CHAPTER III

DATA PREPARATION AND STOCHASTIC SIMULATION

This chapter discusses a data preparation in applying a proposed geostatistical simulation method. In order to evaluate performance of the proposed method, the actual data set from oil reservoir in Pitsanuloke basin was used. The data set consists of fourteen directional wells. Even though, there are several layers of the hydrocarbon bearing units in this field, only five layers were selected for this study.

3.1 Information of data set

The oil field lies within the Phitsanulok basin of Central Thailand. The basin is a major structure of Oligocene age which overlies a folded, partially metamorphosed and block faulted Mesozoic basement. The basin is situated at the triangular intersection of two regional strike slip fault zones. Figure 3.1 shows seismic cross-section of the oil field. In the study area the reservoir interval is up to 550 m in thickness. From the main field, it is subdivided into eleven major units (D, K1, K2, K3, K4, L1, L2, L3, L4, M, and P) which are separated by laterally extensive shale intervals. The lithologies of the oil field consist of sandstone interbedded with claystone, claystone interbedded with sandstone and rare coal seam, and claystone interbedded with sandstone.

This study concentrates on the hydrocarbon bearing units, K2, K3, K4, L2 and L3. Two major reservoir facies are recognized within these intervals, mouthbars and fluvial channels. These layers have the same lithology as claystone interbedded with sandstone. The data set were collected from fourteen directional wells of which has been as renamed "X01", "X03", "X04", "X05", "X07", "X08", "X09", "X17", "X19", "X20", "X21", "X22", "X23", and "X24" throughout this study. This study area extends from 591,841 m to 594,168 m in x-coordinate (East direction), from 1,840,402 m to 1,843,026 m in y-coordinate (North direction), and from 1,500 m to

2,047 m in z-coordinate (depth), covering the area of 9,000,000 m^2 or 9 km^2 approximately. The schematic for these fourteen wells is depicted in Figure 3.2.

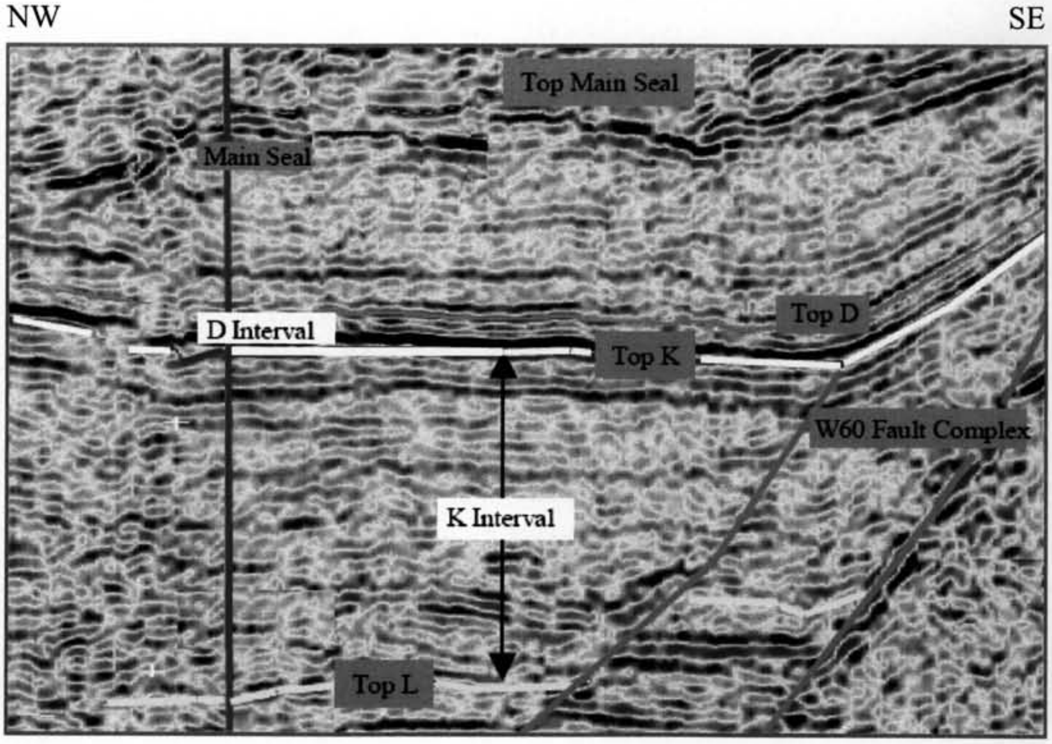


Figure 3.1: Seismic cross-section of the oil field.

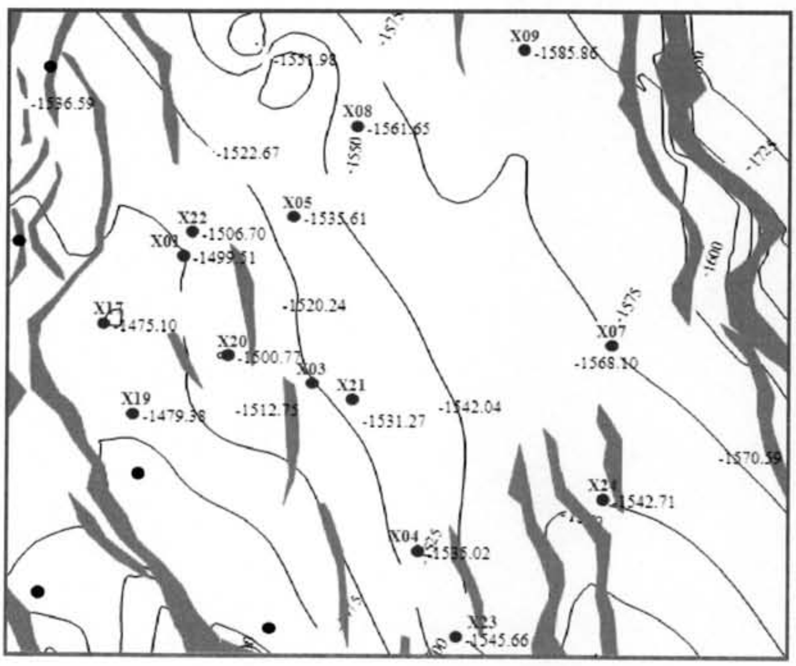


Figure 3.2: Well locations in the oil field.

Figures 3.3 and 3.4 show location maps of porosity data distributed in the oil field in XY, XZ and YZ coordinates and 3-D model respectively.

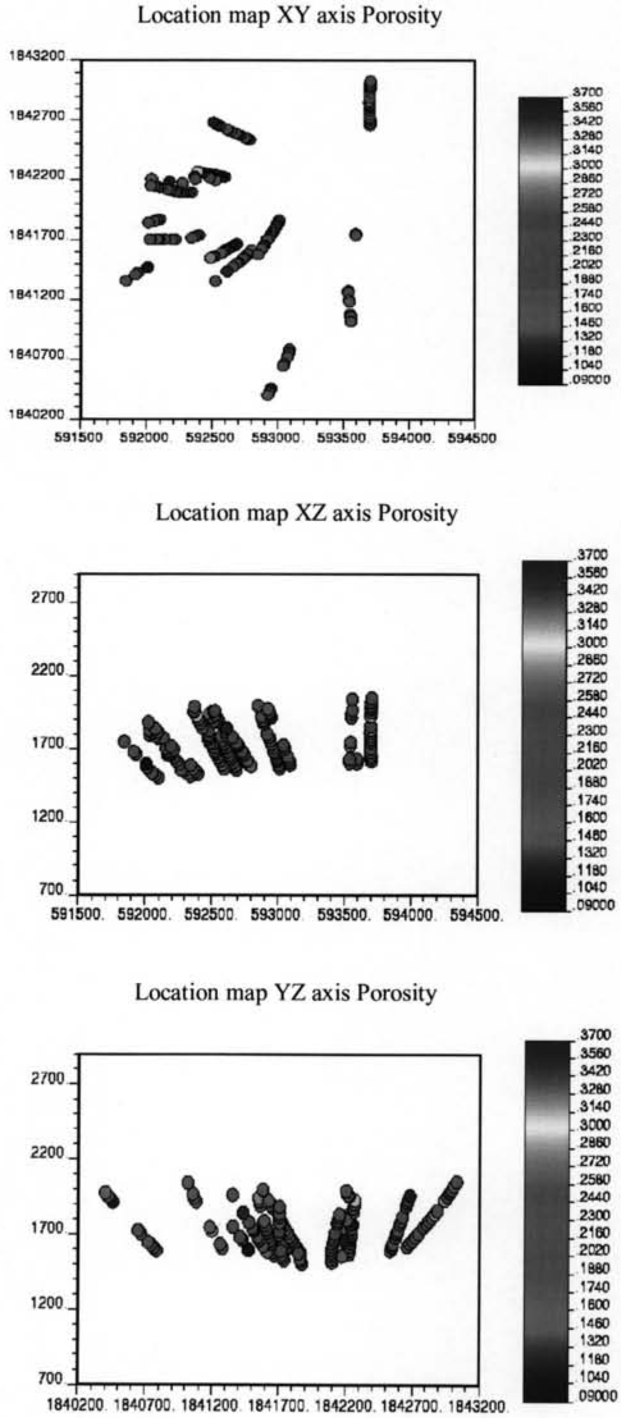


Figure 3.3: Location maps of porosity data of the oil field in XY, XZ and YZ coordinates.

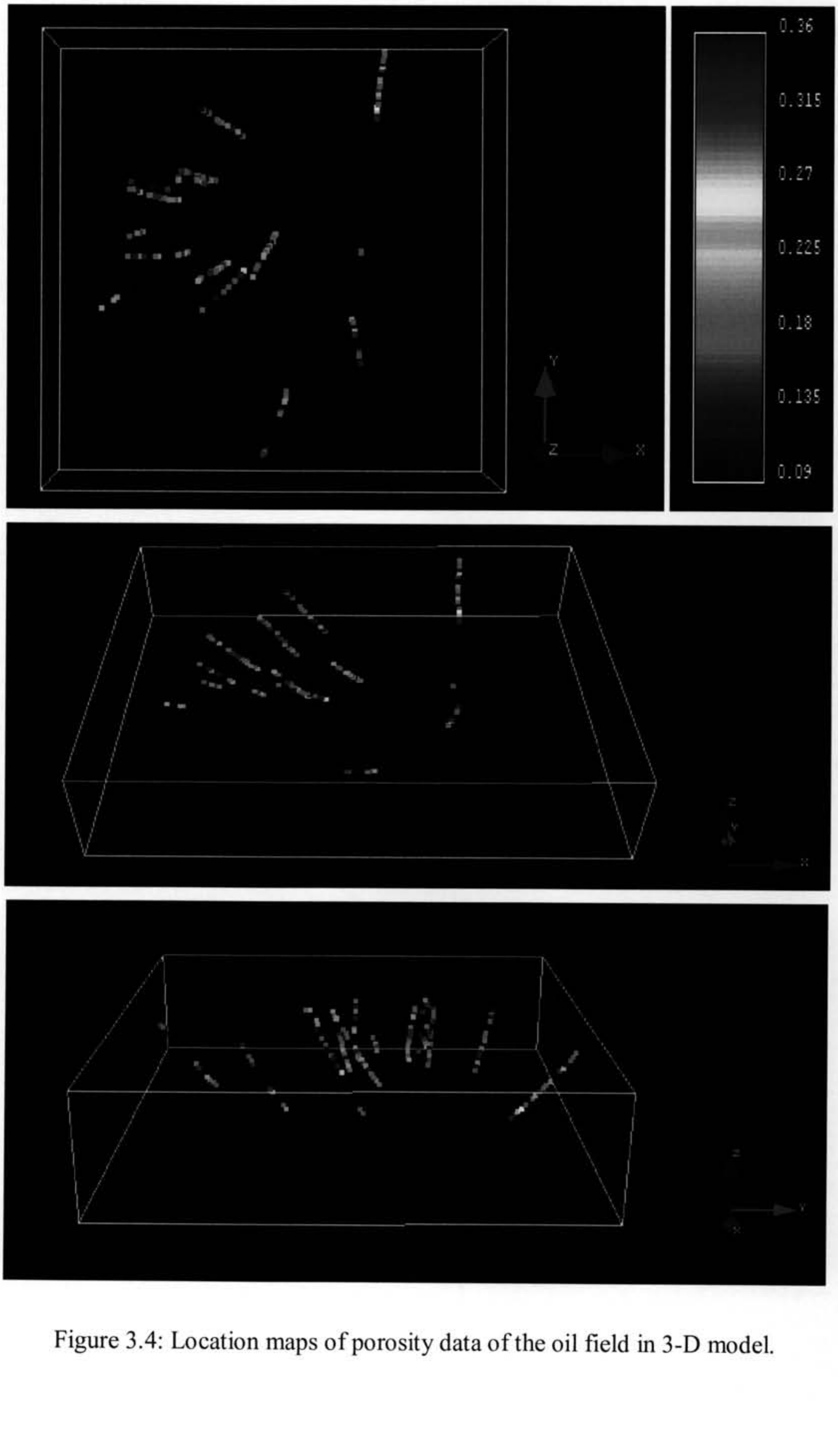


Figure 3.4: Location maps of porosity data of the oil field in 3-D model.

From well log interpretation, there are many petrophysical properties, i.e., porosity, water saturation, resistivity, and etc. that are available. However, this study concentrates on the porosity data for permeability determination. The selected porosity data and their locations are given in Table 3.1.

Table 3.1: Porosity and their locations of the oil field.

