PS Inter-Well Scale Heterogeneity of the Upper Khuff Carbonate Reservoir Units, Outcrop Analog Approach, Central Saudi Arabia*

Mutasim S. Osman[1]

Search and Discovery Article #11321 (2020)**
Posted May 11, 2020

*Adapted from poster presentation given at 2019 AAPG Annual Convention and Exhibition, San Antonio, Texas, May 19-22, 2019
 DOI:10.1306/11321Osman2020

[1]Geosciences, KFUPM, Dhahran, Saudi Arabia (mutasimsami@kfupm.edu.sa)

Abstract

The reservoir units within Khuff carbonates in the Middle East are known to contain about 30% of the World's gas reserves. These reservoirs are also known for their complex heterogeneities at the inter-well scale that is obviously beyond the resolution of seismic data. The Upper Khartam Member exposed in central Saudi Arabia represents a good outcrop analog for the Upper Khuff reservoirs in the subsurface. The aim of this study is to characterize the horizontal intra-reservoir heterogeneity and quality within the inter-well spacing using outcrop analog. Based on specific criteria, three potential reservoir units within the outcrop of Upper Khartam were selected to assess their heterogeneity and quality. The common criteria between these units are: composed of grainstone texture associated with high porosity and permeability values and they reflect good lateral continuity and spatial occurrence along the whole outcrop. The units are deposited above each other, unit A is at the bottom of the outcrop, unit B in the middle and unit C is at the top. Systematic horizontal sampling has been directed with 5 m spacing between each sample and another for the three reservoir units. A total of 90 samples were collected along these units and thin sections and core plugs were prepared from the whole samples and the porosity and permeability values have been measured.

For each unit, several measurements have been estimated and investigated based on different statistical analysis. The techniques that measure the heterogeneity are geostatistical techniques and therefore they provide a single value for the heterogeneity in a dataset. These techniques include; homogeneity index, Lorenz coefficient and dykstra - parsons coefficient. Here, the focus on the Lorenz coefficient and a modified version of it. Based on the measured porosity and permeability values, basic equations were used to investigate the reservoir quality: Reservoir Quality Index (RQI), pore volume to grain volume ratio (ϕz), and the Flow Zone Indicator (FZI). The porosity and permeability of these units, or in other words their quality, have been significantly altered by diagenetic processes as a function of their lateral extension. This resulted in dividing each one of the reservoir units into segments with ranges of qualities and therefore a number of flow zones. The outcomes of this study may represent guides and leads for field geologists and engineers if integrated with subsurface data.

Inter-well Scale Heterogeneity of the Upper Khuff Carbonate Reservoir Units, Outcrop Analog Approach, Central Saudi Arabia

Mutasim Osman, CPG, KFUPM, Dhahran, Saudi Arabia

Abstract: The reservoir units within Khuff carbonates in the Middle East are known to contain about 30% of the World's gas reserves. These reservoirs are also known for their complex heterogeneities at the inter-well scale that is obviously beyond the resolution of seismic data. The Upper Khartam Member exposed in central Saudi Arabia represent good outcrop analog for the Upper Khuff reservoirs in the subsurface. The aim of this study is to characterize the horizontal intra-reservoir heterogeneity and quality within the inter-well spacing using outcrop analog. Based on specific criteria, three potential reservoir units within the outcrop of Upper Khartam were selected to assess their heterogeneity and quality. The common criteria between these units are: composed of grainstone texture associated with high porosity and permeability values and they reflect good lateral continuity and spatial occurrence along the whole outcrop. The units are deposited above each other, unit A is at the bottom of the outcrop, unit B in the middle and unit C is at the top. Systematic horizontal sampling have been directed with 5 m spacing between each sample and another for the three reservoir units. A total of 90 samples were collected along these units and thin sections and core plugs were prepared from the whole samples and the porosity and permeability values have been measured. For each unit, several measurements have been estimated and investigated based on different statistical analysis. The techniques that measure the heterogeneity are geostatistical techniques and therefore they provide a single value for the heterogeneity in a dataset. These techniques include; homogeneity index, Lorenz coefficient and dykstra - parsons coefficient. Here, the focus on the Lorenz coefficient and a modified version of it. Based on the measured porosity and permeability values, basic equations were used to investigate about the reservoir quality: Reservoir Quality Index (RQI), pore volume to grain volume ratio (ϕz) and the Flow Zone Indicator (FZI). The porosity and permeability of these units, or in other words; their quality, have been significantly altered by diagenetic processes in a function of their lateral extension. This resulted in dividing each one of the reservoir units into segments with ranges of qualities and therefore a number of flow zones. The outcomes of this study may represent guides and leads for field geologists and engineers if integrated with subsurface data.

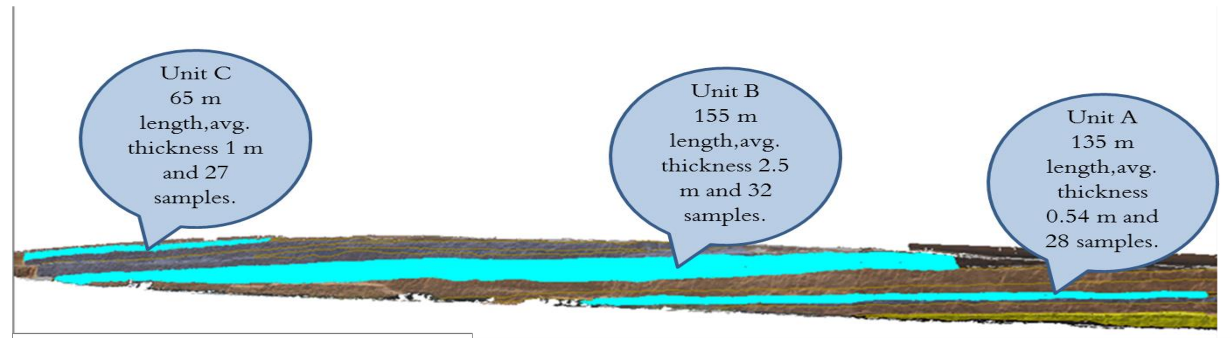
Introduction: The carbonate reservoirs reflect intrinsic heterogeneities in different scales from micro- to giga- scale which make them challenging (Pranter et al., 2006; Fitch et al., 2013). These heterogeneities might be depositional or diagenetic and caused by several factors such as; lithology, lithofacies, depositional environment, mineralogy, pore type and diagenesis. The Khuff-A reservoir in the subsurface which is equivalent to the Upper Khartam Member outcrop is known for its complex vertical and lateral sub-seismic heterogeneity (Janson et al., 2013). These small scale heterogeneities can be determined and evaluated by using equivalent strata from the outcrop of Upper Khartam.

