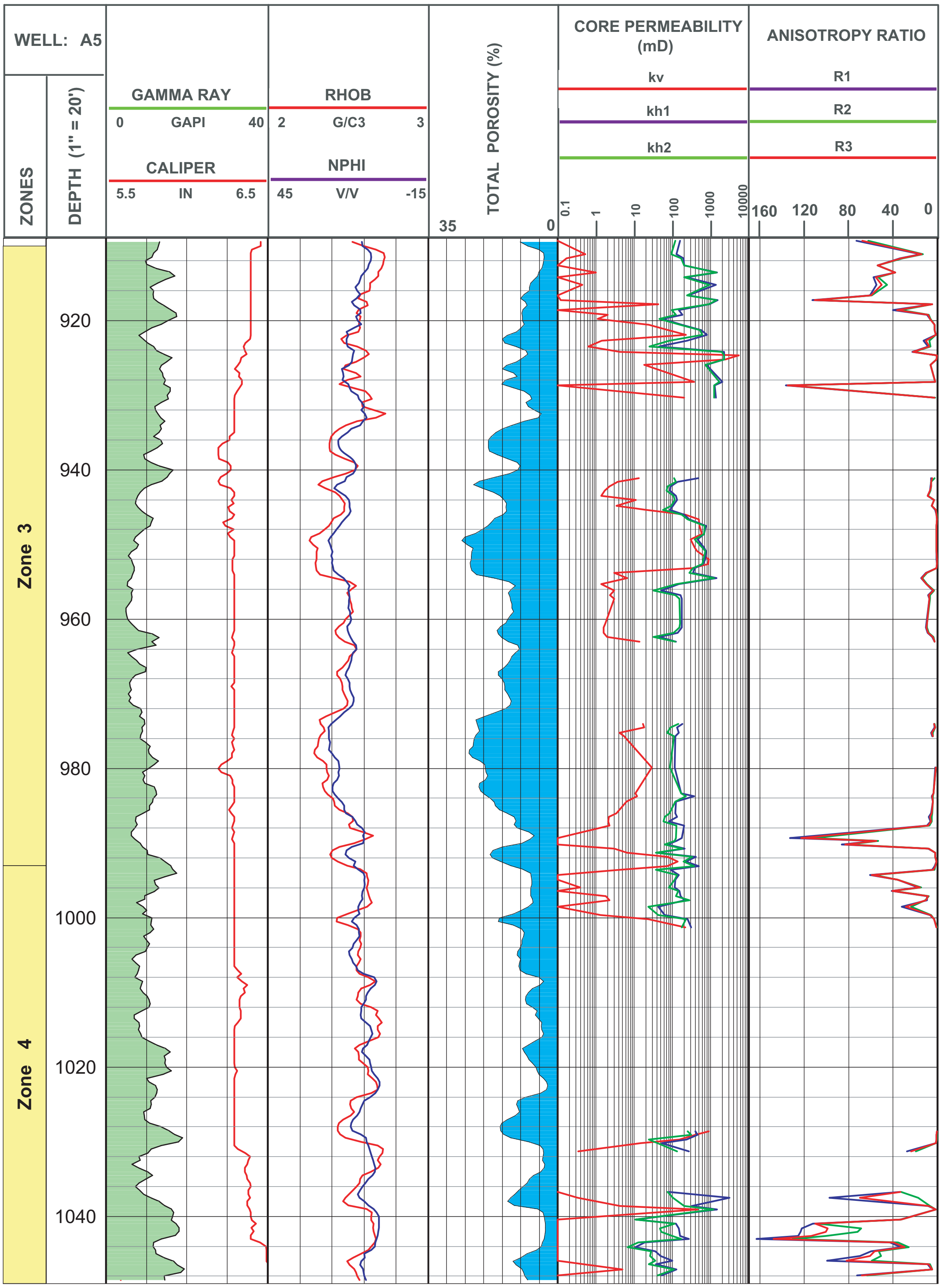


Fig. 2. Plot of open-hole log quantities, core permeability measurements, and anisotropy ratios for Well *A5*. Horizontal and vertical permeability values almost overlap in higher-porosity intervals, and deviate significantly from eachother elsewhere.