Well	X Direction	Y Direction	Depth	Layer	Porosity
X01	592339.18	1842096.88	1509.67	K2	0.22
	592317.46	1842095.95	1530.35	K2	0.17
	592296.03	1842095.28	1551.33	K2	0.21
	592274.79	1842095.33	1572.51	K2	0.21
	592254.11	1842097.26	1594.14	K3	0.20
	592234.15	1842101.08	1616.21	K3	0.19
	592214.32	1842105.55	1638.27	K3	0.15
	592194.46	1842110.06	1660.30	K3	0.15
	592174.91	1842114.70	1682.58	K4	0.15
	592155.52	1842119.48	1704.96	K4	0.20
	592095.07	1842135.19	1769.71	L2	0.22
	592073.89	1842141.00	1790.15	L3	0.14
	592052.23	1842147.05	1810.00	L3	0.20
	592029.91	1842153.41	1829.01	L3	0.17
X03	592685.79	1841665.94	1554.30	K2	0.20
	592672.34	1841656.70	1579.47	K2	0.22
	592658.85	1841647.75	1604.73	K2	0.20
	592645.44	1841638.99	1630.10	K3	0.13
	592632.15	1841630.38	1655.57	K3	0.20
	592618.98	1841621.93	1681.17	K3	0.23
	592605.91	1841613.69	1706.88	K4	0.20
	592592.88	1841605.66	1732.69	K4	0.18
	592579.84	1841597.73	1758.52	K4	0.17
	592566.87	1841590.05	1784.46	K4	0.15
	592513.61	1841560.75	1887.91	L3	0.20
	592499.86	1841553.76	1913.64	L3	0.18
	592485.97	1841546.83	1939.31	L3	0.28
X04	593010.44	1841863.09	1566.94	K2	0.20
	593002.41	1841846.08	1590.08	K2	0.21
	592994.45	1841829.00	1613.27	K2	0.18
	592990.32	1841820.24	1625.25	K2	0.19
	592985.28	1841812.14	1636.49	K3	0.21
	592976.39	1841795.48	1659.81	K3	0.13
	592967.42	1841778.96	1683.19	K3	0.24
	592958.63	1841763.21	1705.90	K3	0.16
	592958.33	1841762.68	1706.69	K3	0.16
	592949.02	1841746.68	1730.30	K4	0.22

Table 3.1: Porosity and their locations of the oil field (continued).

Well	X Direction	Y Direction	Depth	Layer	Porosity
X04	592939.48	1841730.95	1753.99	K4	0.19
	592929.80	1841715.46	1777.79	K4	0.14
	592928.82	1841713.93	1780.18	K4	0.22
	592920.03	1841700.28	1801.75	K4	0.22
	592891.31	1841654.28	1873.93	L2	0.17
	592890.70	1841653.26	1875.44	L2	0.13
	592882.26	1841638.93	1897.96	L2	0.18
	592873.61	1841623.57	1922.24	L3	0.17
	592849.42	1841577.85	1995.88	L3	0.22
	592849.04	1841577.10	1997.72	L3	0.23
X05	592593.18	1842223.45	1563.62	K2	0.17
	592577.14	1842226.51	1588.79	K2	0.16
	592561.19	1842229.66	1614.00	K2	0.21
	592545.56	1842232.79	1639.42	K3	0.18
	592530.11	1842235.98	1664.93	K3	0.11
	592514.89	1842239.10	1690.59	K3	0.19
	592485.08	1842245.14	1742.31	K4	0.16
	592470.29	1842248.15	1768.24	K4	0.18
	592426.39	1842257.11	1846.29	L2	0.15
	592411.94	1842260.04	1872.42	L2	0.19
	592397.59	1842263.01	1898.60	L2	0.18
	592383.45	1842266.02	1924.88	L2	0.31
X07	593593.75	1841750.00	1601.73	K2	0.17
	593594.46	1841737.63	1629.05	K2	0.18
	593597.04	1841713.66	1683.99	K3	0.23
	593598.74	1841701.88	1711.53	K3	0.20
	593600.61	1841690.12	1739.06	K3	0.16
	593602.65	1841678.40	1766.61	K4	0.12
	593604.77	1841666.74	1794.16	K4	0.14
	593606.79	1841655.13	1821.75	K4	0.20
	593614.34	1841609.80	1952.60	L3	0.15
	593616.25	1841598.71	1960.41	L3	0.15
	593618.14	1841587.81	1988.30	L3	0.21
X08	592781.71	1842533.86	1587.43	K2	0.17
	592763.47	1842542.80	1609.49	K2	0.12
	592745.49	1842551.77	1631.77	K2	0.24
	592710.07	1842569.74	1676.74	K3	0.14
	592692.51	1842578.68	1699.36	K3	0.12
	592675.06	1842587.57	1722.09	K3	0.21
	592640.44	1842605.42	1767.73	K4	0.20
	592613.31	1842614.39	1790.66	K4	0.17
	592606.36	1842623.29	1813.73	K4	0.18
	592556.21	1842650.26	1883.46	L2	0.19
	592539.83	1842659.23	1906.93	L2	0.13
	592523.83	1842668.29	1930.64	L3	0.17
	592508.15	1842677.42	1954.53	L3	0.11

Table 3.1: Porosity and their locations of the oil field (continued).

Well	X Direction	Y Direction	Depth	Layer	Porosity
X09	593700.00	1842656.25	1614.64	K2	0.15
	593699.03	1842677.28	1636.01	K2	0.14
	593698.16	1842698.42	1657.28	K2	0.25
	593697.33	1842719.47	1678.64	K2	0.26
	593696.58	1842740.48	1700.04	K3	0.18
	593695.41	1842781.88	1743.46	K3	0.20
	593694.91	1842802.27	1765.46	K3	0.22
	593694.50	1842822.41	1787.69	K3	0.15
	593694.24	1842842.33	1810.13	K4	0.17
	593694.48	1842862.10	1832.69	K4	0.29
	593696.10	1842881.69	1855.41	K4	0.24
	593697.72	1842938.61	1925.09	L2	0.31
	593698.40	1842956.73	1948.99	L2	0.25
	593699.14	1842974.46	1973.18	L3	0.36
	593700.07	1842991.93	1997.55	L3	0.18
	593701.17	1843009.13	2022.11	L3	0.17
	593702.32	1843026.09	2046.83	L3	0.20
X17	592095.94	1841872.10	1499.68	K2	0.21
	592074.61	1841864.39	1517.11	K2	0.16
	592053.25	1841856.86	1534.67	K2	0.21
	592010.78	1841842.91	1570.64	K3	0.19
X19	592006.79	1841471.28	1594.02	K3	0.09
	591931.34	1841421.31	1661.98	K4	0.24
	591912.94	1841408.49	1679.23	K4	0.23
	591840.69	1841356.51	1749.15	L2	0.22
X20	592397.76	1841738.00	1525.37	K2	0.20
	592379.00	1841729.53	1544.78	K2	0.23
	592359.86	1841722.04	1564.22	K2	0.15
	592340.38	1841715.84	1583.57	K3	0.21
	592214.91	1841699.97	1696.40	K4	0.22
	592193.43	1841700.49	1714.81	K4	0.20
	592131.52	1841702.49	1772.82	L2	0.14
	592092.74	1841703.75	1814.14	L3	0.21
	592074.23	1841704.04	1835.55	L3	0.14
	592022.40	1841703.54	1879.76	L3	0.20
X21	592796.69	1841612.15	1579.86	K2	0.27
	592771.95	1841581.28	1620.31	K3	0.14
	592743.75	1841553.02	1660.41	K3	0.13
	592729.34	1841539.32	1680.41	K3	0.18
	592699.71	1841512.37	1720.38	K4	0.11
	592684.30	1841498.90	1740.06	K4	0.18
	592654.25	1841472.20	1779.60	K4	0.18
	592609.37	1841431.72	1839.36	L2	0.12
	592521.56	1841351.01	1960.14	L3	0.20

Table 3.1: Porosity and their locations of the oil field (continued).

Well	X Direction	Y Direction	Depth	Layer	Porosity
X22	592268.96	1842169.39	1552.93	K2	0.16
	592171.30	1842184.84	1654.10	K3	0.11
	592033.30	1842208.44	1794.31	L2	0.15
X23	593088.95	1840779.85	1587.36	K2	0.17
	593084.83	1840759.60	1606.83	K2	0.19
	593080.13	1840739.62	1626.31	K2	0.20
	593074.23	1840719.93	1645.74	K3	0.23
	593048.67	1840663.16	1703.69	K3	0.15
	593039.43	1840644.35	1722.70	K3	0.20
	593012.25	1840588.10	1779.58	K4	0.17
	592949.88	1840457.08	1914.66	L3	0.10
	592931.75	1840420.18	1953.70	L3	0.17
	592922.88	1840401.60	1973.26	L3	0.16
X24	593535.20	1841274.73	1604.42	K2	0.23
	593537.19	1841258.60	1627.82	K2	0.18
	593542.48	1841195.04	1721.56	K3	0.28
	593543.74	1841179.76	1745.23	K3	0.15
	593546.18	1841149.47	1793.09	K4	0.15
	593552.25	1841077.88	1914.96	L2	0.15
	593553.21	1841064.79	1939.69	L2	0.17
	593554.01	1841051.93	1965.11	L3	0.17
	593555.95	1841015.60	2042.03	L3	0.14

Table 3.1 shows the locations and porosity data of each well. However, this study focuses on permeability determination, as a consequence porosity data are classified according to their representative layers rather than well locations.

Table 3.2 shows general information of each layer as the measured depth, thickness, geological formation, porosity and number of data. It is found that the range of porosity values in each layer is not significant difference.

Table 3.2: General information of each layer.

Layer	True Vertical Depth (m)	Thickness (m)	Geological Formation	Porosity	No. of Well	No. of Data
K2	1,500-1,679	179	Sandstone	0.12-0.27	13	36
K3	1,571-1,788	217	Sandstone	0.09-0.28	14	37
K4	1,662-1,855	193	Sandstone	0.11-0.29	12	29
L2	1,749-1,949	200	Sandstone	0.12-0.31	9	18
L3	1,790-2,047	257	Sandstone	0.10-0.36	10	27
Total						147

3.2 Statistical analysis

The statistical analysis of porosity was performed on 147 well log data taken from fourteen wells in the oil field. Table 3.3 shows the statistics of porosity data in the oil field.

Figure 3.5 shows the histogram and cumulative distribution of porosity. The distribution of porosity exhibits a lognormal distribution with a positive skewness providing the mean greater than the median statistic. The lognormal distribution commonly has many quite small values and a few very large values. It can be seen that the histogram and cumulative distribution of porosity show slightly positive skewness of 0.7146. The mean and median of porosity are 0.1856 and 0.18 respectively. The coefficients of variation of porosity is lower than 1 (0.2341) which indicates no presence of some erratic sample values that may have significant impact to the simulation process. The values of porosity are spread out in narrow range from 0.09 to 0.36, thus yielding a low standard deviation of 0.0434 and variance of 0.0019.

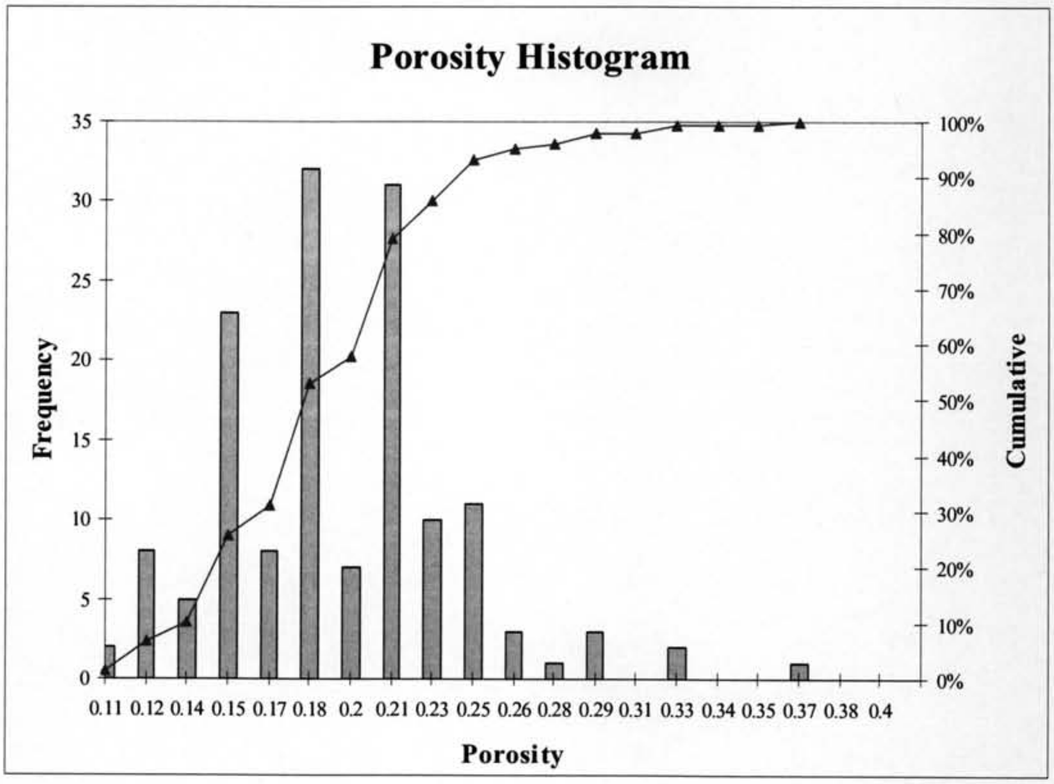


Figure 3.5: Porosity histogram and cumulative plot.

Table 3.3: Statistics of porosity in the oil field.

Statistical Data	Porosity (Ø)
Mean	0.1856
Variance	0.0019
Standard Deviation	0.0434
Median (P50)	0.1800
Minimum	0.0900
Maximum	0.3600
Skewness	0.7146
Kurtosis	1.5521
Coeff. of variation	0.2341

Not only that the overall statistics of porosity in the oil field were calculated, but the statistics of porosity in each layer; K2, K3, K4, L2 and L3 were also calculated as summarized in Table 3.4.

Table 3.4: Statistical summary of porosity in the oil field.

Statistical Data	Porosity (Ø)					
	All Data	Layer K2	Layer K3	Layer K4	Layer L2	Layer L3
Mean	0.1856	0.1942	0.1757	0.1879	0.1867	0.1844
Variance	0.0019	0.0011	0.0018	0.0015	0.0030	0.0025
Standard Deviation	0.0434	0.0334	0.0419	0.0384	0.0550	0.0504
Median (P50)	0.1800	0.2000	0.1800	0.1800	0.1750	0.1700
Minimum	0.0900	0.1200	0.0900	0.1100	0.1200	0.1000
Maximum	0.3600	0.2700	0.2800	0.2900	0.3100	0.3600
Skewness	0.7146	0.1588	0.1270	0.2599	1.1555	1.5554
Kurtosis	1.5221	-0.1260	-0.3298	0.5464	0.7425	4.5196
Coeff. of variation	0.2341	0.1723	0.2384	0.2041	0.2945	0.2734
Number of data	147	36	37	29	18	27

Table 3.4 shows the statistical summary of porosity data in the oil field according to their representative layers. It can be seen that the mean, median and coefficient of variation of porosity in each layer are not significant different when comparing with the overall statistics. The statistics of mean, median and coefficient of variation from all layers vary from 0.1757 to 0.1942, 0.1700 to 0.2000 and 0.1723 to 0.2945, respectively. The values of porosity are spread out in a narrow range that gives a low range of standard deviation from 0.0334 to 0.0550 and a low range of variance from 0.0011 and 0.0030. Generally, the standard deviation and variance of each layer should be lower than that of overall data because of the similar lithology. But the standard deviation and variance in layer of L2 and L3 are higher than the overall data, this is probably due to the limited number of data.