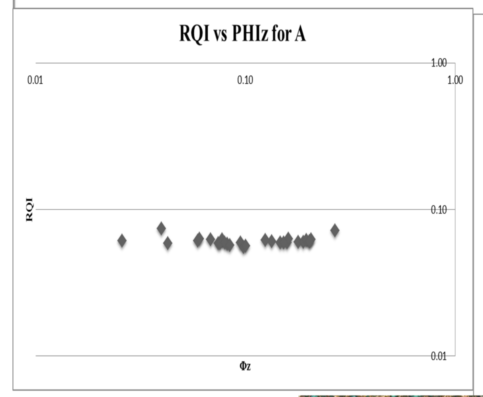
In this study, three potential reservoir units were selected to assess their heterogeneity and quality and make a comparison and ranking for all of them. For each unit several measurements have been estimated. The basic statistics for the porosity and permeability values include; Mean (m), Maximum Value (max.), Standard Deviation (S), Minimum Value (min.), Median (M) and Variance (S^2). Histograms for the porosity and permeability values were constructed to evaluate the nature of their distribution. Cross plots between the porosity and permeability measurements versus the sampling intervals both separately to examine their vertical and lateral variability. Also, for each reservoir unit a cross plot of porosity vs permeability measurements were conducted to see the relation between them and a correlation coefficient was calculated. Then, the previous parameters; RQI, ϕz and FZI were calculated.

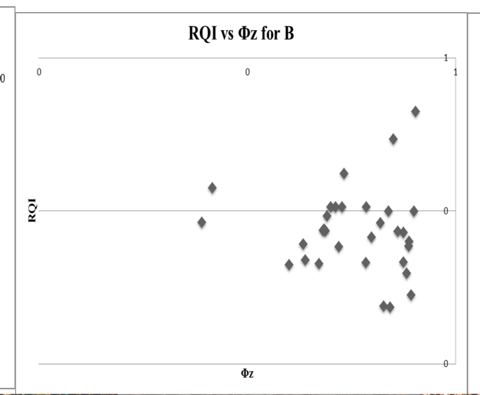
Methods: Three potential reservoir units were selected for detailed description for their heterogeneity and quality. These units are given the names A, B and C from the bottom to the top. The units are deposited above each other, unit A is at the bottom of the outcrop and unit C is at the top. The selection of these units depends on several factors: the intervals that contain grainstone texture associated with higher porosity and permeability from the vertical sections been investigated in the same outcrop, the good correlation between the vertical sections, the good lateral continuity of these units along the whole outcrop and the spatial occurrence of the units.

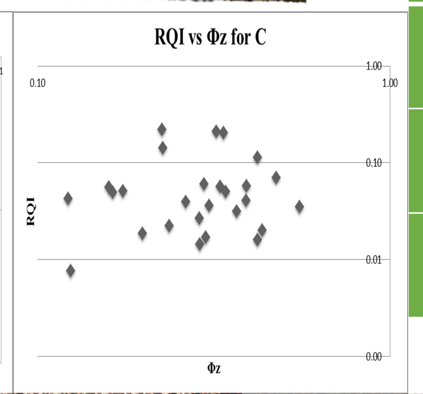
After the selection of these units a detailed description and sampling been conducted for them laterally. The horizontal sampling have been directed with 5 m spacing between each sample and another for the reservoir units A and B, and with 2.5 m spacing for unit C.