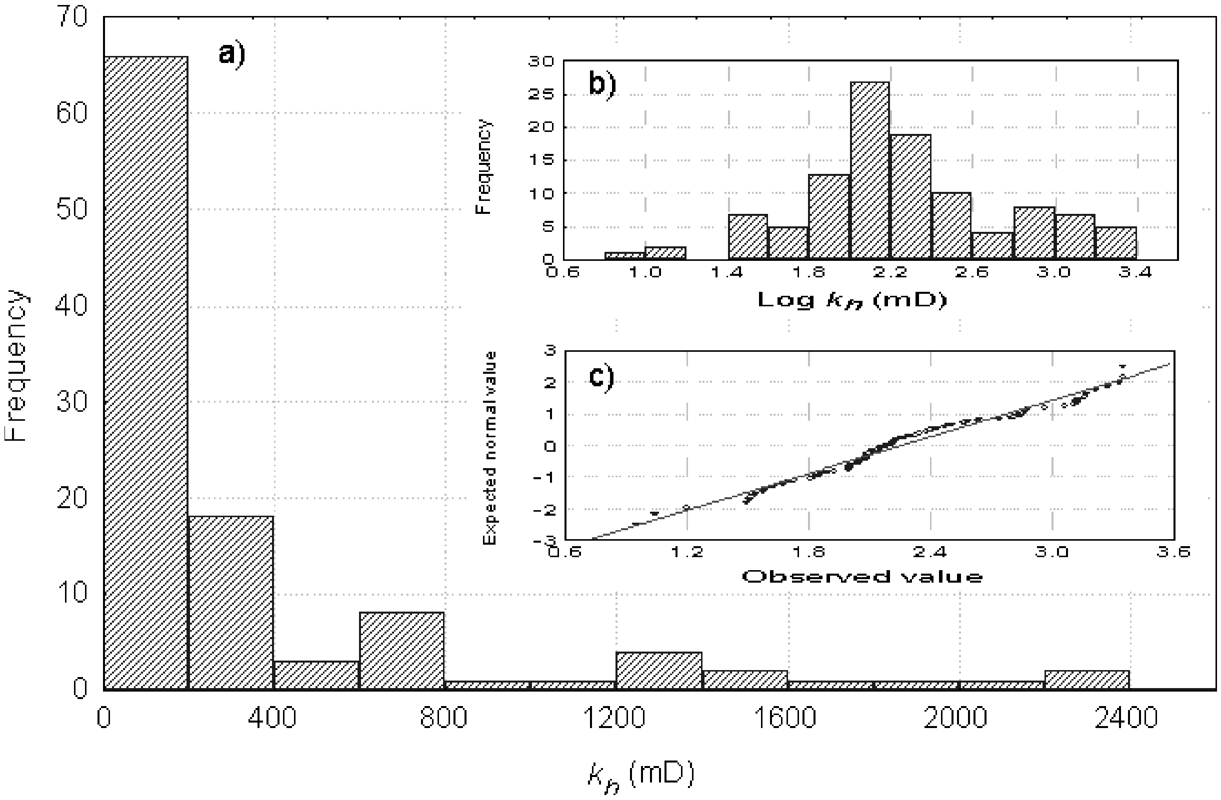


Fig. 3. (a) Histogram of average horizontal permeability measurements (n=108) from Well *A5*. The highly skewed nature of the histogram is apparent.
(b) Histogram of log-transformed average horizontal permeability measurements from the same well, showing a more symmetrical pattern.
(c) Probability plot showing the observed and expected normal values for the histogram in (b). The symmetrical nature of the distribution is indicated by the approximately straight-line fit.

laminations. A 6ft (1.8 m) grainstone horizon marks the basal contact with Zone 5. The allochems in the granular horizons are mainly peloids, intraclasts and bioclasts. Bioclasts include brachiopods, echinoderms, benthonic foraminifera, stromatoporoids and sponges. Dolomitization is widespread in fine-grained rocks, and dolomites appear to have originated from the diagenesis (Powers, 1962; Cantrell *et al.*, 2001). This zone has the lowest porosity with an average value of 8.7%.

DATA SETS

The data used for this study include whole-core and open-hole log data from six vertical wells intersecting the reservoir. Code letters have been used to represent the wells, and the actual depth values are not reported in this paper. However, the relative positions of data points have been preserved by subtracting a constant from each depth value. Considering the number of measurements, results from only two wells (Well *A5* and Well *A3*) are presented to show the general approach adopted in our study. The data for Well *A5* are based on cores from reservoir zones 3 and 4, whereas the data for Well *A3* is from Zone 3 only. Both of these wells were represented by a significant number of whole core measurements: a total of 108 core measurements were available from Well *A5*, and 81 measurements from Well *A3*.

The whole-core permeability measurements provided an ideal data set for this study because they included one vertical and two horizontal measurements at each sampling point. The horizontal measurements were recorded in two perpendicular directions. Using these permeability measurements, it was possible to determine three anisotropy ratios as outlined later.

Complete open-hole log data for each well were also available. These data consisted of a number of well-log derived variables, including, gamma-ray, neutron porosity, total porosity, density, resistivity, water saturation and caliper measurements. Most of these variables and the whole-core permeability measurements were plotted together with calculated anisotropy ratio values to aid interpretation (Fig. 2).

PERMEABILITY DISTRIBUTIONS

To determine the pattern of permeability distribution, statistical analyses of two horizontal permeability measurements (k_{h1} and k_{h2}), the average horizontal permeability (k_h), and the vertical permeability (k_v) were conducted. Analyses included the construction