3.3 Structural analysis (Variogram model)

The structural analysis or variogram model can be used to quantify the spatial variability of spatial phenomena, in this case, porosity. The variogram is a measure of variance in terms of distance and direction. Figure 3.6 performs omni-directional variograms of porosity data from all layers in the oil field with number of lag of 100 in lag separation and lag tolerance of 20 m and 10 m, respectively.

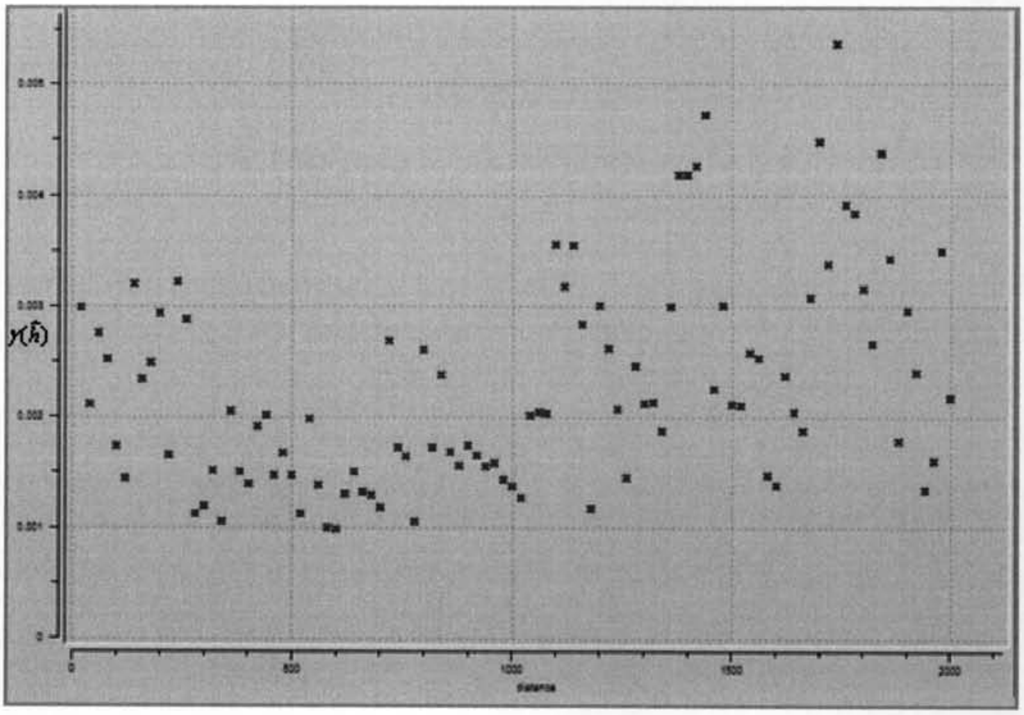
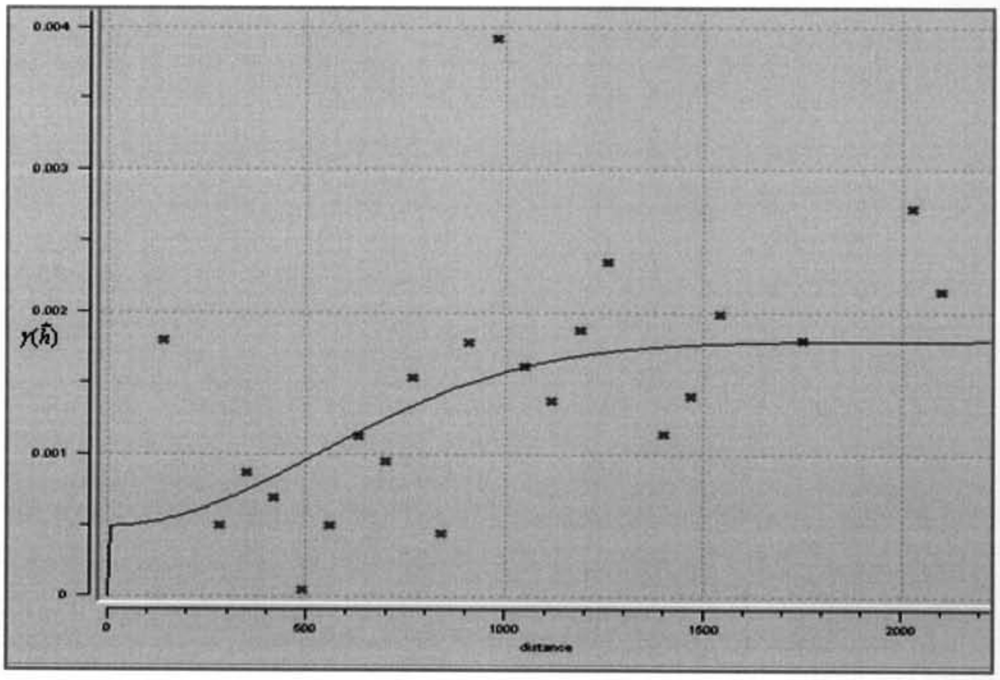
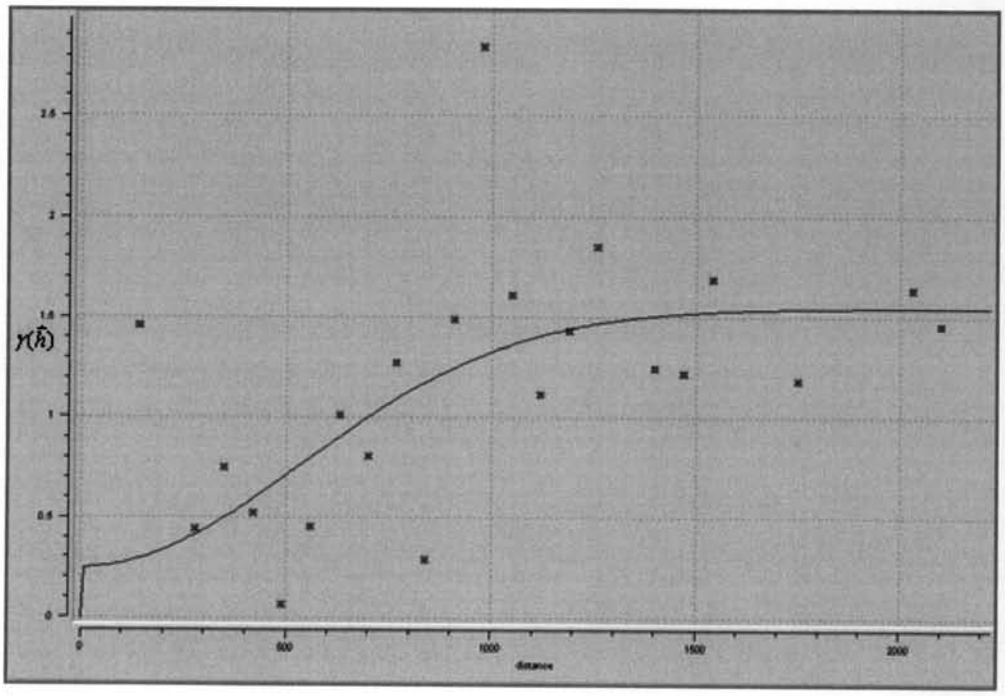


Figure 3.6: Omni-directional variogram of all porosity data.

From Figure 3.6, it was found that this omni-directional variogram presents no spatial correlation at all indicating by the clustering of experimental point variogram values around the data variance. The cause of this variogram behavior is probably from the mixing of data from all layers. Therefore, variogram calculations in each layer were applied for this study. The variogram calculation and modeling are summarized in Figures 3.7 to 3.11 and Table 3.5. Figures 3.7 to 3.11 display omni-directional variograms and normal score transform variograms of porosity in the layer of K2, K3, K4, L2, and L3. Only K3 layer was modeled by spherical model with 0.16% sill, 0.02% nugget and range of 820 m, while the other layers were modeled by Gaussian model with 0.13% to 0.29% sill, 0.02% to 0.05% nugget and the ranges of 860 m to 1,302 m. It also can be seen that these variogram models provide a low nugget effect when the nugget value is relatively small comparing to the sill value, with an exception in layer K2 where the nugget effect is greater than 30 percents of sill value. And, the sill of these variograms are very close to the data variance meaning that these variograms are good to quantify the spatial variability structure of porosity variable.

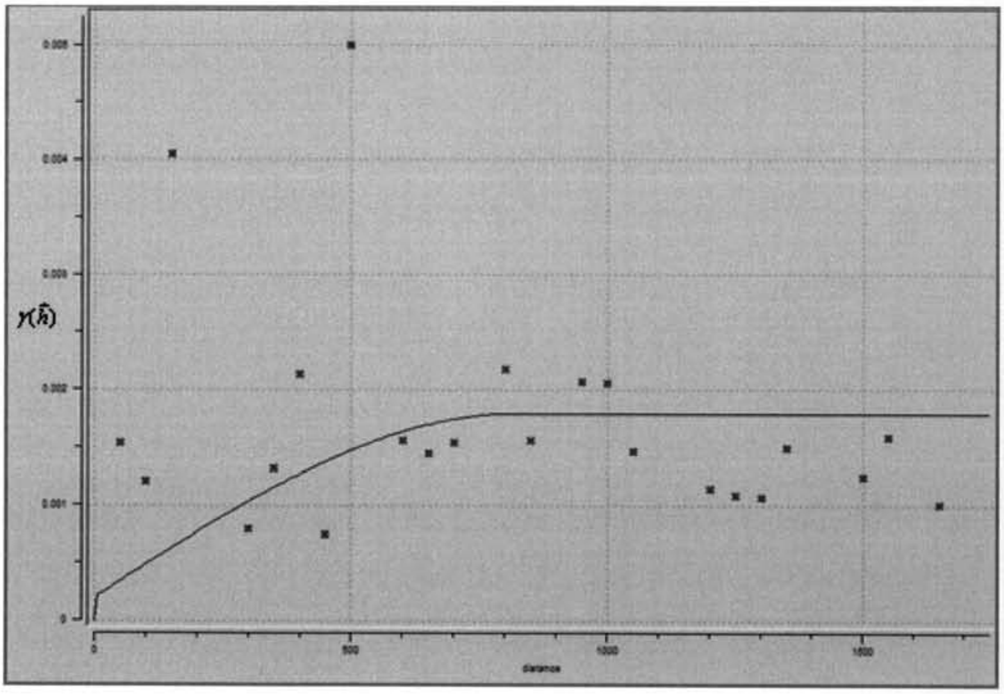


(a)

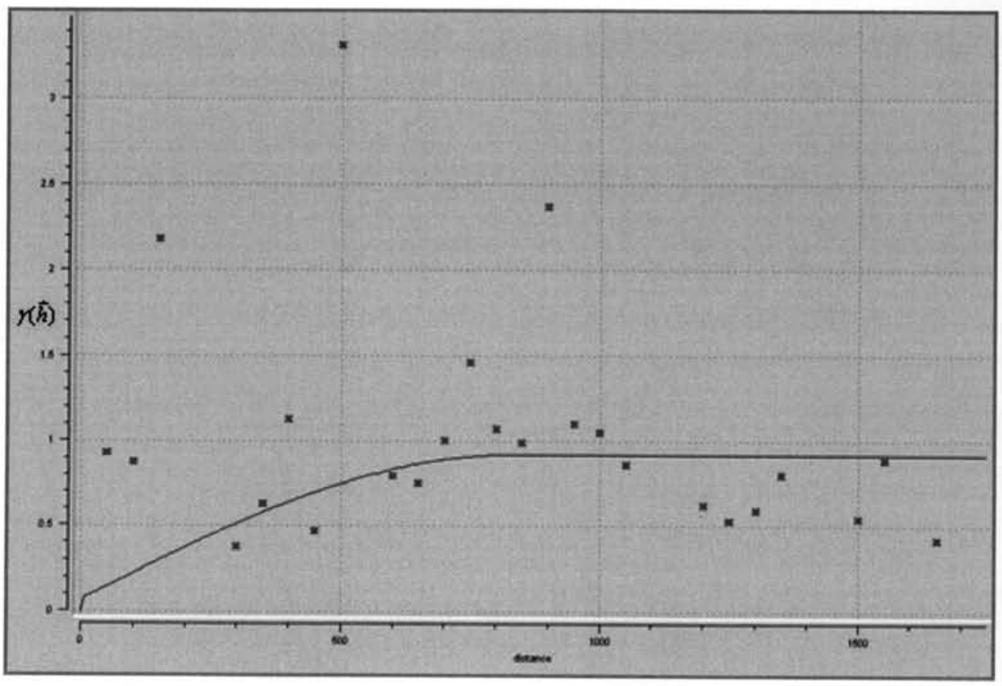


(b)

Figure 3.7: Omni-directional variograms of porosity in K2 layer:
(a) the original data and (b) normal score transform.