Results

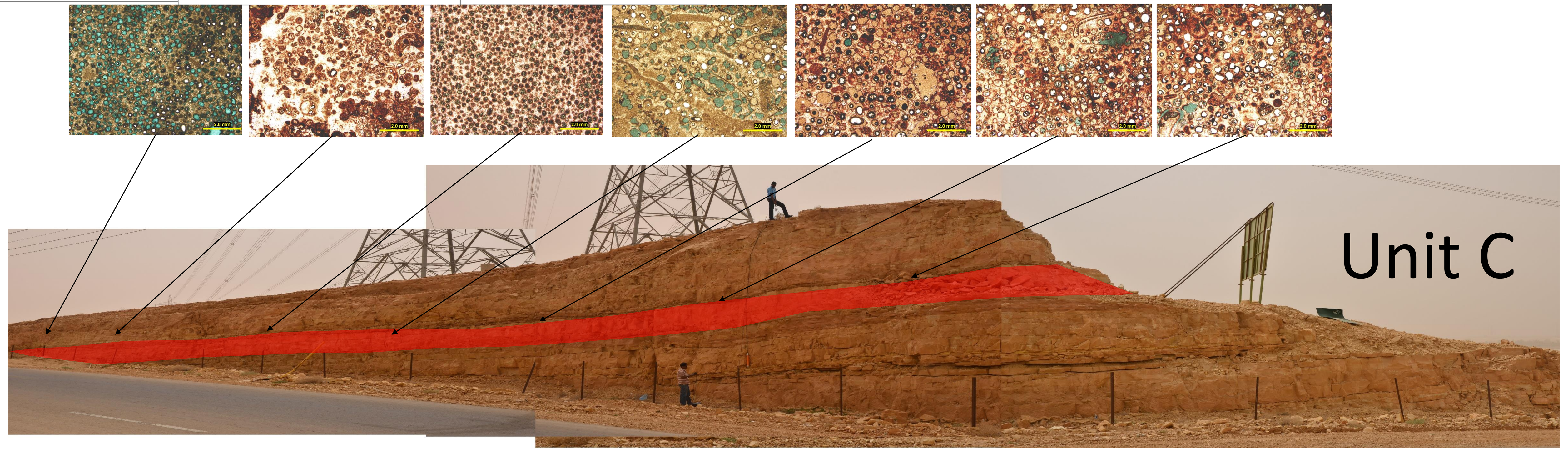


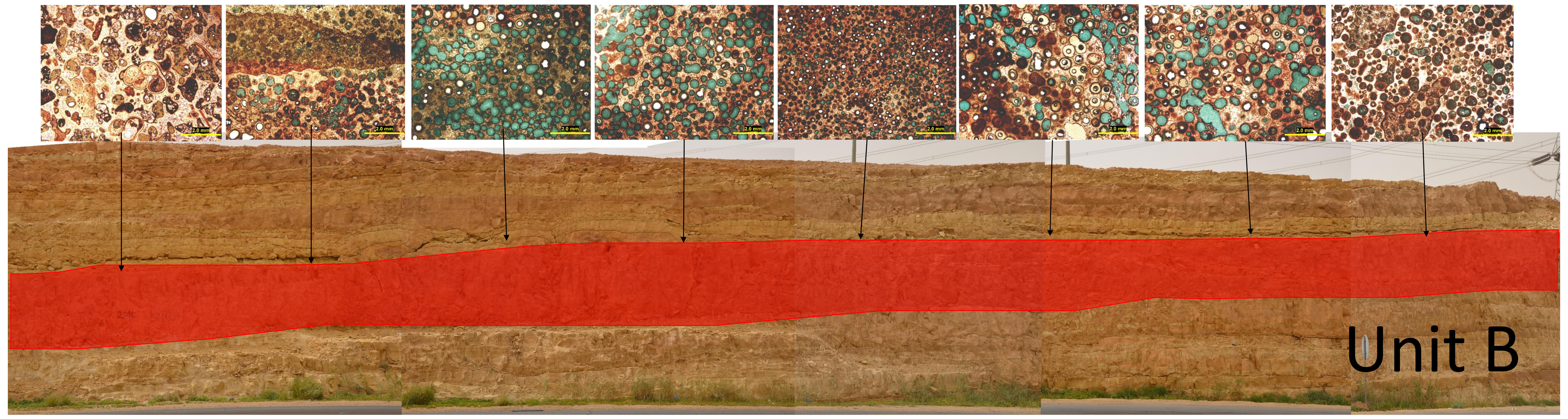


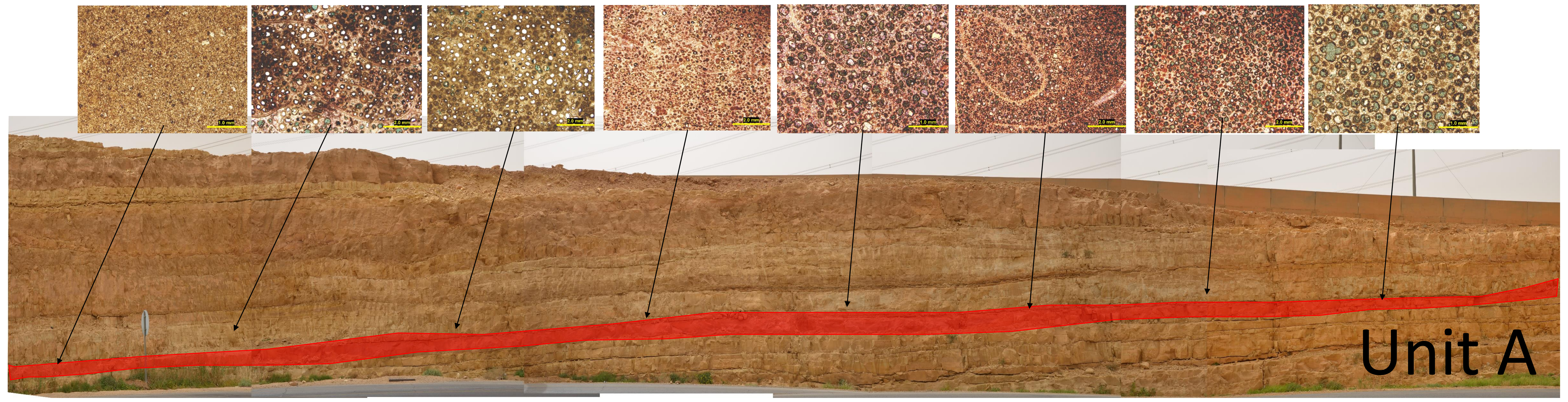




Reservoir Name	Average Φ (%)	S for Φ	Average k (mD)	S for k	R^2 for Φ vs k	R^2 for RQI vs Φz
A	10	4.8	0.4	0.2	0.92	0.177
B	26	9.5	4	14.4	0.3	0.162
C	22.6	6.5	1.7	3.2	0.069	0.004







Reservoir Heterogeneity and Quality

- Selection of Three Potential Reservoir Units — Three units named A, B and C
- Horizontal Sampling 5 m Spacing — 90 samples collected
- Laboratory Analysis — Φ and κ, Thin Sections and SEM

Conclusions: The Khuff reservoirs exhibit vertical and lateral heterogeneities which cannot captured fully within the inter-well spacing from the subsurface data. The outcrop of the Upper Khartam Member in Central Saudi Arabia represents an excellent analog for the upper parts of Khuff-B and the whole Khuff-A reservoirs. The detailed study for the lateral profiles of the reservoir units revealed that the reservoir unit B is the best in term of quality but it is the worst in term of variability. The reservoir unit C is considered the most heterogeneous unit because of the variation in the microfacies, petrophysical properties and mineral composition. The least heterogeneous unit is A because of the small differences in term of microfacies and petrophysical properties. On the other hand, overprinted reservoir qualities of the studied bodies in function of their lateral extension was differentially obliterated by diagenesis. This resulted in a segmentation of individual reservoir units into segments with ranges of qualities and hence several hydraulic subunits. XRD data indicated a proportional relationship between FZI and calcite and quartz. Also the damage caused by the pore-lining clay minerals is noteworthy. Furthermore, the diagenetic control on reservoir characteristics is also controlled by stylolites and fractures, which respectively form barriers (stylolites) to and conduits (fractures) for vertical fluid flow and most likely control differential cementation and dissolution processes.

References:

Adam, A. Swennen, R., Abdulghani, W., Abdlmutalib, A., Hariri, M., Abdulraheem, A. 2018. Reservoir heterogeneity and quality of Khuff carbonates in outcrops of central Saudi Arabia. Marine and Petroleum Geology. V. 89 (3), 721-751.

Al-Jallal, A. I. 1995. The Khuff Formation: Its Reservoir potential in Saudi Arabia and other gulf countries; Depositional and stratigraphic approach. Middle East Petroleum Geosciences, v. I. p. 103-119.

Fitch, P., Davies, S. and Lovell, M. 2013. Reservoir Quality and Reservoir Heterogeneity: Petrophysical Application of the Lorenz Coefficient. Petrophysics, v. 54, p. 465 – 474.

Hodgetts, D. [2013] Laser scanning and digital outcrop geology in the petroleum industry: A review. Marine and Petroleum Geology, 46, 335-354.