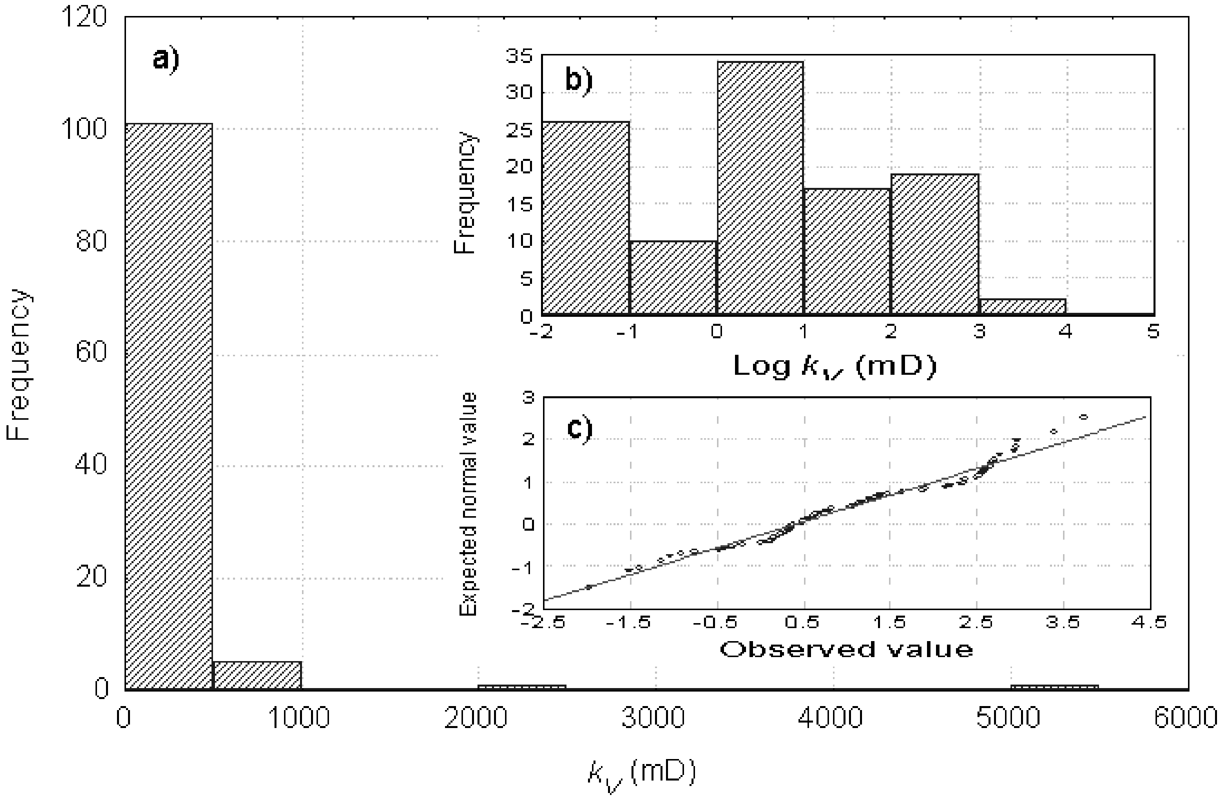


Fig. 4. (a) Histogram of vertical permeability measurements (n=108) from Well *A5*. The pattern is similar to the corresponding histogram of horizontal permeability in Fig. 3a.
(b) Histogram of log-transformed vertical permeability measurements from the same well, showing a bimodal distribution.
(c) Probability plot showing the observed and expected normal values for the histogram in (b). The symmetrical nature of the distribution is indicated by the approximately straight-line fit.

Table 1. Statistical parameters of the whole-core permeability measurements (Well *A5*).

Parameters	k_v	k_{h1}	k_{h2}	k_h
Samples	108	108	108	108
Arithmetic mean	152.57	405.38	318.95	362.17
Geometric mean	2.69	207.22	150.42	182.41
Harmonic mean	0.07	111.83	76.96	96.95
Standard deviation	586.88	569.98	467.75	499.72
Coefficient of variation	3.85	1.41	1.47	1.38
Skewness	7.36	2.58	2.5	2.3
Kurtosis	61.71	6.96	6.1	4.81

of histograms, determination of statistical parameters, and the study of correlations between permeability measurements.

Histograms of the average horizontal permeability and the vertical permeability for Well *A5* are illustrated in Figs. 3 and 4, respectively. Both of these histograms display positively skewed patterns with only a few outlier values. Most permeability values are below 500 mD. The histograms of the log-transformed permeability values and the corresponding probability plots showing the observed values versus expected normal values are also included in Figs. 3 and 4. These diagrams indicate the lognormal nature of the permeability distributions.

Statistical parameters representing each set of measurements are listed in Table 1, and include values for the arithmetic, geometric and harmonic mean, the standard deviation, the coefficient of variation together with skewness, and kurtosis. The results indicate that the means of vertical permeability are much smaller than the corresponding means of horizontal permeability measurements. Similar observations have been reported from the Arab-D reservoir in the *Abqaiq* oilfield (Sahin and Saner, 2001).

The coefficient of variation is defined as the ratio of the standard deviation to the mean. This parameter has commonly been used to define various classes of heterogeneity (Corbett and Jensen, 1992; Jensen *et*

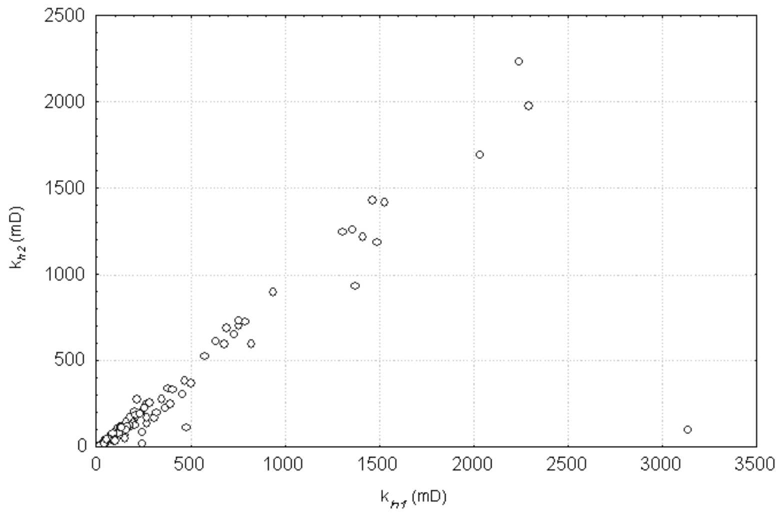


Fig. 5. Correlation plot for horizontal permeability (k_{h1} and k_{h2}) measurements. The relatively high positive correlation coefficient (0.84) indicates the isotropic distribution of permeability in the horizontal plane.

al., 1997). If the coefficient of variation is greater than 1.0, permeability distributions are considered to be very heterogeneous and this is the case for our distributions. The coefficient of variation also provides a basis for comparisons of the variability of the different distributions. As shown in Table 1, this coefficient for vertical permeability is much greater than corresponding values for horizontal permeabilities, reflecting greater heterogeneity in the vertical permeability distribution. It should also be noted that the variability of two horizontal permeability measurements are very similar with values of coefficient of variation ranging between 1.41 and 1.47 (see Table 1).

Skewness is a measure of the deviation of a distribution from symmetry. The skewness of a normal distribution is zero, so that a positive value for this parameter indicates a distribution with a positive skew, and vice versa. As shown in Table 1, skewness values for our case are greater than zero, indicating the positively skewed nature of the distributions. Kurtosis is used to measure the flatness or peakedness of a distribution, relative to a normal distribution. A common measure of kurtosis is defined as the fourth moment about the mean expressed in dimensionless form (Spiegel, 1972). Although this measure is equal to three for a normal distribution, it is commonly taken as zero, so that a distribution more peaked than the normal results in a positive value (leptokurtic), and more flat than the normal results in a negative one (platykurtic). Most of our permeability distributions were characterized by positive kurtosis and hence were leptokurtic. This indicates that there are more than expected permeability values around the mean permeability value.