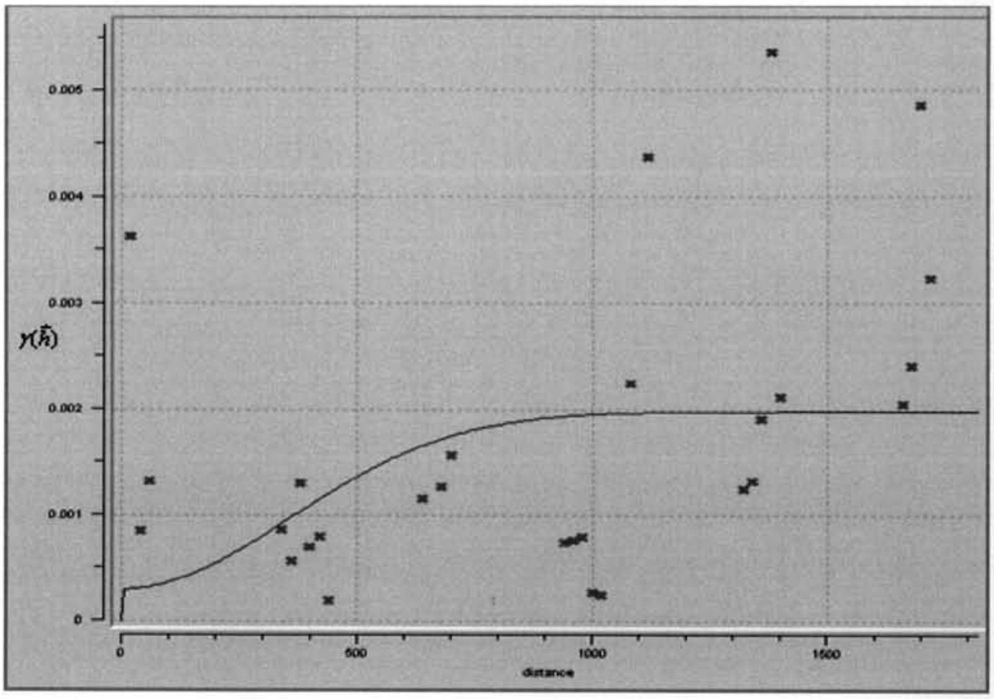
(a)



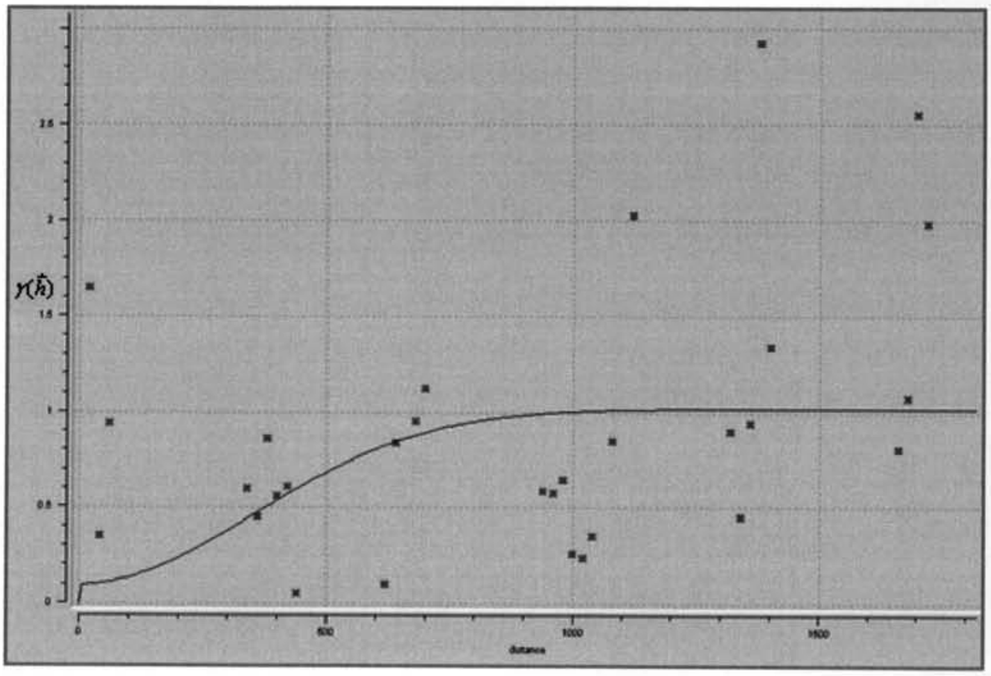
(b)

Figure 3.8: Omni-directional variograms of porosity in K3 layer:

(a) the original data and (b) normal score transform.



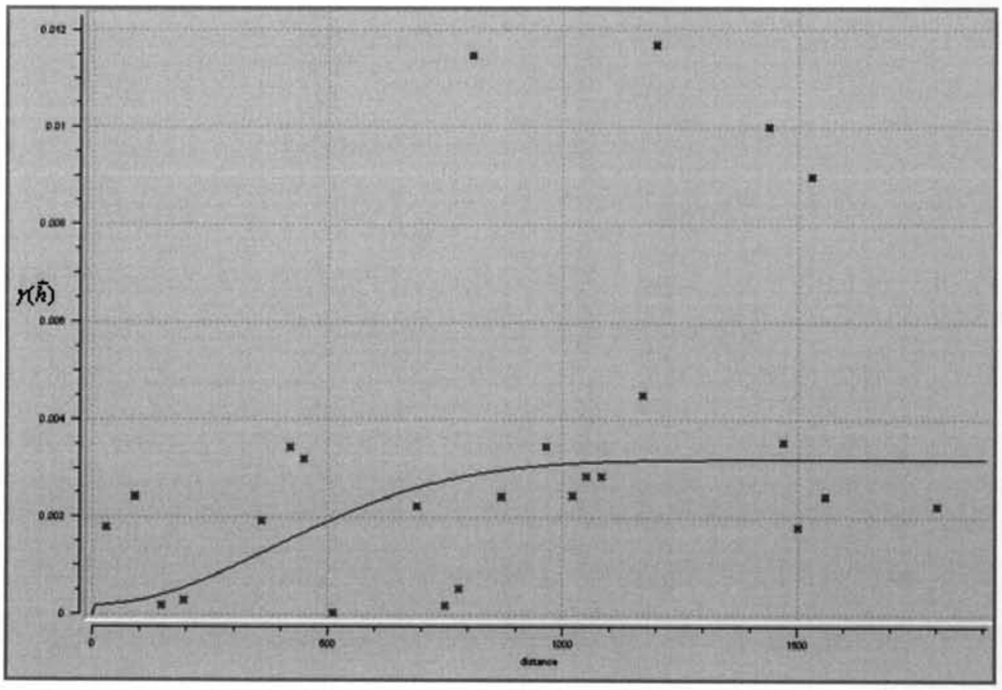
(a)



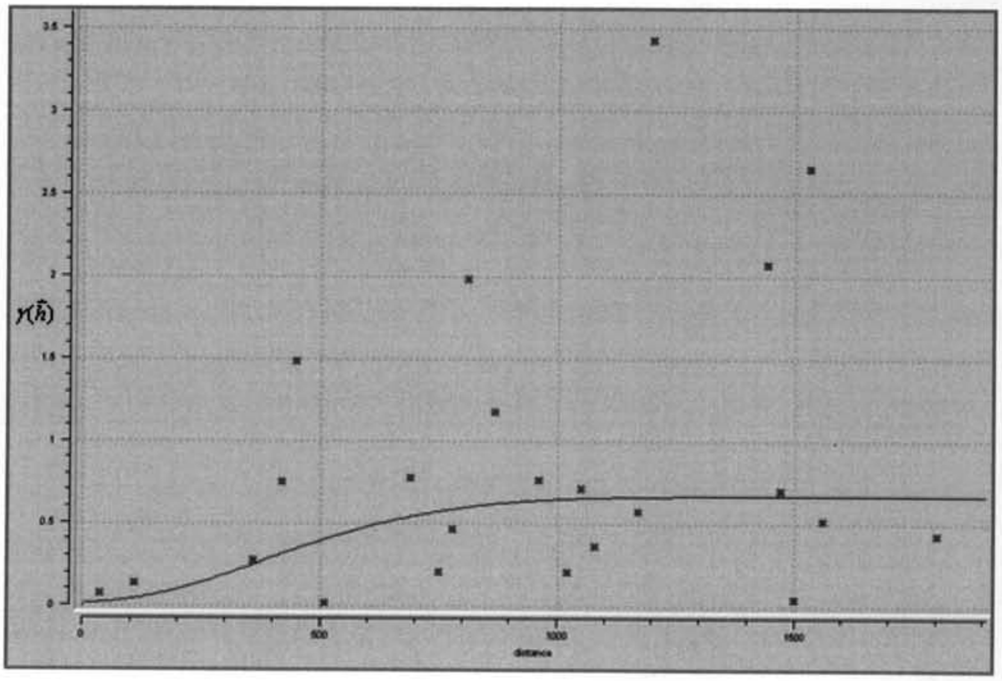
(b)

Figure 3.9: Omni-directional variograms of porosity in K4 layer:

(a) the original data and (b) normal score transform.

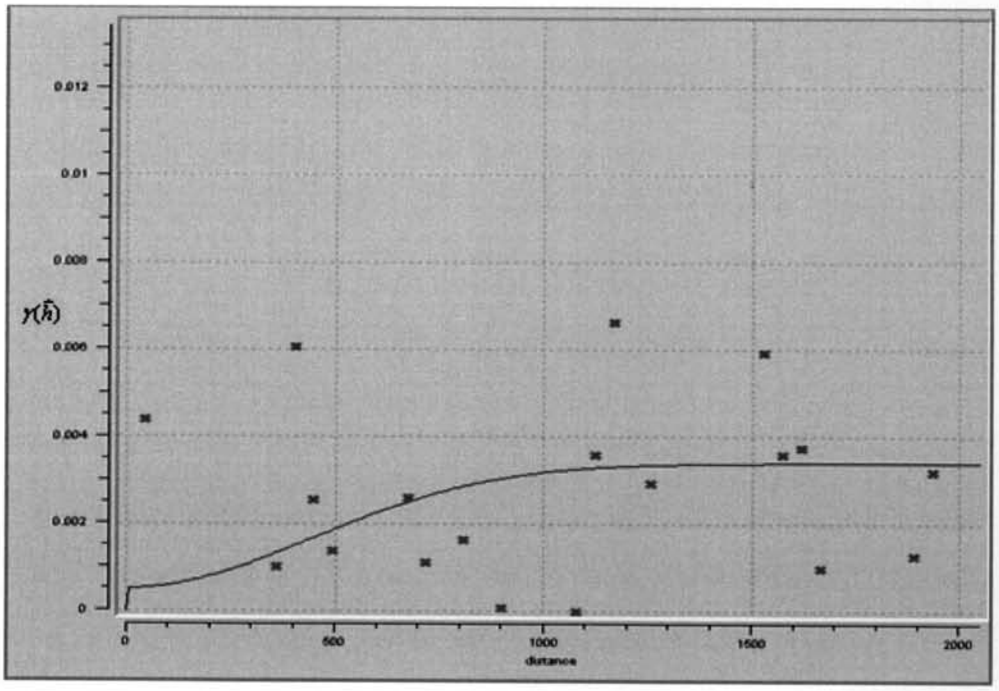


(a)

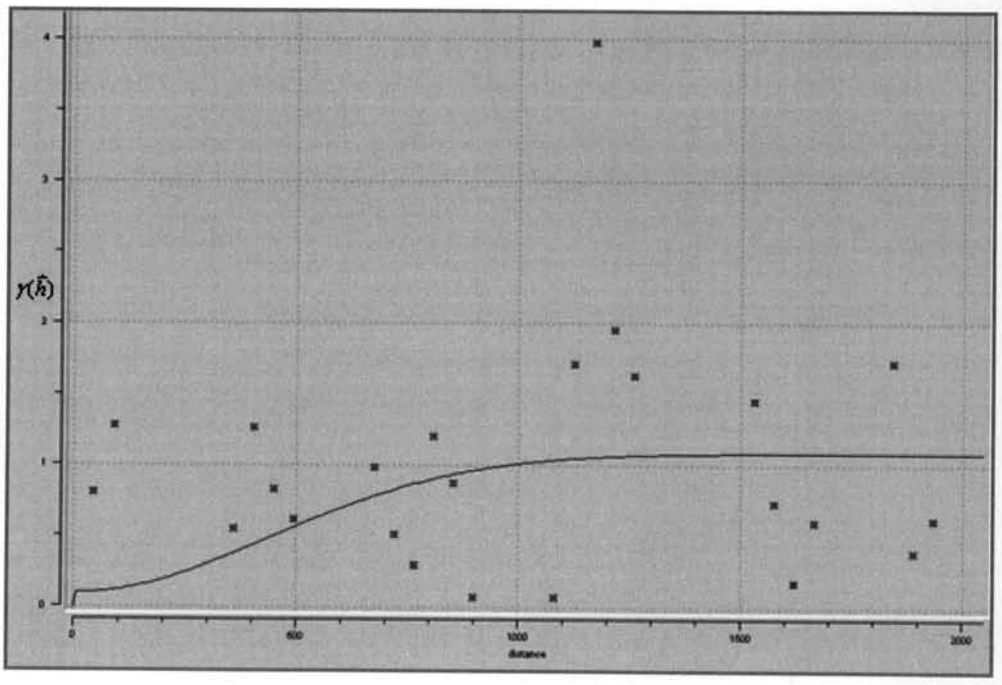


(b)

Figure 3.10: Omni-directional variograms of porosity in L2 layer:
(a) the original data and (b) normal score transform.



(a)



(b)

Figure 3.11: Omni-directional variograms of porosity in L3 layer:
(a) the original data and (b) normal score transform.

Table 3.5: Omni-directional variogram parameters and variance of porosity

Layer	Variance	Type	Original Data			Normal Score Data		
			Sill	Nugget	Range (m)	Sill	Nugget	Range (m)
K2	0.0012	Gaussian	0.0013	0.0005	1302	1.30	0.25	1302
K3	0.0017	Spherical	0.0016	0.0002	820	0.85	0.07	820
K4	0.0014	Gaussian	0.0017	0.0003	860	0.92	0.09	860
L2	0.0030	Gaussian	0.0030	0.0002	936	0.65	0.02	936
L3	0.0025	Gaussian	0.0029	0.0005	1080	0.99	0.10	1080

From visual inspection, it can be seen that these variogram models are reasonably fitted into the experimental points variogram. The variogram models are quantified based on their adopted models and parameters. Now, in prior to adopt these variogram models in the simulation process, the reliability of these variograms should be accessed, and this can be done in the cross validation process.

3.4 Cross validation

Cross validation is a technique to compare estimated and true values using only the information available in sample data set. In cross validation process, the estimation is tested at the locations of existing samples for proving how representative of these variograms before carrying out to the next simulation step.