Janson, X., Lucia, F. J., Jennings, J. W., Bellian, J. A., AbuBshait, A. A., Al-Dukhayyil, R. K., Mueller, H. W. and Cantrell, D. 2013. Outcrop-based 3D geological and reservoir model of the uppermost Khuff Formation in central Saudi Arabia, in Pöppelreiter, M., ed., Permo-Triassic Sequence of the Arabian Plate: EAGE Special Publication, p. 269 – 302.

Koehrer, B., Aigner, T. and Pöppelreiter, M. 2011. Field-scale geometries of Upper Khuff reservoir geobodies in an outcrop analogue (Oman Mountains, Sultanate of Oman). Petroleum Geoscience, v. 17, p. 3 – 16.

Mohaghegh, S., Arefi, R., Ameri, S. and Hefner, M. H. 1994. A Methodological Approach for Reservoir Heterogeneity Characterization Using Artificial Neural Networks. SPE Annual Technical Conference & Exhibition held in New Orleans, LA, U.S.A.

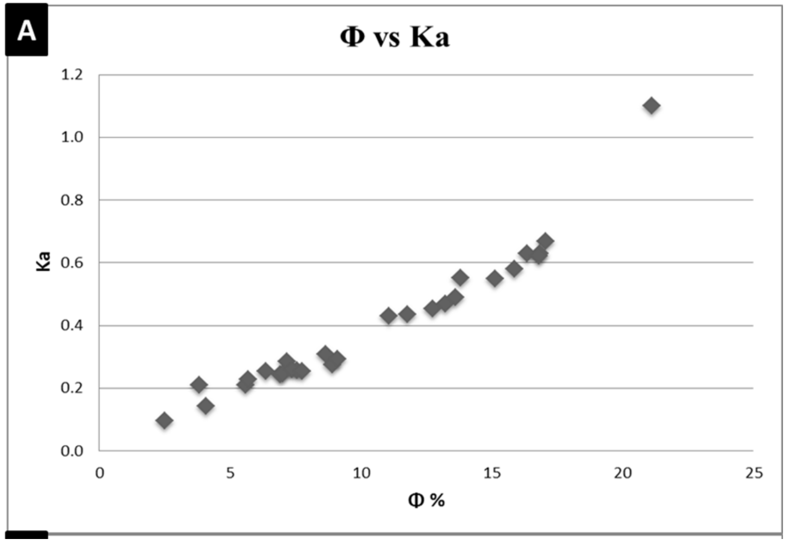
Vaslet, D., Le Nindre, Y.M., Vachard, D., Broutin, J., Crasquin-Soleau, S., Berthelin, M., Gailot, J., Halawani, M. and Al-Husseini, M. [2005] The Permian-Triassic Khuff Formation of Central Saudi Arabia.GeoArabia, 10(4), 77-134.

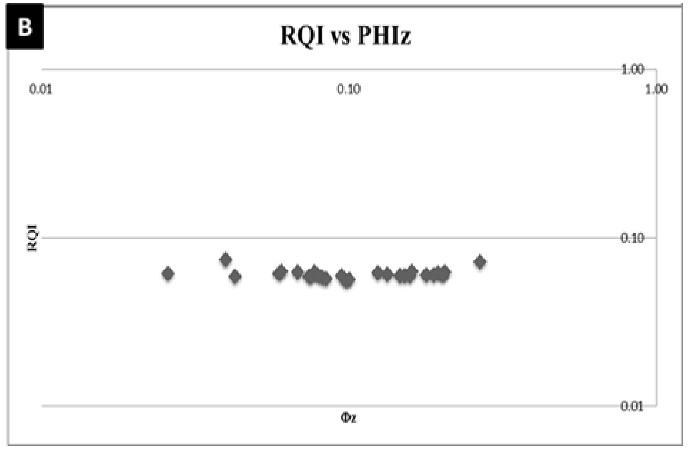
Acknowledgments: The authors would like to acknowledge the support provided by King Abdulaziz City for Science and Technology (KACST) through the Science and Technology Unit at King Fahd University of Petroleum and Minerals (KFUPM) for funding this work through the project NSTIP-14-OIL310-04 as part of the National Science, Technology and Innovation Plan. Also, would like to acknowledge the support provided by the College of Petroleum Engineering and Geosciences at KFUPM for their support.