PERMEABILITY CORRELATIONS

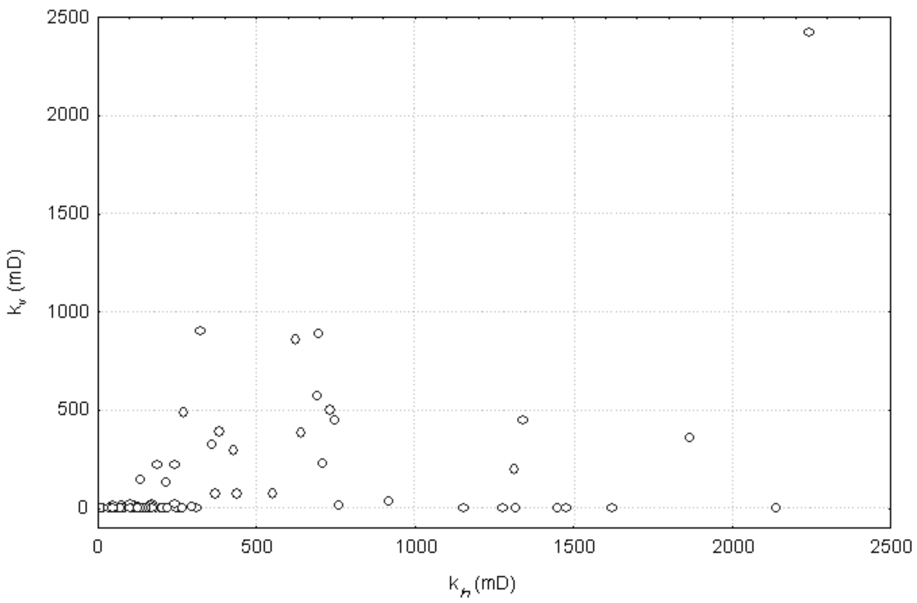
To determine the pattern of correlation between various permeability measurements, Pearson's linear correlation coefficients between pairs of measurements were determined. For Well *A5*, the correlation diagram for the pair k_{h1}-k_{h2} is illustrated in Fig. 5, and the correlation diagram for the pair k_v-k_h in Fig. 6. Similar correlation patterns were recorded for Well *A3*. The overall distribution of points and a very high positive correlation between the two horizontal measurements in Fig. 5 indicate the close similarities of corresponding horizontal permeability values, and hence the isotropic distribution of permeability in the horizontal plane. The correlation coefficient between the two horizontal permeability measurements is equal to 0.84. On the other hand, the correlation between the vertical and horizontal measurements is generally poor, as illustrated in Fig. 6. Scrutiny of points in Fig. 6 indicates that there are two clusters of points. One cluster represents points having very small k_v values with a full range of k_h values. This cluster represents the muddy facies. The second cluster is characterized by equally variable k_v and k_h values and represents granular facies. These two facies are also distinguished from the anisotropy ratio-porosity relationship presented later.

The poor correlation between the k_v-k_h pair is possibly a reflection of the fact that geological factors controlling the horizontal and vertical permeability values are generally independent in nature. It is well-known that bedding planes and laminations are dominant controls enhancing horizontal permeability, but that these same features act as barriers to flow in a vertical direction (Lake, 1988). However, this general pattern may be disturbed by the presence of vertical and/or inclined fractures or bioturbation, which may enhance flow in the vertical direction.

PERMEABILITY ANISOTROPY

Permeability anisotropy can be incorporated into engineering calculations as the square root of the ratio of the horizontal to the vertical permeability. This

Fig. 6. Correlation plot for the average horizontal permeability (k_h) and the vertical permeability (k_v) measurements. The correlation in this case is poor with the correlation coefficient being only 0.48.



parameter is referred to as the anisotropy ratio. Based on the whole-core permeability measurements described earlier, it was possible to determine the following anisotropy ratios:

$$R_1 = \sqrt{k_{h1}/k_v} \quad \text{...} \quad (1)$$

$$R_2 = \sqrt{k_{h2}/k_v} \quad \text{...} \quad (2) \quad \text{and}$$

$$R_3 = \sqrt{k_h/k_v} \quad \text{where } k_h = (k_{h1}+k_{h2})/2 \quad \text{.......} \quad (3)$$

Because of the similarity of the horizontal permeability values at each measurement point as reflected by the correlation patterns, plots against depth of the above-mentioned three ratios (R_1, R_2, and R_3) showed almost identical patterns as illustrated in Fig. 2. These plots are characterized by three thin (each approximately 20 ft thick) intervals with relatively high anisotropy ratios between which are quite uniform distributions of very low values. High ratio intervals are located at approximately 920 ft, 990 ft and 1,040 ft. Overall fluctuations in ratios are considerable with a maximum value reaching approximately 160 and minimum at 0.

A comparison of the corresponding open-hole log plots with the anisotropy ratios in Fig. 2 indicates that high anisotropy ratios are generally correlated with lithological changes. At 920 ft, the high ratios are probably due to the presence of thin beds of dolomite and limestone as identified on the neutron and density logs. At 990 ft, they are related to alternating low and high porosity stringers. Finally, at 1,040 ft, a very low porosity interval with oblique hairline fractures and/or a very thinly bedded interval with a variable lithology may have given rise to the fluctuations. The latter generally provides parallel neutron and density logs due to the averaging effect, yet the vertical and horizontal permeability measurements differ considerably resulting in higher anisotropy ratios.