Ordinary Kriging (OK) was selected in this study to estimate the porosity value at sampled locations due to this method inherits a realistic assumption than others linear interpolation method. For example, Simple Kriging (SK) and Universal Kriging (UK) which are also linear interpolation, require a prior knowledge of mean and distribution function of variable. Table 3.6 shows the example of Kriging weights for estimating the porosity value at location (592985.28 m, 1841812.14 m, 1636.49 m) in x, y, and z coordinates in well X04.

Table 3.6: The Example of Kriging weights for calculating estimated porosity.

Well	Layer	X Direction	Y Direction	Depth (m)	Porosity	λ	λ*Porosity
X20	K3	592340.38	1841715.84	1583.57	0.21	0.0356	0.0075
X01	K3	592254.11	1842097.26	1594.14	0.20	0.3104	0.0621
X03	K3	592618.98	1841621.93	1681.17	0.23	0.3822	0.0879
X07	K3	592620.68	1841610.15	1711.53	0.20	0.2718	0.0544
Total						1.00	0.212

From Table 3.6, four Kriging weights are obtained from solving the Kriging matrix. The estimated porosity at this location is equal to 0.212, and the actual measured is 0.21. The Kriging matrix is constructed conditioned to surrounding data and variogram model.

Tables 3.7 to 3.11 show the true and estimated values of porosity in layers K2, K3, K4, L2 and L3, respectively. The errors calculated from the difference between true and estimated values are also tabulated. The distribution of error indicates the biasness and precision of the estimated model. Not only distribution of error is provided, but the statistics of estimated data is also calculated. Figures 3.12 to 3.16 show the error distribution in layers K2, K3, K4, L2 and L3, respectively. The scatter plot between true value and estimated values in layers K2, K3, K4, L2 and L3 are shown in Figures 3.17 to 3.21, respectively. Tables 3.12 to 3.16 show a comparison of the statistical data between true and estimated values of layers K2, K3, K4, L2 and L3, respectively.

Table 3.7: The true and estimated values of porosity in K2 layer.

Well	Porosity		
	True Value (Z)	Estimated Value (Z*)	Error (Z-Z*)
X01	0.170	0.167	0.003
X01	0.220	0.210	0.010
X01	0.210	0.216	-0.006
X01	0.210	0.203	0.007
X03	0.200	0.205	-0.005
X03	0.220	0.226	-0.006
X03	0.200	0.208	-0.008
X04	0.200	0.190	0.010
X04	0.210	0.206	0.004
X04	0.180	0.188	-0.008
X04	0.190	0.189	0.001
X05	0.170	0.165	0.005
X05	0.160	0.149	0.011
X05	0.210	0.203	0.007
X07	0.170	0.178	-0.008
X07	0.180	0.183	-0.003
X08	0.170	0.174	-0.004
X08	0.120	0.130	-0.010
X08	0.240	0.248	-0.008

Table 3.7: The true and estimated values of porosity in K2 layer (continued).

Well	Porosity		
	True Value (Z)	Estimated Value (Z*)	Error (Z-Z*)
X09	0.150	0.160	-0.010
X09	0.140	0.133	0.007
X09	0.250	0.261	-0.011
X09	0.260	0.265	-0.005
X17	0.210	0.210	0.000
X17	0.160	0.167	-0.007
X17	0.210	0.215	-0.005
X20	0.200	0.203	-0.003
X20	0.230	0.225	0.005
X20	0.150	0.144	0.006
X21	0.270	0.251	0.019
X22	0.160	0.153	0.007
X23	0.170	0.180	-0.01
X23	0.190	0.184	0.006
X23	0.200	0.210	-0.01
X24	0.180	0.179	0.001
X24	0.230	0.229	0.001

They are 36 porosity data available within K2 layer, and the input variogram model is Gaussian model with sill and nugget of 0.13% and 0.05% with range of 1,302 m. From Table 3.7, the error distribution or the difference between the true and estimated values of porosity displays a narrow range of porosity error, the range of porosity error of -0.011 to 0.019.

The error distribution shows roughly a lognormal distribution. Considering the error statistics with the mean and variance closing to zero, it can be said that the estimation is slightly bias and high precision, thus proving the high reliability of the input variogram model for K2 layer.

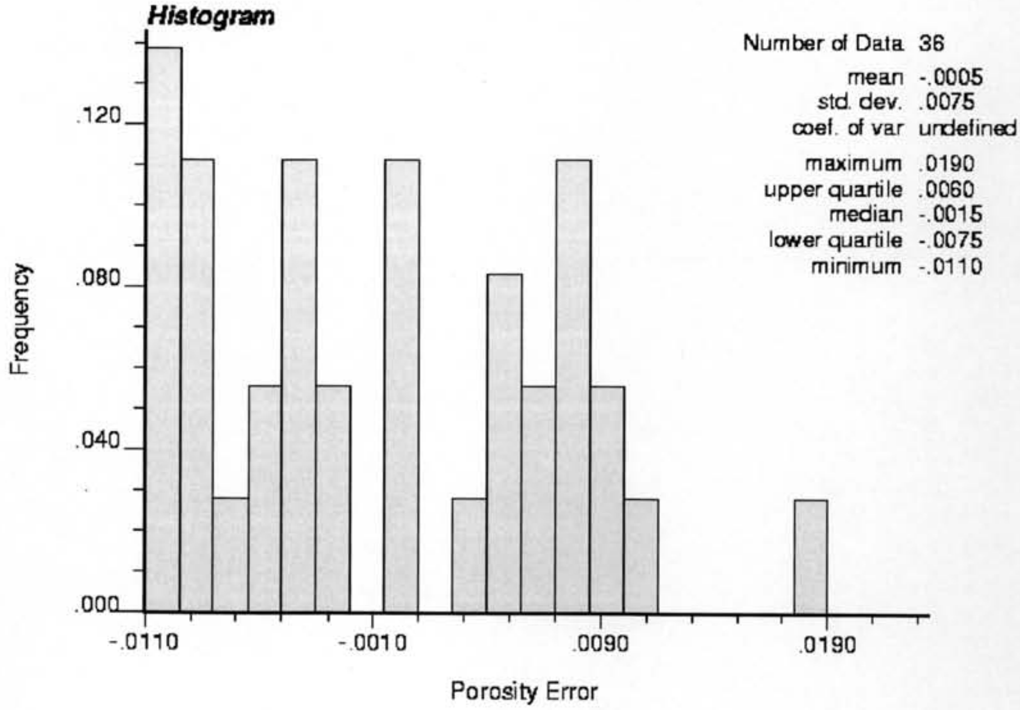


Figure 3.12: The error distribution of porosity in K2 layer.

Table 3.8: The true and estimated values of porosity in K3 layer.

Well	Porosity		
	True Value (Z)	Estimated Value (Z*)	Error (Z-Z*)
X01	0.190	0.199	-0.009
X01	0.200	0.198	0.002
X01	0.150	0.150	0.000
X01	0.150	0.151	-0.001
X03	0.130	0.135	-0.005
X03	0.200	0.205	-0.005
X03	0.230	0.236	-0.006
X04	0.210	0.212	-0.002
X04	0.130	0.131	-0.001
X04	0.240	0.230	0.010
X04	0.160	0.160	0.000
X04	0.160	0.160	0.000
X05	0.180	0.171	0.009
X05	0.110	0.115	-0.005
X05	0.190	0.197	-0.007

Table 3.8: The true and estimated values of porosity in K3 layer (continued).

Well	Porosity		
	True Value (Z)	Estimated Value (Z*)	Error (Z-Z*)
X07	0.230	0.235	-0.005
X07	0.200	0.205	-0.005
X07	0.160	0.151	0.009
X08	0.140	0.144	-0.004
X08	0.120	0.122	-0.002
X08	0.210	0.193	0.017
X09	0.180	0.200	-0.020
X09	0.200	0.207	-0.007
X09	0.220	0.200	0.020
X09	0.150	0.200	-0.050
X17	0.190	0.195	-0.005
X19	0.090	0.120	-0.030
X20	0.210	0.210	0.000
X21	0.140	0.139	0.001
X21	0.130	0.130	0.000
X21	0.180	0.179	0.001
X22	0.110	0.116	-0.006
X23	0.230	0.210	0.020
X23	0.150	0.198	-0.048
X23	0.200	0.223	-0.023
X24	0.280	0.234	0.046
X24	0.150	0.155	-0.005

They are 37 porosity data available within K3 layer, and the input variogram model is Spherical model with sill and nugget of 0.16% and 0.02% with range of 820 m. From Table 3.8, the error distribution or the difference between the true and estimated values of porosity displays a slightly wide range of porosity error, the range of porosity error of -0.050 to 0.046.

The error distribution shows roughly a normal distribution. Considering the error statistics with the mean and variance closing to zero, it can be said that the estimation is medium bias and high precision, thus proving the high reliability of the input variogram model for K3 layer.

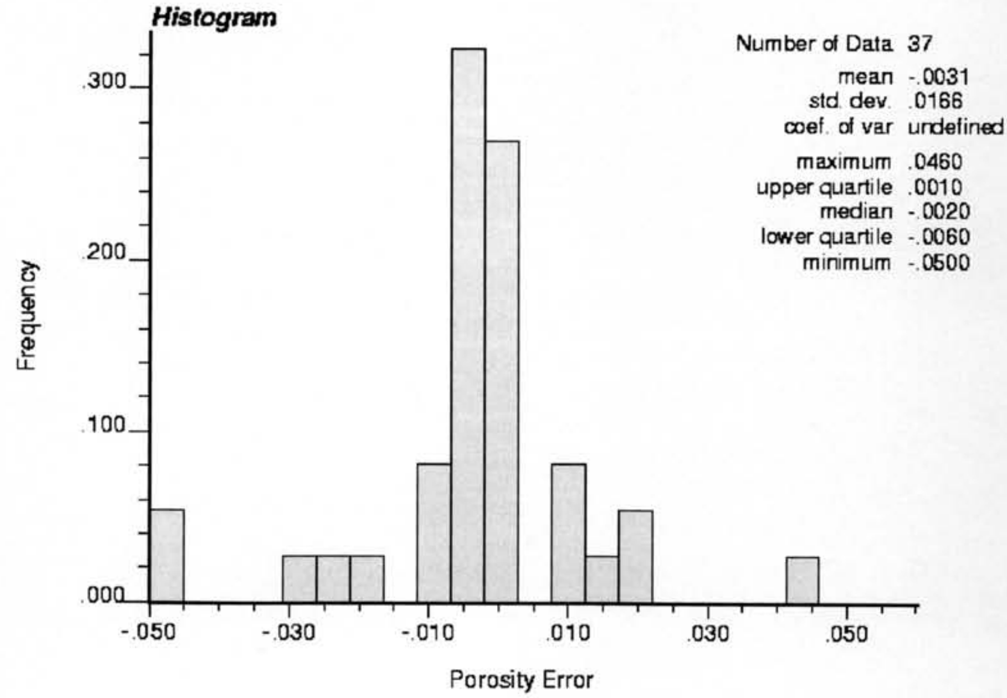


Figure 3.13: The error distribution of porosity in K3 layer.

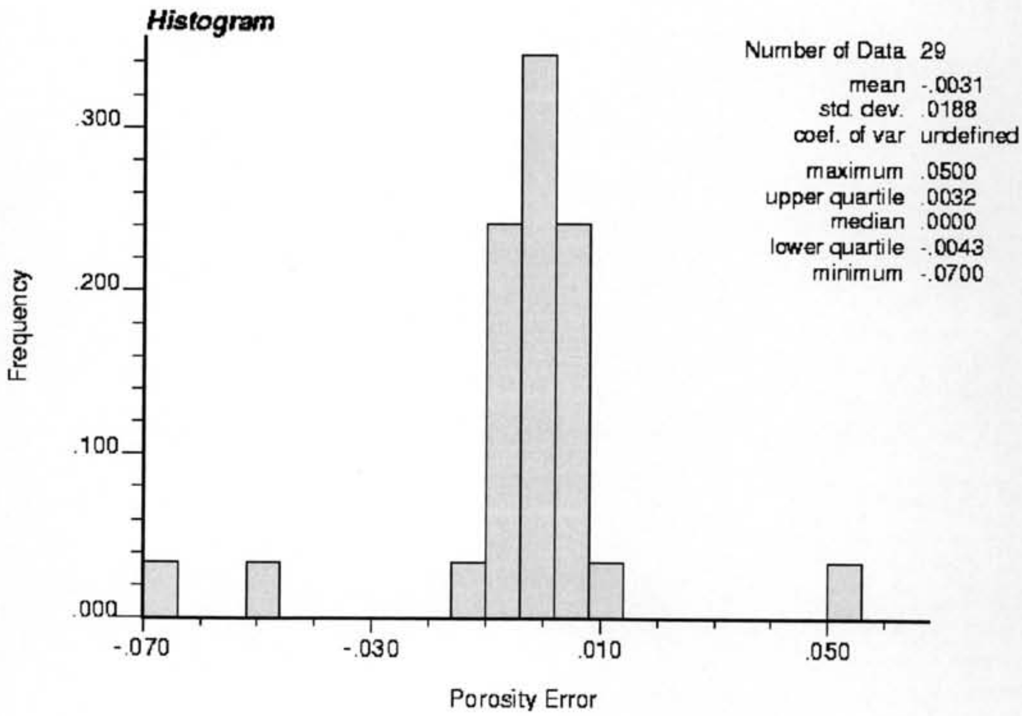


Figure 3.14: The error distribution of porosity in K4 layer.

Table 3.9: The true and estimated values of porosity in K4 layer.

Well	Porosity		
	True Value	Estimated Value	Error
	(Z)	(Z*)	(Z-Z*)
X01	0.150	0.150	0.000
X01	0.200	0.197	0.003
X03	0.200	0.204	-0.004
X03	0.180	0.182	-0.002
X03	0.180	0.175	0.005
X03	0.150	0.145	0.005
X04	0.220	0.220	0.000
X04	0.190	0.182	0.008
X04	0.140	0.144	-0.004
X04	0.220	0.220	0.000
X04	0.220	0.220	0.000
X05	0.160	0.154	0.006
X05	0.180	0.180	0.000
X07	0.120	0.133	-0.013
X07	0.140	0.146	-0.006
X07	0.200	0.200	0.000
X08	0.200	0.202	-0.002
X08	0.170	0.174	-0.004
X08	0.180	0.188	-0.008
X09	0.170	0.240	-0.070
X09	0.290	0.240	0.050
X09	0.240	0.290	-0.050
X19	0.240	0.237	0.003
X19	0.230	0.232	-0.002
X20	0.220	0.216	0.004
X20	0.200	0.205	-0.005
X21	0.110	0.118	-0.008
X21	0.180	0.175	0.005
X21	0.180	0.180	0.000

They are 29 porosity data available within K4 layer, and the input variogram model is Gaussian model with sill and nugget of 0.17% and 0.03% with range of 860 m. From Table 3.9, the error distribution or the difference between the true and estimated values of porosity displays a slightly wide range of porosity error, the range of porosity error of -0.070 to 0.050.