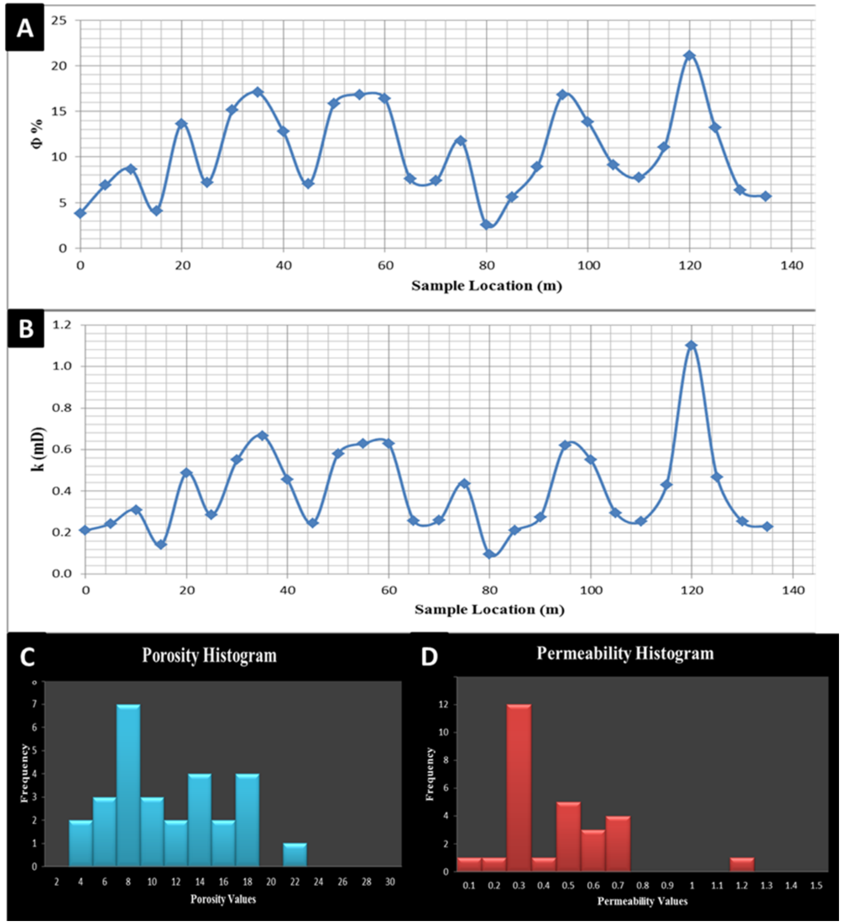
Reservoir Unit A

Sample Location (m)	Fractional Φ	ϕ (%)	Ka (md)	RQI	ϕz	FZI
0	0.0383	3.8270	0.2103	0.0736	0.0398	1.8498
5	0.0691	6.9100	0.2432	0.0589	0.0742	0.7936
10	0.0867	8.6730	0.3083	0.0592	0.0950	0.6234
15	0.0409	4.0910	0.1432	0.0587	0.0427	1.3773
20	0.1363	13.6340	0.4885	0.0594	0.1579	0.3765
25	0.0719	7.1920	0.2852	0.0625	0.0775	0.8069
30	0.1513	15.1310	0.5496	0.0598	0.1783	0.3357
35	0.1705	17.0540	0.6673	0.0621	0.2056	0.3021
40	0.1276	12.7620	0.4544	0.0593	0.1463	0.4050
45	0.0703	7.0290	0.2458	0.0587	0.0756	0.7767
50	0.1587	15.8680	0.5804	0.0601	0.1886	0.3184
55	0.1683	16.8300	0.6283	0.0607	0.2024	0.2998
60	0.1636	16.3580	0.6300	0.0616	0.1956	0.3151
65	0.0757	7.5710	0.2574	0.0579	0.0819	0.7068
70	0.0736	7.3630	0.2599	0.0590	0.0795	0.7422
75	0.1177	11.7740	0.4361	0.0604	0.1335	0.4528
80	0.0252	2.5190	0.0947	0.0609	0.0258	2.3560
85	0.0559	5.5930	0.2099	0.0608	0.0592	1.0268
90	0.0891	8.9130	0.2739	0.0550	0.0979	0.5625
95	0.1680	16.7970	0.6214	0.0604	0.2019	0.2992
100	0.1381	13.8120	0.5505	0.0627	0.1603	0.3912
105	0.0912	9.1200	0.2936	0.0563	0.1004	0.5614
110	0.0777	7.7650	0.2541	0.0568	0.0842	0.6747
115	0.1107	11.0690	0.4292	0.0618	0.1245	0.4968
120	0.2111	21.1140	1.1014	0.0717	0.2677	0.2679
125	0.1323	13.2330	0.4677	0.0590	0.1525	0.3871
130	0.0638	6.3760	0.2529	0.0625	0.0681	0.9183
135	0.0570	5.6960	0.2290	0.0630	0.0604	1.0424

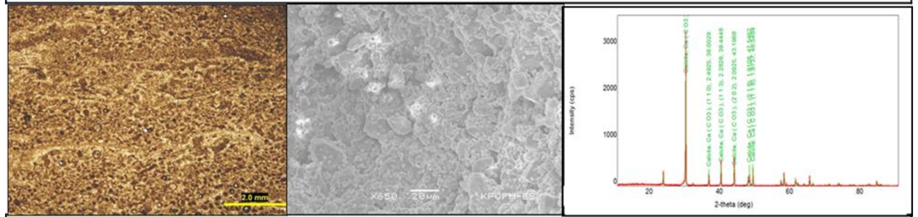
Statistical Parameters	Φ statistics	K statistics
m	10.5026	0.3988
S	4.8619	0.2154
Max.	21.1140	1.1014
M	9.0165	0.3010
Min.	2.5190	0.0947
S²	23.6385	0.0464