From the anisotropy ratio equations, it is obvious that higher ratio values could either be due to very high horizontal permeability relative to vertical or to very low vertical permeability relative to horizontal. A comparison of individual higher anisotropy ratio values with corresponding permeability measurements showed that the majority of these ratios were due to unusually low vertical permeability values.

The histogram for the anisotropy ratio (R_3), illustrated in Fig. 7, shows a strong positive skew with highly fluctuating behaviour. A significant proportion of the data are clustered at the lower end of the distributions with values below 10, and a much smaller proportion of data with frequent gaps are displayed in the tails of the distribution. The log-normal nature of this distribution is clear from both the probability plot and the histogram of the log-transformed values displayed in the same figure.

Statistical parameters for the three anisotropy ratios are listed in Table 2. As in the case of the permeability distributions, these parameters include three types of mean, standard deviation, coefficient of variation, skewness, and kurtosis. Skewness and kurtosis values are positive in all cases, indicating that the distributions are positively skewed and leptokurtic. Due to close similarities in the values of three ratios, the corresponding statistical parameters are very similar. A comparison of the values of three types of means for each ratio indicates that the arithmetic mean is the largest and the harmonic mean the smallest, consistent with the theoretical expectations (Spiegel, 1972).

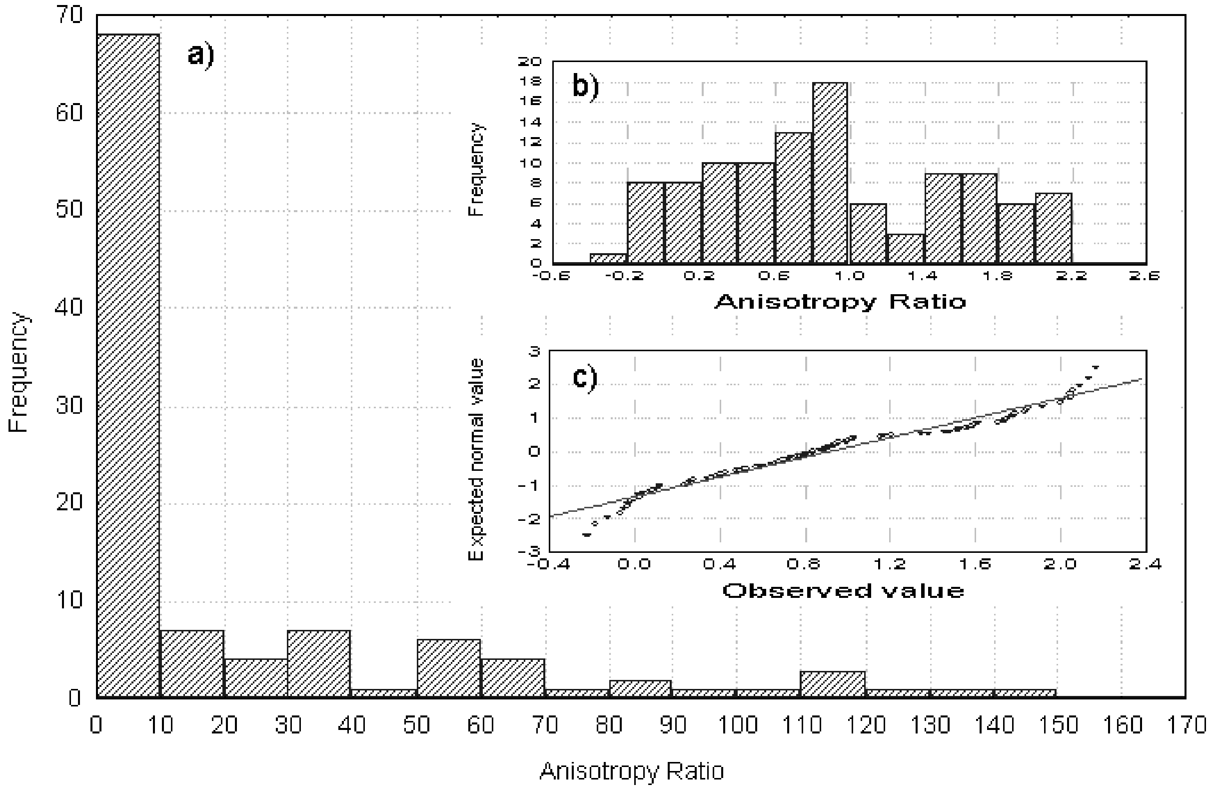


Fig. 7. (a) Frequency histogram of the anisotropy ratio (R_3) for Well *A5*. The pattern of the distribution is similar to those observed for permeability measurements (see Figs 3 and 4).
(b) Frequency histogram of log-transformed anisotropy ratios from the same well, showing the bi-modal character of the data.
(c) Probability plot showing the observed and expected normal values for the histogram illustrated in (b). The bi-modal character of the distribution is reflected by the alignment of points along lines with different slopes.

Parameters	R_1	R_2	R_3
Samples	108	108	108
Arithmetic mean	25.37	20.87	23.38
Geometric mean	8.77	7.47	8.23
Harmonic mean	3.54	3.03	3.35
Standard deviation	37.26	30.46	33.92
Coefficient of variation	1.47	1.46	1.45
Skewness	1.9	2	1.89
Kurtosis	2.81	3.59	2.9

Table 2. Statistical parameters of anisotropy ratios (Well *A5*).

ANISOTROPY RATIO - POROSITY RELATIONSHIP

The general pattern of permeability anisotropy in the reservoir indicates that there is a possible relationship between the anisotropy ratios and lithology, with muddy facies generally possessing higher anisotropy ratios. But it was not possible to quantify such a relationship because of the lack of complete lithological information. However, we had sufficient porosity data to look at the relationship from another perspective. The statistical parameters of the porosity data for Well *A5* are listed in Table 3, and the same data are summarized in the form of a histogram in Fig. 8. This histogram illustrates the bimodal nature of the porosity distribution and indicates the co-existence of two populations, one representing muddy facies and the other granular facies. The cut-off porosity value separating these two populations appears to be located at approximately 11%.