The error distribution shows roughly a normal distribution. Considering the error statistics with the mean and variance closing to zero, it can be said that the estimation is medium bias and high precision, thus proving the high reliability of the input variogram model for K4 layer.

Table 3.10: The true and estimated values of porosity in L2 layer.

Well	Porosity		
	True Value	Estimated Value	Error
	(Z)	(Z*)	(Z-Z*)
X01	0.220	0.221	-0.001
X04	0.170	0.158	0.012
X04	0.130	0.126	0.004
X04	0.180	0.170	0.010
X05	0.150	0.149	0.001
X05	0.190	0.191	-0.001
X05	0.310	0.307	0.003
X05	0.180	0.189	-0.009
X08	0.190	0.197	-0.007
X08	0.130	0.150	-0.020
X09	0.310	0.250	0.060
X09	0.250	0.310	-0.060
X19	0.220	0.170	0.050
X20	0.140	0.134	0.006
X21	0.120	0.113	0.007
X22	0.150	0.147	0.003
X24	0.150	0.153	-0.003
X24	0.170	0.167	0.003

They are 18 porosity data available within L2 layer, and the input variogram model is Gaussian model with sill and nugget of 0.30% and 0.02% with range of 936 m. From Table 3.10, the error distribution or the difference between the true and estimated values of porosity displays a slightly wide range of porosity error, the range of porosity error of -0.060 to 0.060.

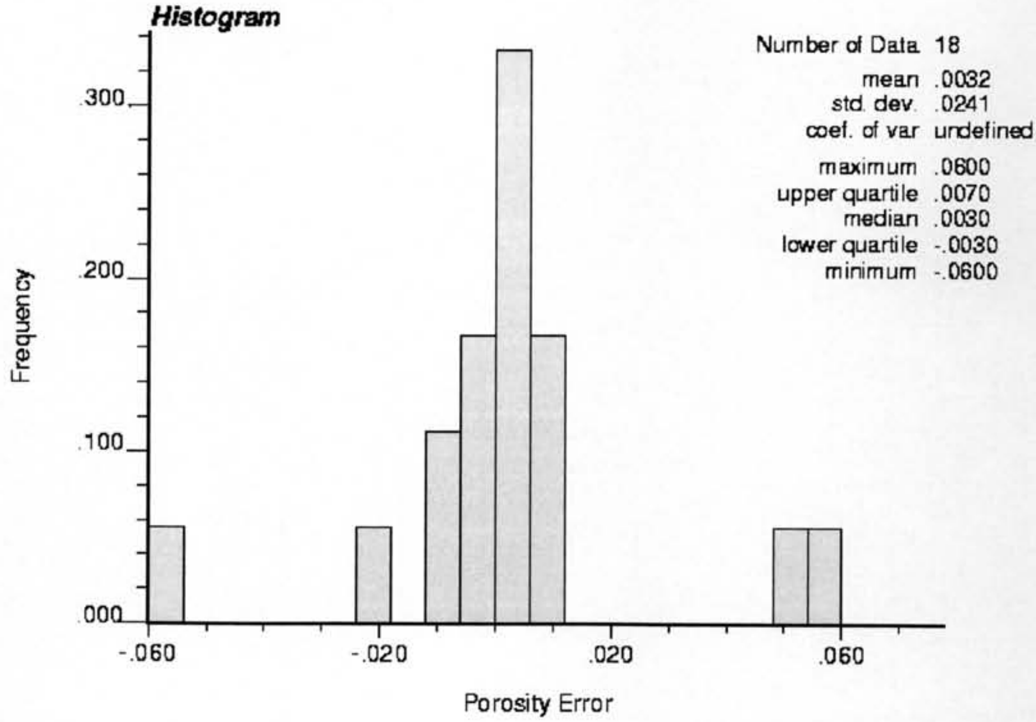


Figure 3.15: The error distribution of porosity in L2 layer.

The error distribution shows roughly a normal distribution. Considering the error statistics with the mean and variance closing to zero, it can be said that the estimation is medium bias and high precision, thus proving the high reliability of the input variogram model for L2 layer.

Table 3.11: The true and estimated values of porosity in L3 layer.

Well	Porosity		
	True Value (Z)	Estimated Value (Z*)	Error (Z-Z*)
X01	0.140	0.126	0.014
X01	0.200	0.204	-0.004
X01	0.170	0.184	-0.014
X03	0.200	0.203	-0.003
X03	0.180	0.194	-0.014
X03	0.280	0.293	-0.013
X04	0.170	0.156	0.014
X04	0.220	0.228	-0.008
X04	0.230	0.222	0.008

Table 3.11: The true and estimated values of porosity in L3 layer (continued).

Well	Porosity		
	True Value	Estimated Value	Error
	(Z)	(Z*)	(Z-Z*)
X07	0.15	0.15	0.004
X07	0.15	0.15	-0.004
X07	0.21	0.18	0.026
X08	0.17	0.17	0.001
X08	0.11	0.11	-0.001
X09	0.36	0.23	0.13
X09	0.18	0.22	-0.043
X09	0.17	0.13	0.043
X09	0.20	0.33	-0.128
X20	0.21	0.20	0.01
X20	0.14	0.15	-0.007
X20	0.20	0.21	-0.011
X21	0.20	0.20	0.003
X23	0.10	0.13	-0.026
X23	0.17	0.16	0.007
X23	0.16	0.17	-0.007
X24	0.17	0.15	0.019
X24	0.14	0.16	-0.02

They are 27 porosity data available within L3 layer, and the input variogram model is Gaussian model with sill and nugget of 0.29% and 0.05% with range of 1,080 m. From Table 3.11, the error distribution or the difference between the true and estimated values of porosity displays a wide range of porosity error, the range of porosity error of -0.128 to 0.130.

The error distribution shows roughly a normal distribution. Considering the error statistics with the mean and variance closing to zero, it can be said that the estimation is medium bias and moderate precision, thus proving the reasonable reliability of the input variogram model for L3 layer.

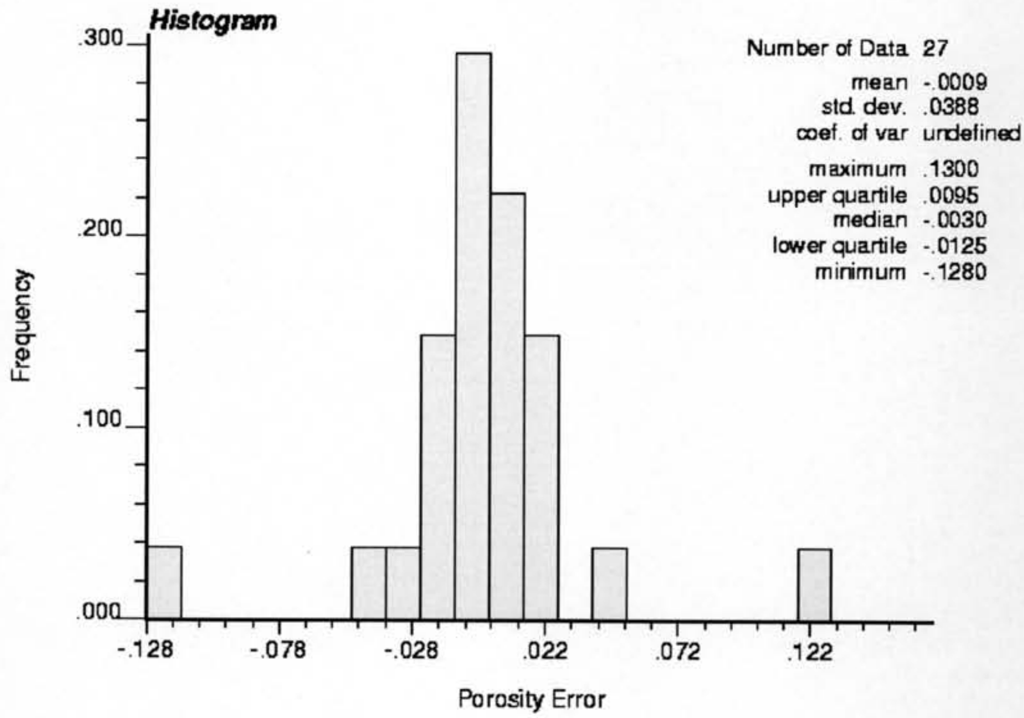


Figure 3.16: The error distribution of porosity in L3 layer.

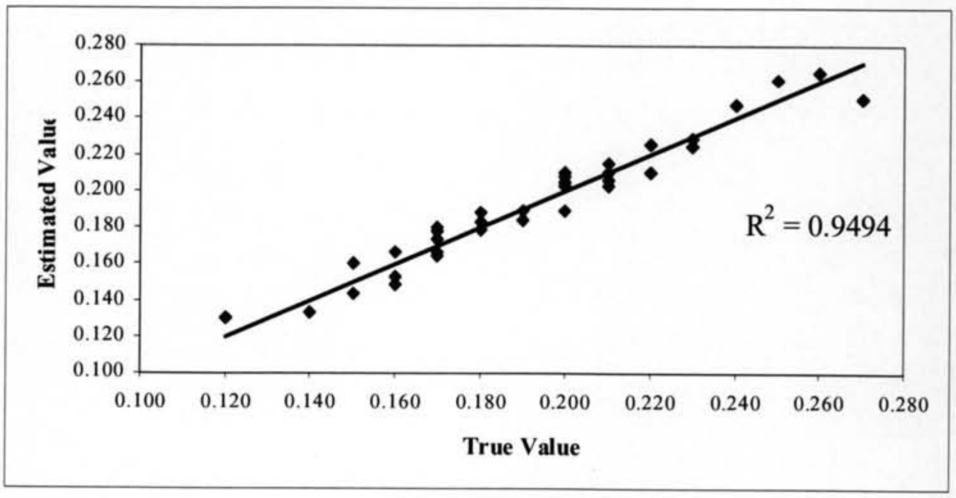


Figure 3.17: Scatter plot between true values and estimated values of K2 layer.

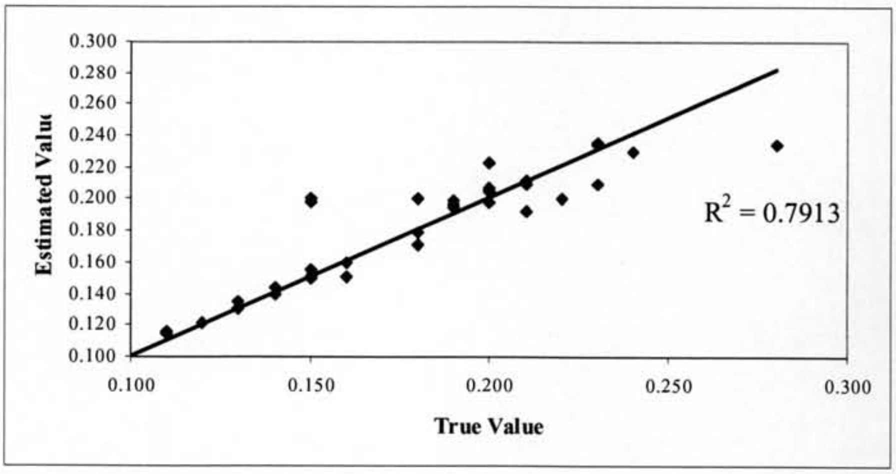


Figure 3.18: Scatter plot between true values and estimated values of K3 layer.

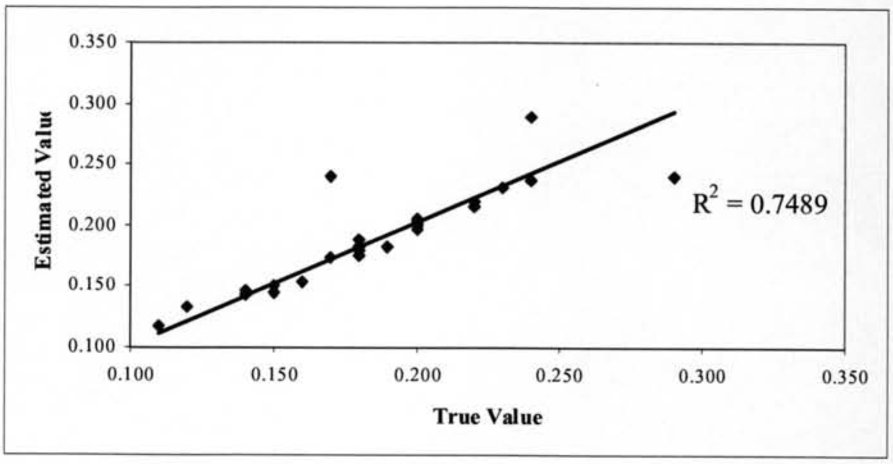


Figure 3.19: Scatter plot between true values and estimated values of K4 layer.

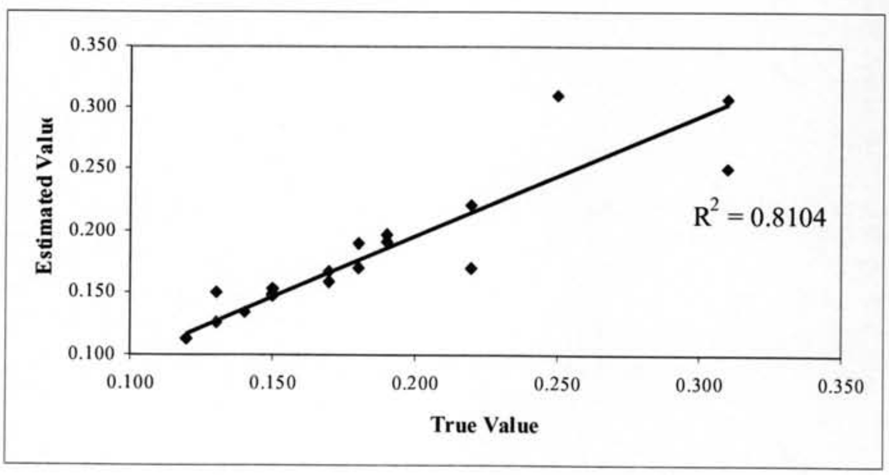


Figure 3.20: Scatter plot between true values and estimated values of L2 layer.