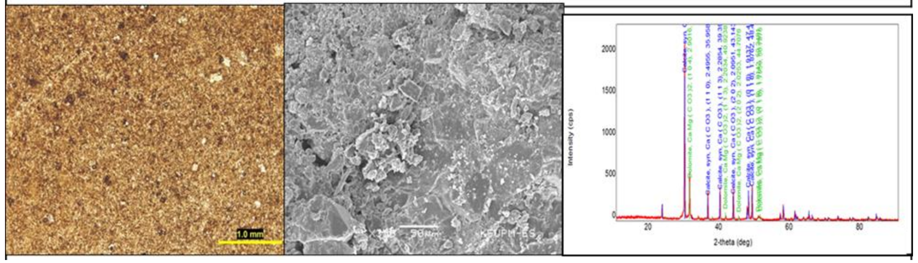




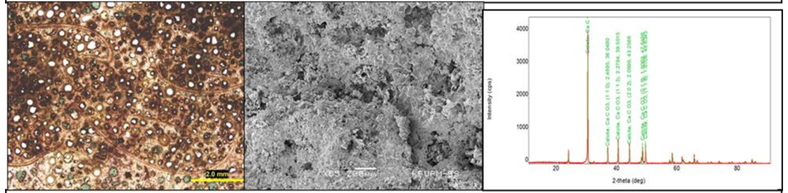
A – 80; Φ: 2.5 %, κ: 0.08 mD



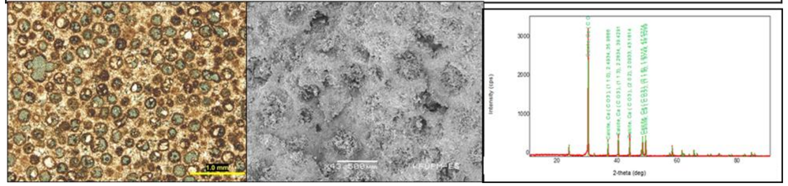
A – 25; Φ: 7.2 %, κ: 0.28 mD



A – 50; Φ: 15.8 %, κ: 0.58 mD



A – 120; Φ: 21 %, κ: 1.1 mD



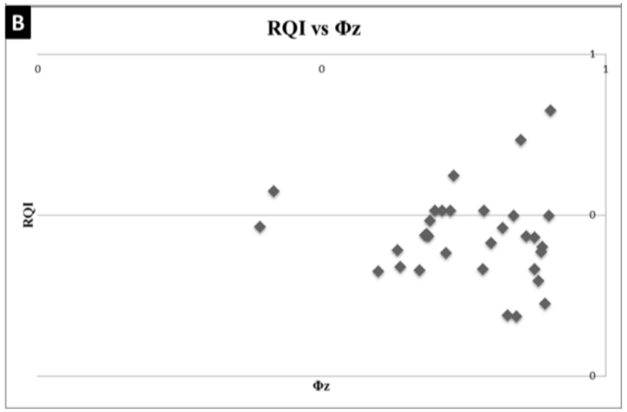
Reservoir Unit B

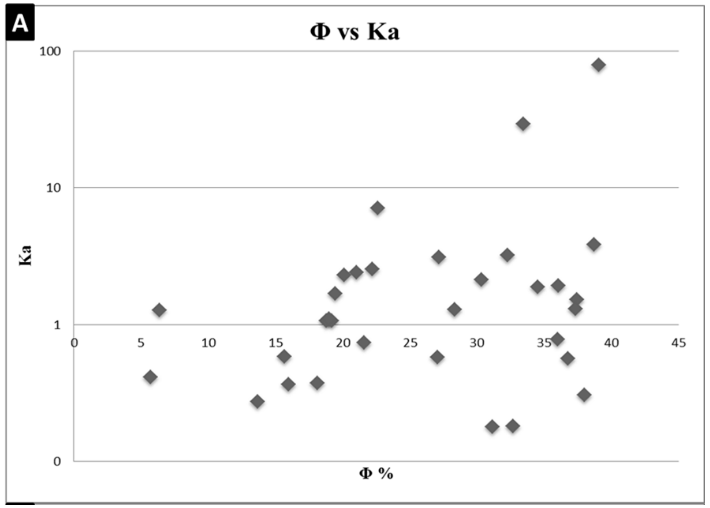
A

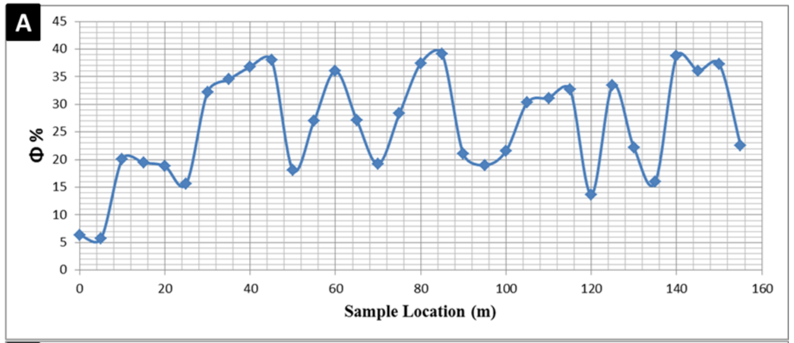
Sample Location (m)	Fractional Φ	ϕ (%)	Ka (md)	RQI	ϕz	FZI
0	0.0638	6.3760	1.2810	0.1407	0.0681	2.0667
5	0.0572	5.7240	0.4122	0.0843	0.0607	1.3878
10	0.2010	20.1040	2.2956	0.1061	0.2516	0.4217
15	0.1945	19.4545	1.6804	0.0923	0.2415	0.3821
20	0.1881	18.8050	1.0651	0.0747	0.2316	0.3227
25	0.1567	15.6680	0.5832	0.0606	0.1858	0.3261
30	0.3226	32.2570	3.2061	0.0990	0.4762	0.2079
35	0.3453	34.5255	1.8870	0.0734	0.5273	0.1392
40	0.3679	36.7940	0.5678	0.0390	0.5821	0.0670
45	0.3800	38.0020	0.3056	0.0282	0.6130	0.0459
50	0.1814	18.1350	0.3760	0.0452	0.2215	0.2041
55	0.2707	27.0680	0.5779	0.0459	0.3711	0.1236
60	0.3600	36.0010	0.7797	0.0462	0.5625	0.0821
65	0.2717	27.1660	3.1057	0.1062	0.3730	0.2846
70	0.1921	19.2140	1.0636	0.0739	0.2378	0.3106
75	0.2833	28.3340	1.2909	0.0670	0.3954	0.1695
80	0.3745	37.4540	1.5181	0.0632	0.5988	0.1056
85	0.3909	39.0890	78.4389	0.4448	0.6417	0.6931
90	0.2102	21.0190	2.3965	0.1060	0.2661	0.3984
95	0.1901	19.0080	1.1086	0.0758	0.2347	0.3231
100	0.2158	21.5780	0.7391	0.0581	0.2752	0.2112
105	0.3033	30.3330	2.1247	0.0831	0.4354	0.1909
110	0.3116	31.1570	0.1785	0.0238	0.4526	0.0525
115	0.3270	32.7010	0.1819	0.0234	0.4859	0.0482
120	0.1369	13.6920	0.2755	0.0445	0.1586	0.2808
125	0.3347	33.4700	29.1496	0.2930	0.5031	0.5825
130	0.2218	22.1830	2.5333	0.1061	0.2851	0.3722
135	0.1597	15.9690	0.3681	0.0477	0.1900	0.2509
140	0.3872	38.7200	3.8611	0.0992	0.6319	0.1569
145	0.3604	36.0350	1.9216	0.0725	0.5634	0.1287
150	0.3731	37.3090	1.3104	0.0588	0.5951	0.0989
155	0.2261	22.6100	7.0778	0.1757	0.2922	0.6013

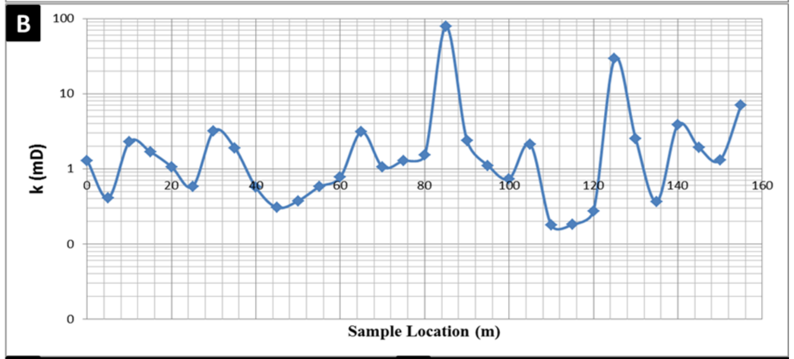
B

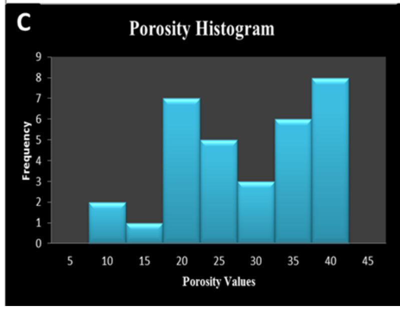
Statistical Parameters	Φ statistics	k statistics
m	26.1236	4.8019
S	9.5555	14.3629
Max.	39.0890	78.4389
M	27.1170	1.2859
Min.	5.7240	0.1785
S²	91.3073	206.2934