A plot of the anisotropy ratio (R_3) against porosity for Well *A5* is illustrated in Fig. 9. This plot displays an obvious negative correlation between the anisotropy ratio and porosity, with a correlation coefficient of approximately –0.65. However, this relationship is not a simple one and the scatter diagram reveals two main clusters of points. One is characterized by higher porosities and considerably

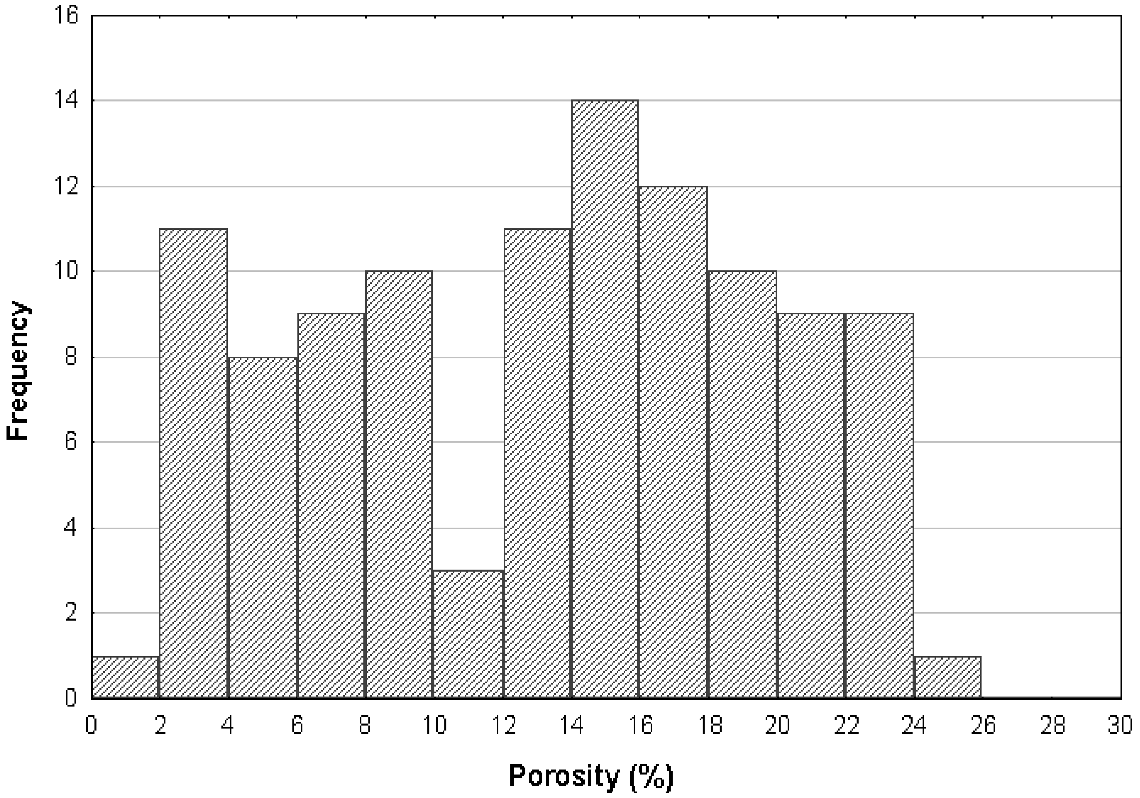


Fig. 8. Frequency histogram of porosity measurements for Well *A5*, displaying two populations separated by approximately 11% porosity.

Parameters	Porosity (%)
Samples	108
Arithmetic mean	13.25
Geometric mean	11.13
Harmonic mean	8.51
Standard deviation	6.46
Coefficient of variation	0.49
Skewness	-0.17
Kurtosis	-1.11

Table 3. Statistical parameters of core porosity measurements (Well *A5*).

lower ratios without any significant fluctuations. The second cluster of points is characterized by lower porosities and higher anisotropy ratios with considerable variation. This relationship is also obvious from the open-hole log plots illustrated in Fig. 2. A dominant pattern observed in these plots is that the horizontal and vertical permeability values are closer to each other in higher-porosity intervals, and deviate significantly in lower-porosity intervals. Therefore, higher porosity areas are expected to yield lower anisotropy ratios, and lower porosity areas higher ones, as shown in Fig. 9. It should be noted that the porosity cut-off value separating the two clusters in Fig. 9 is about 11%. This value matches closely with the porosity cut-off separating the two populations in Fig. 8.

To assess whether the anisotropy ratio versus porosity relationship observed in Well *A5* is laterally persistent, we constructed the same plot for Well *A3*. The plot for this well, illustrated in Fig. 10, indicates that its pattern is very similar to that for Well *A5*. The only difference appears to be in the size of the anisotropy ratio fluctuations representing lower-porosity facies. The fluctuations for these facies are relatively small in the case of Well *A3*. This is due to the fact that Well *A3* intersects Zone 3 which consists mainly of grain-dominated facies with only a small proportion of mud-rich intervals. On the other hand, Well *A5* intersects both Zone 3 and Zone 4. The latter zone includes considerable proportion of mud-rich facies. Consequently, a reasonable number of measurements from both granular and muddy facies is represented in Well *A5* data, resulting in a wider spectrum of anisotropy ratios values.