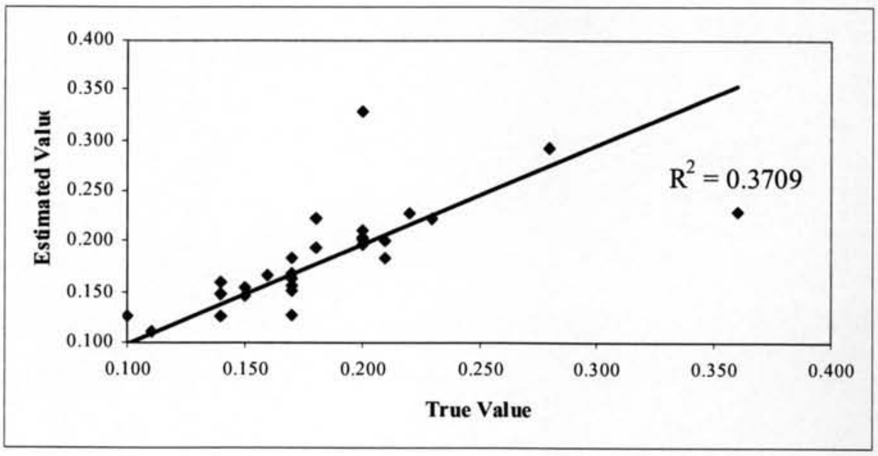


Figure 3.21: Scatter plot between true values and estimated values of L3 layer.

Table 3.12: Comparison of statistics between true and estimated values of K2 layer.

Statistical Data	Porosity	
	True Value	Estimated Value
Mean	0.1942	0.1946
Variance	0.0011	0.0011
Standard Deviation	0.0334	0.0334
Median (P50)	0.2000	0.1965
Minimum	0.1200	0.1300
Maximum	0.2700	0.2650
Coeff. of variation	0.1723	0.1716
Number of data	36	36

Table 3.13: Comparison of statistics between true and estimated values of K3 layer.

Statistical Data	Porosity	
	True Value	Estimated Value
Mean	0.1757	0.1788
Variance	0.0018	0.0014
Standard Deviation	0.0419	0.0369
Median (P50)	0.1800	0.1950
Minimum	0.0900	0.1150
Maximum	0.2800	0.2360
Coeff. of variation	0.2384	0.2063
Number of data	37	37

Table 3.14: Comparison of statistics between true and estimated values of K4 layer.

Statistical Data	Porosity	
	True Value	Estimated Value
Mean	0.1879	0.1913
Variance	0.0015	0.0014
Standard Deviation	0.0384	0.0378
Median (P50)	0.1800	0.1880
Minimum	0.1100	0.1180
Maximum	0.2900	0.2900
Coeff. of variation	0.2041	0.1976
Number of data	29	29

Table 3.15: Comparison of statistics between true and estimated values of L2 layer.

Statistical Data	Porosity	
	True Value	Estimated Value
Mean	0.1867	0.1834
Variance	0.0030	0.0030
Standard Deviation	0.0550	0.0547
Median (P50)	0.1750	0.1685
Minimum	0.1200	0.1130
Maximum	0.3100	0.3100
Coeff. of variation	0.2945	0.2984
Number of data	18	18

Table 3.16: Comparison of statistics between true and estimated values of L3 layer.

Statistical Data	Porosity	
	True Value	Estimated Value
Mean	0.1844	0.1853
Variance	0.0025	0.0024
Standard Deviation	0.0504	0.0487
Median (P50)	0.1700	0.1840
Minimum	0.1000	0.1110
Maximum	0.3600	0.3280
Coeff. of variation	0.2734	0.2627
Number of data	27	27

From Figures 3.17 to 3.21, only the scatter plot in L3 layer provides a low R^2 of 0.3709, while the other layers display a good relationship with the high R^2 in the range of 0.7489 to 0.9494, as can be seen that most data distribute along the 45° line or unit slope.

From Tables 3.12 to 3.16, the true and the estimated values statistics are in a good agreement. The mean, variance, quartile statistics and coefficient of variation of the true and estimated values are identical in some layer, for example the variances in K2 and L2 layers. In overall, the reproduction of estimated values statistics is solely an influence of the surrounding data and the input variogram model. Thus, a conclusion can be made that porosity variograms of this study are reasonably well representative and could be used in the simulation process.

3.5 Geostatistical Simulation

In this study, geostatistical simulation technique named Sequential Gaussian Simulation (SGS) was adopted to simulate porosity data across the field. Built on the multiGaussian framework, SGS can generate porosity data by conditioning to porosity data itself and its correlation structure via variogram model. Based on the fact that the permeability measurement values from core analysis are only available in K2 and K3 layers, only simulation maps of porosity in K2 and K3 layers were generated to estimate permeability equation. Consequently, the study area was covered by a grid with 100x100x300 nodes in K2 layer and a grid with 100 x100x600 nodes for the stochastic simulation corresponding to a cell size of 30x30x1 meters in K2 layer and 30x30x0.5 meters in K3 layer. The input parameters for this simulation are shown in Table 3.17. Simulation maps of porosity in K2 and K3 layers are shown in Figures 3.16 and 3.17, respectively.

Table 3.17: Simulation inputs used in SGS.

Simulation Inputs	Layer K2			Layer K3		
Variogram Model	Type	Gaussian		Type	Spherical	
	Sill	Nugget	Range (m)	Sill	Nugget	Range (m)
	0.0013	0.0005	1302	0.0016	0.0002	820
Search Criteria	Search Distance (m)		70	Search Distance (m)		50
	Search Condition		Isotropic	Search Condition		Isotropic
Conditioned data	Original Data			Original Data		
	Maximum	12		Maximum	12	
	Previously Simulated Data			Previously Simulated Data		
	Maximum	12		Maximum	12	
Block Arrangement	Block Size	30x30x1		Block Size	30x30x0.5	
	Grid Nodes	100x100x300		Grid Nodes	100x100x600	

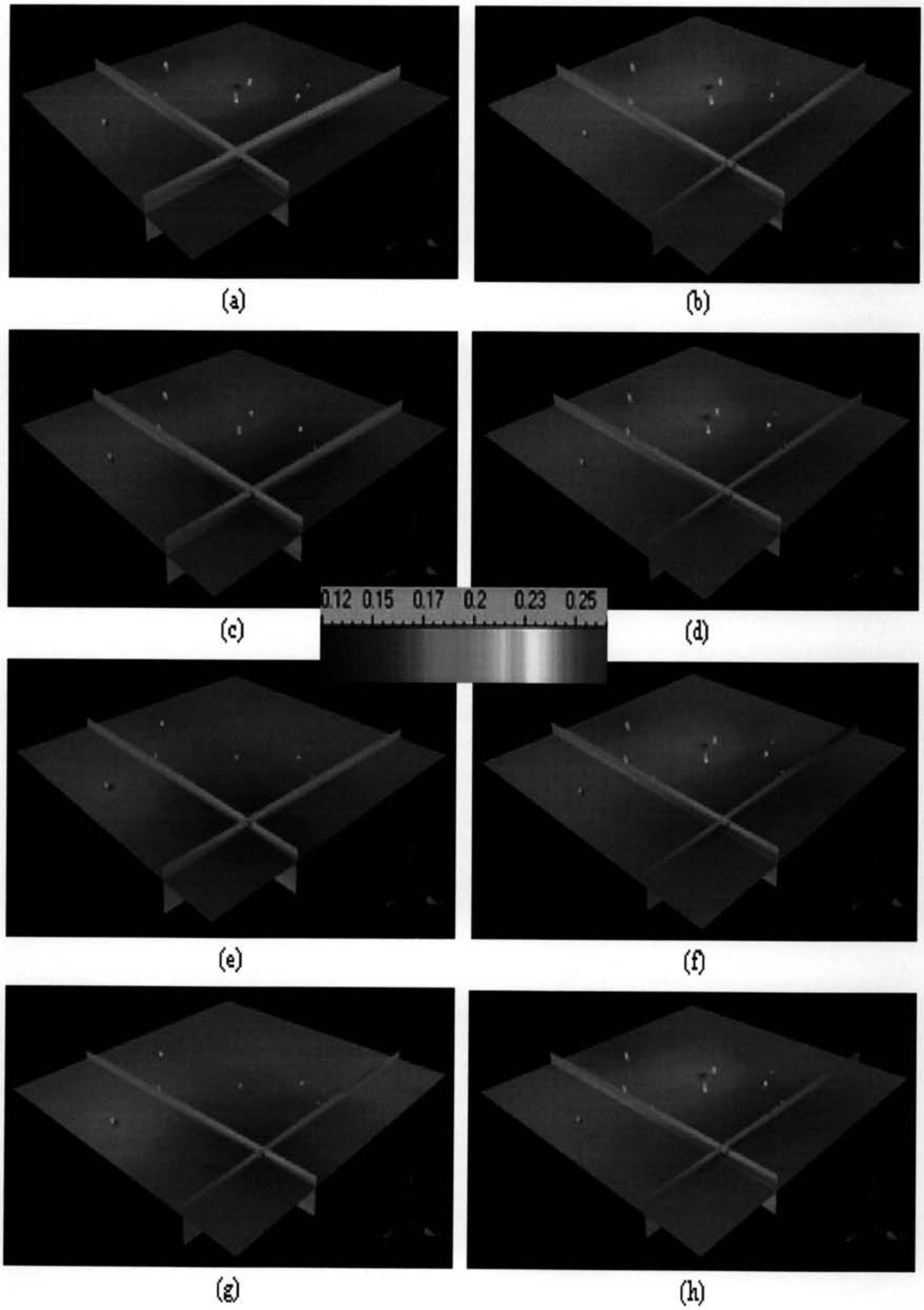


Figure 3.22: The simulation maps of porosity in K2 layer; (a) realization 1, (b) realization 2, (c) realization 3, (d) realization 4, (e) realization 5, (f) realization 6, (g) realization 7, and (h) realization 8.

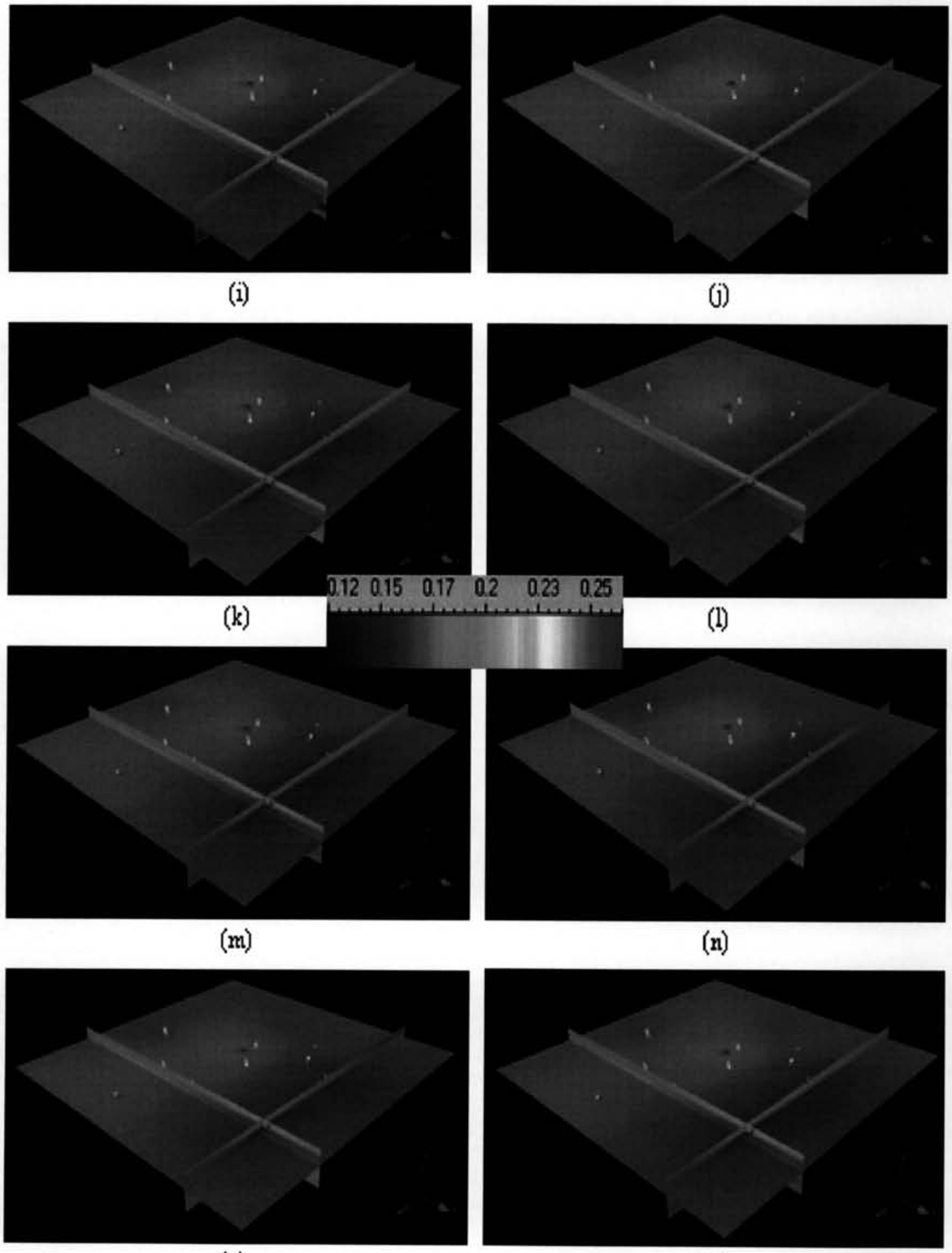


Figure 3.22: The simulation maps of porosity in K2 layer (continued); (i) realization 9, (j) realization 10, (k) realization 11, (l) realization 12, (m) realization 13, (n) realization 14, (o) realization 15, and (p) realization 16.