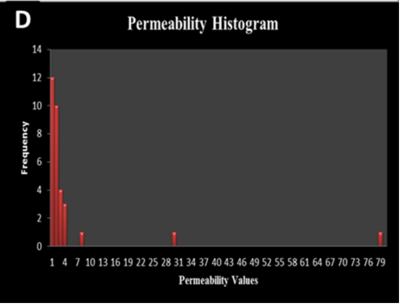




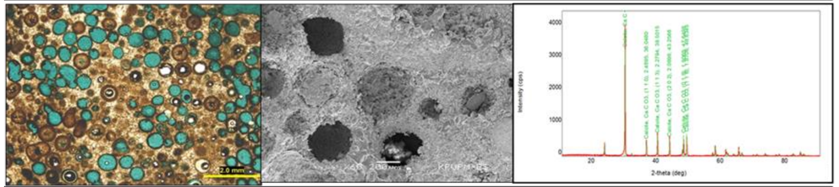




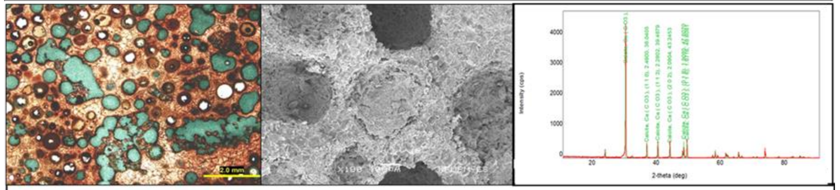




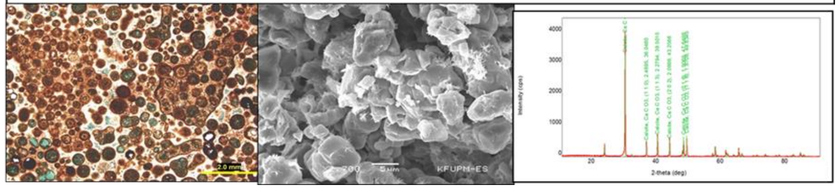
B – 125; Φ: 33.5 %, κ: 29 mD



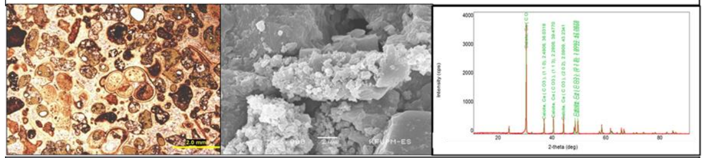
B – 145; Φ: 36 %, κ: 1.9 mD



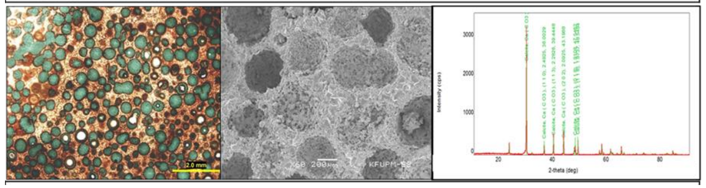
B – 155; Φ: 22.6 %, κ: 7.1 mD



B – 0; Φ: 6.4 %, κ: 1.2 mD



B – 85; Φ: 39 %, κ: 78.4 mD



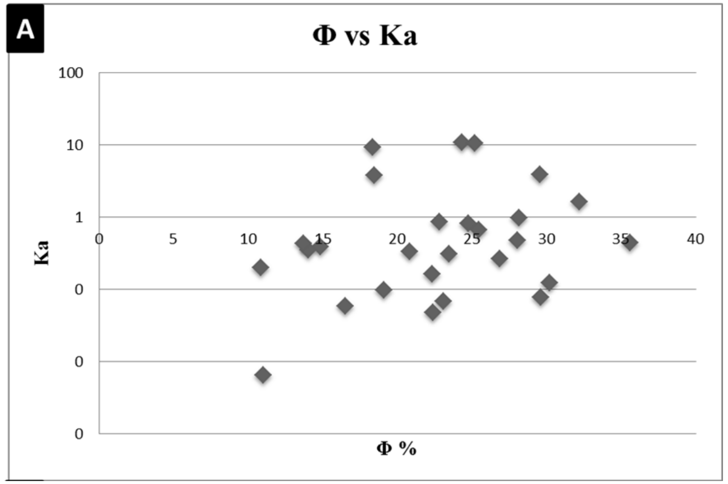
Reservoir Unit C

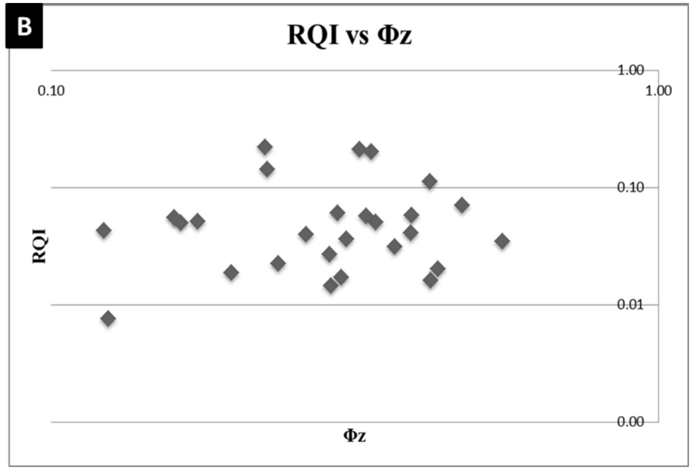
A

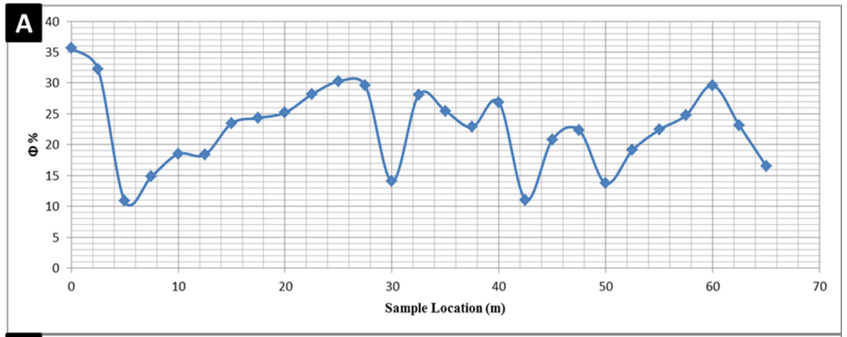
Sample Location (m)	Fractional Φ	ϕ (%)	Ka (md)	RQI	ϕz	FZI
0	0.3563	35.6280	0.4373	0.0348	0.5535	0.0629
2.5	0.3222	32.2170	1.6006	0.0700	0.4753	0.1473
5	0.1088	10.8760	0.1987	0.0424	0.1220	0.3478
7.5	0.1484	14.8430	0.3902	0.0509	0.1743	0.2921
10	0.1849	18.4850	3.7866	0.1421	0.2268	0.6267
12.5	0.1837	18.3710	9.1524	0.2216	0.2251	0.9848
15	0.2346	23.4600	0.3107	0.0361	0.3065	0.1179
17.5	0.2433	24.3275	10.8113	0.2093	0.3215	0.6511
20	0.2520	25.1950	10.5006	0.2027	0.3368	0.6019
22.5	0.2814	28.1390	0.9615	0.0580	0.3916	0.1482
25	0.3024	30.2390	0.1240	0.0201	0.4335	0.0464
27.5	0.2958	29.5840	3.8164	0.1128	0.4201	0.2684