DISCUSSION

Based on the results from both wells, it can be concluded that for the reservoir under consideration, there is a close relationship between the anisotropy ratio and porosity. Thus, for a good quality reservoir with relatively high porosities, anisotropy ratios can be expected to be relatively low without significant

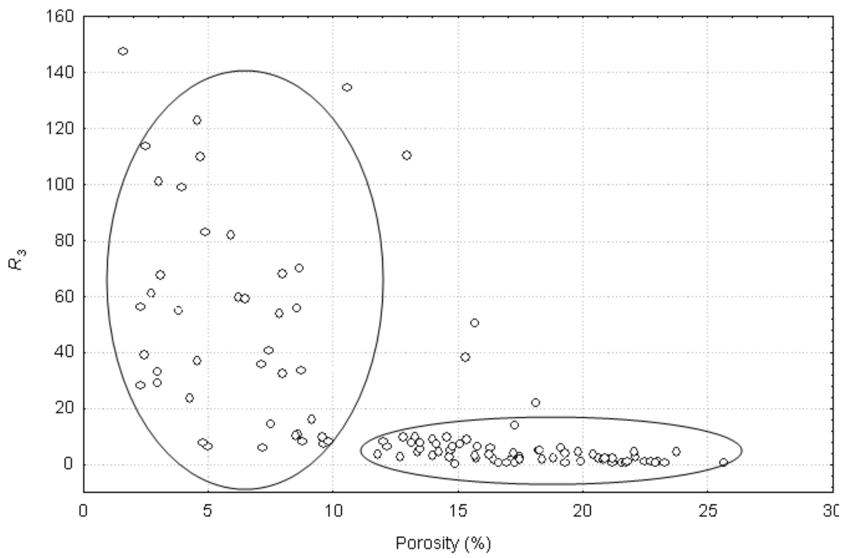


Fig. 9. Plot of anisotropy ratio (R_3) versus porosity for Well *A5*, displaying two distinct clusters of points: one is characterized by higher porosities and considerably lower ratios without any significant fluctuations. The second is characterized by lower porosities and higher anisotropy ratios with considerable fluctuations.

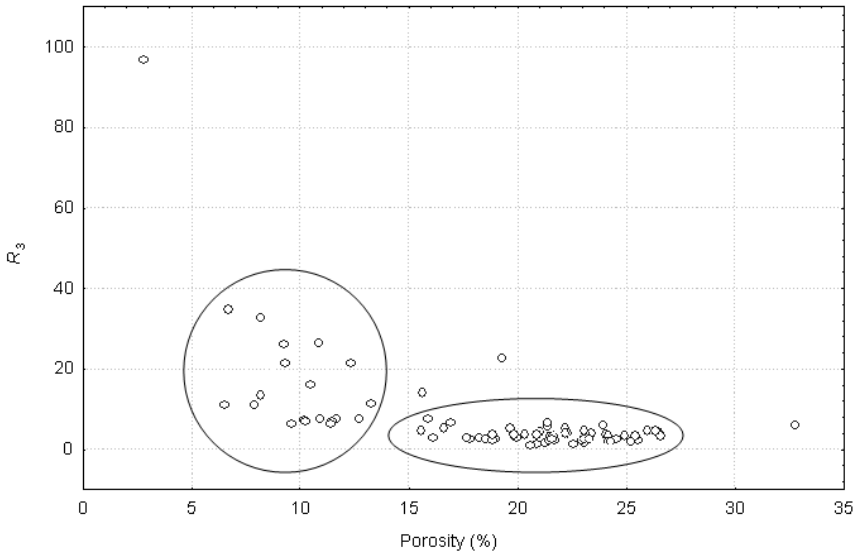


Fig. 10. Plot of anisotropy ratio (R_3) versus porosity for Well *A3*, displaying a similar pattern to the corresponding plot for Well *A5* (Fig. 9).

fluctuations. On the other hand, poor quality reservoir rocks are associated with highly fluctuating ratios. In other words, the distribution of permeability anisotropy in the reservoir is dependent on the facies distribution. Granular facies with higher porosities are more homogeneous reservoir rocks, and hence yield considerably lower and more uniform ratio values. Muddy and mixed granular-muddy facies represent greater heterogeneity in terms of permeability distributions. Therefore, the anisotropy ratios in these facies will show considerable fluctuations.

Considering the rock-fabric, Lucia *et al.* (2001) proposed a more complex model for the Arab-D facies and recognized three classes each having a wide spectrum of porosity and permeability values. Considering their model, it is apparent that to produce the plot illustrated in Fig. 9, we must have different k_h and k_v relationships above and below the 11% porosity cut-off. For any facies with porosity greater than 11%, k_h and k_v values are very similar, resulting in anisotropy ratios close to one. On the other hand, below 11% porosity, k_h and k_v values are highly variable giving rise to greater fluctuations in anisotropy ratios: the grain-dominated facies show probably very similar values of k_h and k_v and hence anisotropy values closer to one, in contrast to mud-dominated facies with greater anisotropy ratio values. Investigation of the correlation patterns of k_h and k_v measurements below and above the 11% porosity cut-off revealed that there is almost no correlation between these measurements below the cut-off. However, a significant correlation was observed between the same measurements above the cut-off.

As pointed out above, results provided in this study are based on the whole core measurements. To determine zonal anisotropy parameters, up-scaling of anisotropy ratios would be required. Depending on the direction of flow with respect to the stratification, different mean values have been used to represent the permeability of a stratified sequence (Richardson *et al*., 1987; Jensen *et al*., 1987). Thus, if the flow is parallel to the strata, the arithmetic mean is used. If the flow is perpendicular to the strata, the harmonic mean is considered to be more appropriate. However, in other cases, where the flow is neither strictly parallel nor perpendicular, or where different facies are not clearly stratified, the geometric mean is used (Isaaks and Srivastava, 1989).

Assuming a relatively uniform stratified sequence with horizontal flow in our case, the horizontal permeability values can be averaged using the arithmetic mean and the vertical permeability using the harmonic mean as discussed above. Combining the permeability measurements based on samples within a uniform zone in this manner, it is possible to derive the horizontal and the vertical permeability values, and hence to determine the anisotropy ratio for the entire zone.