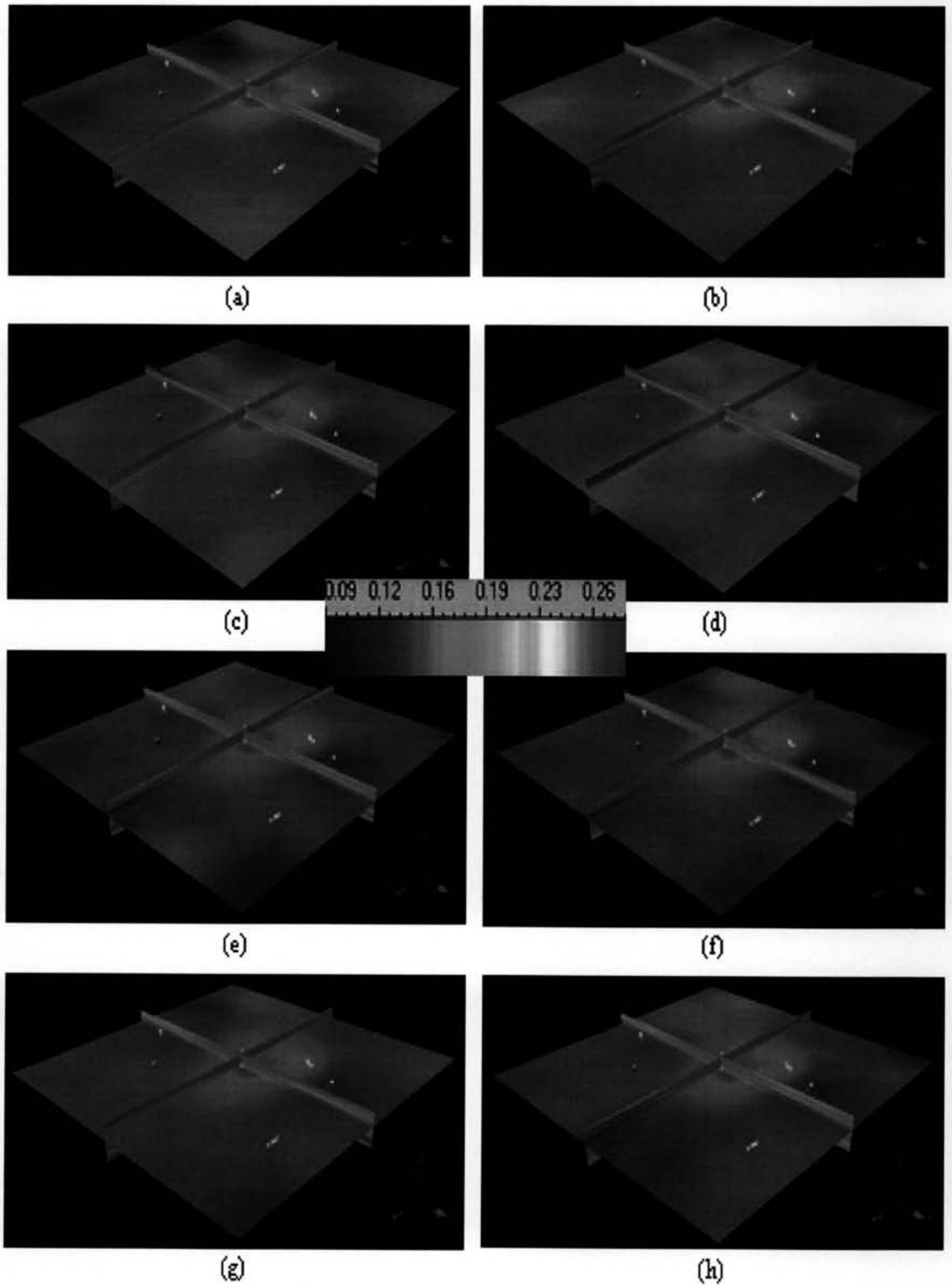


Figure 3.23: The simulation maps of porosity in K3 layer; (a) realization 1, (b) realization 2, (c) realization 3, (d) realization 4, (e) realization 5, (f) realization 6, (g) realization 7, and (h) realization 8.

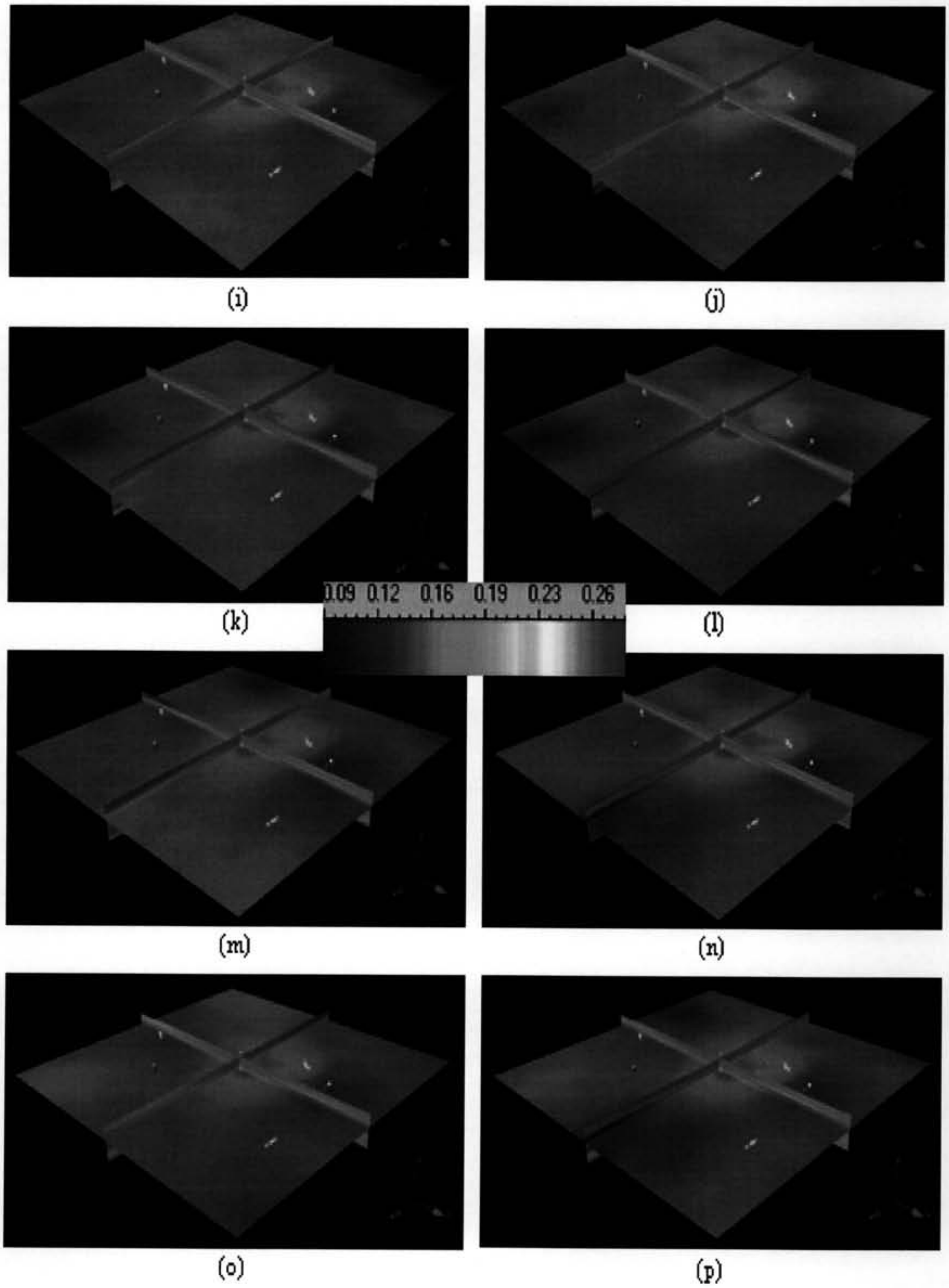


Figure 3.23: The simulation maps of porosity in K3 layer (continued); (i) realization 9, (j) realization 10, (k) realization 11, (l) realization 12, (m) realization 13, (n) realization 14, (o) realization 15, and (p) realization 16.

Sixteen simulation realization maps were generated for each layer. By superimposing the original well data on realization maps, the influence of original well data on simulated data can be examined. It can be seen that the distribution of simulated data of both porosities is, in a good agreement with original well data distribution in general. In other word, the simulated data reflects the overall spatial variation structure of original data. The statistical comparison between original data and simulation data of layer K2 and K3 is presented in Tables 3.18 and 3.19 respectively.

Table 3.18: Statistical comparison between original data and simulation maps in K2 layer.

Statistical data	Porosity				
	Original data	Simulation			
		Realization 1	Realization 2	Realization 3	Realization 4
Number of data	36	3,000,000	3,000,000	3,000,000	3,000,000
Mean	0.194	0.195	0.194	0.194	0.195
Variance	0.001151	0.000045	0.000060	0.000041	0.000045
Maximum	0.270	0.270	0.270	0.270	0.270
Upper Quartile	0.210	0.198	0.198	0.197	0.199
Median	0.200	0.195	0.195	0.194	0.196
Lower Quartile	0.170	0.193	0.192	0.192	0.194
Minimum	0.120	0.120	0.120	0.120	0.120

Statistical data	Porosity				
	Original data	Simulation			
		Realization 5	Realization 6	Realization 7	Realization 8
Number of data	36	3,000,000	3,000,000	3,000,000	3,000,000
Mean	0.194	0.194	0.194	0.193	0.194
Variance	0.001151	0.000042	0.000059	0.000055	0.000045
Maximum	0.270	0.270	0.270	0.270	0.270
Upper Quartile	0.210	0.197	0.197	0.196	0.198
Median	0.200	0.195	0.194	0.194	0.195
Lower Quartile	0.170	0.192	0.192	0.192	0.192
Minimum	0.120	0.120	0.120	0.120	0.120

Table 3.18: Statistical comparison between original data and simulation maps in K2 layer (continued).

Statistical data	Porosity				
	Original data	Simulation			
		Realization 9	Realization 10	Realization 11	Realization 12
Number of data	36	3,000,000	3,000,000	3,000,000	3,000,000
Mean	0.194	0.195	0.194	0.195	0.195
Variance	0.001151	0.000042	0.000038	0.000046	0.000046
Maximum	0.270	0.270	0.270	0.270	0.270
Upper Quartile	0.210	0.198	0.197	0.199	0.199
Median	0.200	0.195	0.194	0.196	0.196
Lower Quartile	0.170	0.193	0.192	0.193	0.193
Minimum	0.120	0.120	0.120	0.120	0.120

Statistical data	Porosity				
	Original data	Simulation			
		Realization 13	Realization 14	Realization 15	Realization 16
Number of data	36	3,000,000	3,000,000	3,000,000	3,000,000
Mean	0.194	0.194	0.193	0.193	0.193
Variance	0.001151	0.000070	0.000040	0.000042	0.000067
Maximum	0.270	0.270	0.270	0.270	0.270
Upper Quartile	0.210	0.198	0.196	0.196	0.197
Median	0.200	0.195	0.193	0.194	0.195
Lower Quartile	0.170	0.190	0.191	0.193	0.191
Minimum	0.120	0.120	0.120	0.120	0.120

Table 3.19: Statistical comparison between original data and simulation maps in K3 layer.

Statistical data	Porosity				
	Original data	Simulation			
		Realization 1	Realization 2	Realization 3	Realization 4
Number of data	37	6,000,000	6,000,000	6,000,000	6,000,000
Mean	0.176	0.174	0.173	0.172	0.173
Variance	0.001803	0.000184	0.000214	0.000210	0.000217
Maximum	0.280	0.292	0.281	0.280	0.281
Upper Quartile	0.200	0.183	0.183	0.182	0.183
Median	0.180	0.175	0.175	0.174	0.174
Lower Quartile	0.150	0.166	0.164	0.163	0.163
Minimum	0.090	0.090	0.090	0.090	0.090

Table 3.19: Statistical comparison between original data and simulation maps in K3 layer (continued).

Statistical data	Porosity				
	Original data	Simulation			
		Realization 5	Realization 6	Realization 7	Realization 8
Number of data	37	6,000,000	6,000,000	6,000,000	6,000,000
Mean	0.176	0.174	0.172	0.172	0.172
Variance	0.001803	0.000220	0.000219	0.000192	0.000250
Maximum	0.280	0.283	0.280	0.280	0.280
Upper Quartile	0.200	0.184	0.182	0.182	0.183
Median	0.180	0.175	0.173	0.173	0.173
Lower Quartile	0.150	0.164	0.162	0.163	0.160
Minimum	0.090	0.090	0.090	0.090	0.090

Statistical data	Porosity				
	Original data	Simulation			
		Realization 9	Realization 10	Realization 11	Realization 12
Number of data	37	6,000,000	6,000,000	6,000,000	6,000,000
Mean	0.176	0.176	0.175	0.171	0.174
Variance	0.001803	0.000188	0.000221	0.000194	0.000249
Maximum	0.280	0.280	0.294	0.280	0.291
Upper Quartile	0.200	0.185	0.185	0.182	0.184
Median	0.180	0.177	0.176	0.172	0.176
Lower Quartile	0.150	0.167	0.165	0.161	0.164
Minimum	0.090	0.090	0.090	0.090	0.090

Statistical data	Porosity				
	Original data	Simulation			
		Realization 13	Realization 14	Realization 15	Realization 16
Number of data	37	6,000,000	6,000,000	6,000,000	6,000,000
Mean	0.176	0.173	0.172	0.173	0.174
Variance	0.001803	0.000235	0.000227	0.000222	0.000221
Maximum	0.280	0.280	0.282	0.280	0.296
Upper Quartile	0.200	0.184	0.182	0.184	0.184
Median	0.180	0.175	0.172	0.176	0.175
Lower Quartile	0.150	0.163	0.161	0.163	0.163
Minimum	0.090	0.090	0.090	0.090	0.090

As can be seen from Tables 3.18 and 3.19, the statistical distributions are correctly reproduced accounting for the expected statistical fluctuation. The mean values are almost unchanged. Even though, the variances of simulated data seem to be lower than that of the original data variances, but the quartile statistics of data and the simulated data are quite similar. In overall, the simulated data is a reproduction of original data distribution, the overall main structure of high and low data distribution trends are still preserved through the simulation model.