30	0.1404	14.0370	0.3476	0.0494	0.1633	0.3026
32.5	0.2808	28.0830	0.4774	0.0409	0.3905	0.1048
35	0.2547	25.4680	0.6635	0.0507	0.3417	0.1483
37.5	0.2285	22.8530	0.8496	0.0605	0.2962	0.2044
40	0.2687	26.8680	0.2673	0.0313	0.3674	0.0852
42.5	0.1105	11.0470	0.0065	0.0076	0.1242	0.0613
45	0.2082	20.8170	0.3331	0.0397	0.2629	0.1511
47.5	0.2234	22.3360	0.1617	0.0267	0.2876	0.0929
50	0.1373	13.7320	0.4288	0.0555	0.1592	0.3486
52.5	0.1910	19.1030	0.0975	0.0224	0.2361	0.0950
55	0.2241	22.4070	0.0471	0.0144	0.2888	0.0499
57.5	0.2479	24.7910	0.8099	0.0568	0.3296	0.1722
60	0.2962	29.6230	0.0781	0.0161	0.4209	0.0383
62.5	0.2308	23.0805	0.0683	0.0171	0.3001	0.0569
65	0.1654	16.5380	0.0585	0.0187	0.1982	0.0942

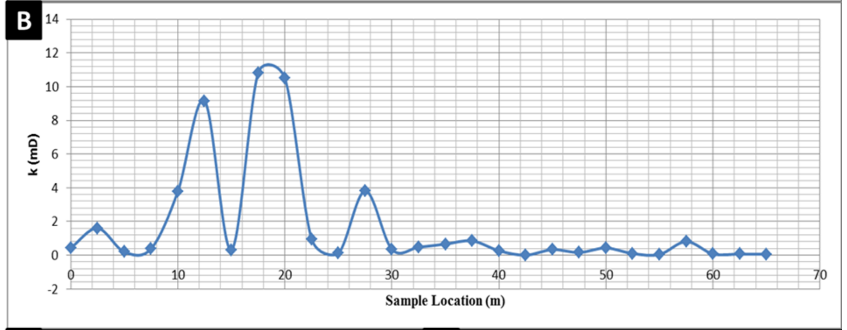
B

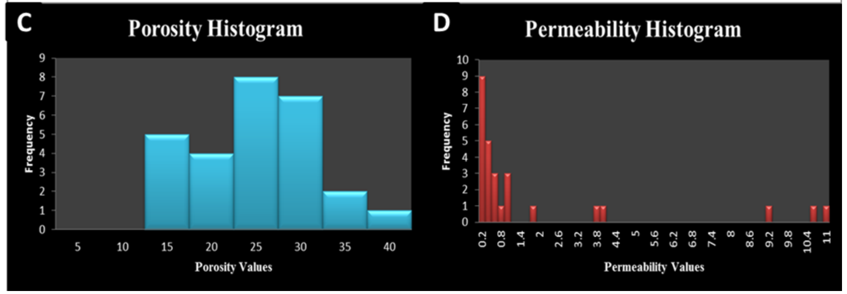
Statistical Parameters	Φ statistics	k statistics
m	22.6721	1.7328
S	6.4790	3.1944
Max.	35.6280	10.8113
M	23.0805	0.3902
Min.	0.0692	0.0065
S²	41.9772	9.8265



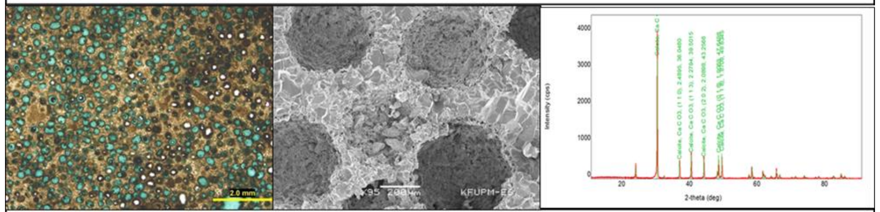




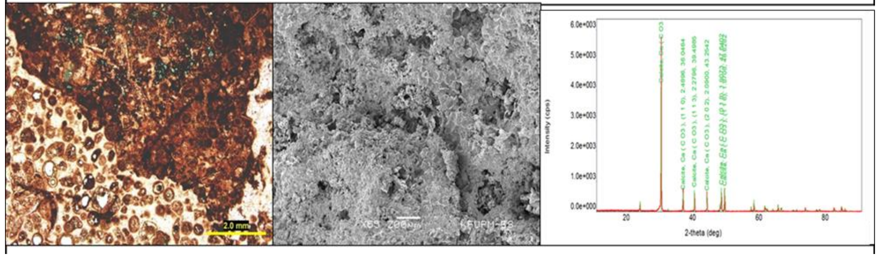




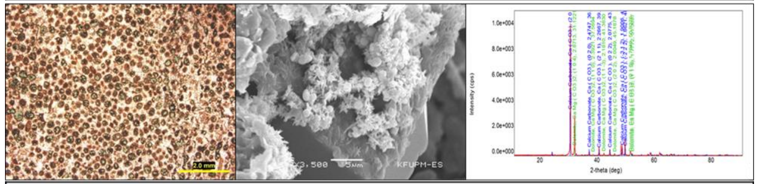
C – 0; Φ: 35.6 %, κ: 0.43 mD



C – 5; Φ: 10.8 %, κ: 0.19 mD



C – 10; Φ: 18.5 %, κ: 3.7 mD



C – 20; Φ: 25.2 %, κ: 10.5 mD