CONCLUSIONS

The main conclusions drawn from this study of a carbonate reservoir in Eastern Saudi Arabia are summarized as follows:

1. Statistical distributions representing permeability and anisotropy ratios display similar patterns with a dominant positive skew. Mean values for the vertical permeability are considerably lower than the corresponding parameters for the horizontal permeability distributions.
2. Values of the coefficient of variation for the horizontal permeability and anisotropy ratio are similar with values close to 1.5, indicating the very heterogeneous nature of these distributions. This coefficient for vertical permeability is greater than the corresponding values for the horizontal permeability, reflecting greater heterogeneity in the vertical permeability distribution.
3. Higher fluctuations in anisotropy ratios along wells can be correlated with low-porosity muddy and/or mud-rich / granular intervals within the reservoir.
4. Granular facies with higher porosities yield considerably lower anisotropy ratios without any significant fluctuations. In other words, the best reservoir facies are expected to present fewer problems during production.
5. Very high values of the anisotropy ratio are generally due to unusually low vertical permeability measurements recorded in compact and undisturbed mud-rich intervals acting as barriers to vertical flow.

ACKNOWLEDGEMENTS

This study is partly based on a paper *(SPE 81472)* originally presented at the 2003 SPE Middle East Oil & Gas Show and Conference, held in Bahrain. Saudi Aramco provided the basic data, and the study was undertaken at the Research Institute, King Fahd University of Petroleum and Minerals (KFUPM). Financial support was provided by Saudi Aramco, Al-Khafji Joint Operations, and Schlumberger Dhahran Carbonate Research Center . The authors wish to thank the management of the above-mentioned organizations for their support and permission to publish this paper. Review comments on a previous version by Deborah Bliefnick and Wayne Wright are acknowledged with thanks.

Nomenclature

k_{h1} = Horizontal permeability (maximum)
k_{h2} = Horizontal permeability
k_h = Average horizontal permeability
k_v = Vertical permeability
R_1, R_2, R_3 = Anisotropy ratios
NPHI = Neutron porosity
PHIT = Total porosity
RHOB = Bulk density
GR = Gamma ray

REFERENCES

CANTRELL, D. L., SWART, P. K., HANDFORD, R. C., KENDALL, C. G., WESTPHAL, H. 2001.Geology and production significance of dolomite, Arab-D reservoir, Ghawar Field, Saudi Arabia. *GeoArabia*, **6** (1), 45-60.

CORBETT, P. W. M. and JENSEN, J. L., 1992. Estimating mean permeability: how many measurements do we need? *First Break,* **10** (3), 89-94.

FAROUQ, A., ROJAS, S.M., ZHU, T., and DYER, S., 1988. Scaled model studies of carbon dioxide floods. *SPE 18083*, Annual Technical Conference and Exhbibition, October 2-5, Houston, Texas, pp. 273-284.

FORREST, F. C, Jr., 1971. The reservoir engineering aspect of waterflooding. Monograph Volume 3, Henry L. Doherty Series, SPE, New York, 141p.

HENLEY, W., OWENS, W. and CRAIG, F. F., 1961. A scale-model study of bottom water drives. *Journal of Petroleum Technology*, **13** (2), 90-98.

HUGHES, G. W., 1996. A new bioevent stratigraphy of Late Jurassic Arab-D carbonates of Saudi Arabia. *GeoArabia,* **1** (3), 417-434.

ISAAKS, E. H., and SRIVASTAVA, R. M., 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York, 561pp.

JENSEN, J. L., HINKLEY, D.V., and LAKE, L.W., 1987. A statistical study of reservoir permeability: distributions, correlations, and averages. *SPE Formation Evaluation,* **2** (4), 461-468.

JENSEN, J. L., LAKE, L.W., CORBET, P.W. M. and GOGGIN, D. J., 1997. Statistics for Petroleum Engineers and Geoscientists. Prentice Hall, Upper Saddle River, New Jersey, 390pp.

JOSHI, S.D., and DING, W., 1996. Horizontal well application, reservoir management. Second International Conference and Exhibition on Horizontal Well Technology, 18-20 November 1996, Calgary.

LAKE, H. D., 1988. The origins of anisotropy. *Journal of Petroleum Technology,* 395-396, April 1988.

LUCIA, F. J., JENNINGS, Jr., J. W., RAHNIS, M., and MEYER, F. O. 2001. Permeability and rock fabric from wireline logs, Arab-D reservoir, Ghawar field, Saudi Arabia. *GeoArabia*, **6** (4), 619-646

MENOUAR, H. K., and HAKIM, A.A., 1995. Water coning and critical rates in vertical and horizontal wells. *SPE 29877*, SPE Middle East Oil Show and Conference, 11-14 March 1995, Bahrain.

MUSKAT, M., 1937. The flow of homogeneous fluids through porous media, International Human Resources Development Corporation, McGraw-Hill, New York.

POWERS, R.W., 1962. Arabian Upper Jurassic carbonate reservoir rocks. In: W. E. Ham, (Ed), Classification of carbonate rocks. *AAPG Memoir* **1**, 122-192.

RICHARDSON, J. G., SANGREE, J. B., and SNEIDER, R. M., 1987. Permeability distributions in reservoirs. *Journal of Petroleum Technology*, **39** (10), 1197-1199.

SAHIN, A., and SANER, S., 2001. Statistical distributions and correlations of petrophysical parameters in the Arab-D reservoir, Abqaiq oilfield, Eastern Saudi Arabia. *Journal of Petroleum Geology*, **24** (1), 101-114.

SPIEGEL, M. R., 1972. Theory and Problems of Statistics, Schaum's Outline Series, McGraw-Hill, New York, 359p.

WILHITE, P. G., 1986. Waterflooding. SPE Textbook Series, 3. SPE, Richardson, Texas, 326pp.