CHAPTER SIX

RESERVOIR QUALITY

Chapter Six

Reservoir Quality

Porosity and permeability are the two critical parameters that control the reservoir quality of a sandstone. Prediction of reservoir quality (as controlled by porosity and permeability) of a target sandstone is a valuable exploration tool. Once a discovery is made, porosity and permeability are necessary to estimate pore volume, hydrocarbon pore volume, recoverable reserves, production rates and well spacing. Porosity and permeability are also key parameters in basin modeling. Such models help to interpret the sedimentary, hydrodynamic, geochemical and tectonic processes that affected a given area over geologic time (Bloch and Helmold, 1995).

In the present work, helium porosity and air permeability, together with grain and bulk densities, for 60 cylindrical plugs approximately 2.5 cm by 2.5 cm were measured (Table 6.1) to assess the hydrocarbon reservoir quality of the surface sandstone. Porosity, permeability (both vertical and horizontal) and grain density data (provided by Suez Oil Company) were used in assessing the reservoir quality of the subsurface sandstone. These data (Table 6.2) consist of measurements made on plugs cut at intervals of about one foot from cores of six wells intersecting the reservoir.

In addition to the above-mentioned datasets, point-counted porosity data for one hundred and three thin sections (Table 4.4) were also used in assessing the reservoir quality of the studied surface and subsurface sandstones. These data have also been used to consider the effect of diagenesis on the reservoir quality of the studied surface and subsurface

Table 6.1: Petrophysical parameters of the studied surface sandstone.

S. No.	P Ø%	Ts Ø%	Micro Ø%	K (md)	σg (g/cc)	σb (g/cc)	PI
1- Araba Formation							
1	21.4	2.5	18.9	162	2.63	2.07	1.27
2	15.0	1.7	13.4	19	2.69	2.28	1.18
4	11.0	11.5	-0.5	19	2.67	2.38	1.12
5	20.3	3.3	17.0	57	2.60	2.07	1.25
6	21.5	1.3	20.3	49	2.63	2.06	1.27
7	21.2	8.5	12.7	75	2.57	2.02	1.27
8	24.7	4.5	20.2	73	2.62	1.97	1.33
9	12.3	0.0	12.3	3	2.68	2.35	1.14
10	15.3	0.3	15.0	11	2.61	2.21	1.18
11	15.5	3.0	12.5	32	2.60	2.20	1.18
Max	24.7	11.5	20.3	162	2.69	2.38	1.33
Min	11.0	0.0	12.3	3	2.57	1.97	1.12
Avg	17.8	3.6	15.8	50	2.63	2.16	1.22
2- Naqus Formation							
12	-	24.0	-	-	-	-	-
13	19.2	12.3	6.9	240	2.62	2.12	1.24
14	23.5	-	-	276	2.61	2.00	1.31
15	24.8	17.3	7.6	657	2.59	1.95	1.33
18	-	12.3	-	-	-	-	-
21	24.8	-	-	959	2.62	1.97	1.33
22	24.5	23.0	1.5	839	2.62	1.98	1.32
23	24.6	-	-	664	2.62	1.98	1.33
25	-	12.3	-	-	-	-	-
26	8.3	-	-	1	2.54	2.33	1.09
28	-	15.5	-	-	-	-	-
29	19.3	-	-	-	2.42	1.95	1.24
31	-	25.0	-	-	-	-	-
32	25.3	18.3	7.0	1102	2.62	1.96	1.34
35	14.3	5.0	9.3	29	2.54	2.18	1.17
39	18.2	3.5	14.7	36	2.62	2.15	1.22
40	22.8	11.5	11.3	732	2.63	2.03	1.30
41	23.3	-	-	-	2.61	2.01	1.30
43	12.6	0.0	12.6	2	2.60	2.27	1.14
47	-	25.0	-	-	-	-	-
48	23.6	-	-	-	2.48	1.89	1.31
51	18.9	5.0	13.9	62	2.63	2.13	1.23
52	26.3	24.3	2.0	2422	2.62	1.93	1.36
54	24.8	-	-	4234	2.63	1.98	1.33
55	26.0	27.8	-1.8	3512	2.61	1.94	1.35

P Ø =Helium porosity, Ph Ø =Horizontal helium porosity, Pv Ø =Vertical helium porosity, Ts Ø =Thin-section porosity, Micro Ø =Microporosity, K =Permeability, Kh =Horizontal permeability, Kv =Vertical permeability, σb =Bulk density, σg =Grain density, PI=Packing index

Table 6.1*(continued)*: Petrophysical parameters of the studied surface sandstone.

S. No.	P Ø%	Ts Ø%	Micro Ø%	K (md)	σg (g/cc)	σb (g/cc)	PI
58	27.4	27.8	-0.3	2986	2.63	1.91	1.38
59	27.0	-	-	1826	2.61	1.91	1.37
61	17.9	8.5	9.4	22	2.62	2.15	1.22
62	23.5	18.5	5.0	2875	2.61	2.00	1.31
64	24.2	-	-	989	2.62	1.98	1.32
65	24.7	22.5	2.2	1323	2.63	1.98	1.33
67	25.1	19.5	5.6	13975	2.62	1.97	1.33
70	-	3.8	-	-	-	-	-
73	-	4.5	-	-	-	-	-
76	24.4	15.5	8.9	367	2.61	1.97	1.32
77	21.2	-	-	-	2.43	1.92	1.27
78	25.0	-	-	276	2.61	1.96	1.33
79	-	16.3	-	-	-	-	-
80	24.3	21.5	2.8	388	2.59	1.96	1.32
82	23.2	-	-	305	2.63	2.02	1.30
83	-	17.5	-	-	-	-	-
84	24.1	-	-	442	2.64	2.00	1.32
85	-	23.8	-	-	-	-	-
86	25.6	22.5	3.1	650	2.63	1.95	1.34
87	23.5	19.3	4.2	292	2.64	2.02	1.31
90	26.1	22.5	3.6	16325	2.62	1.93	1.35
91	23.9	-	-	1282	2.58	1.96	1.31
92	24.1	22.0	2.1	783	2.64	2.01	1.32
93	23.4	-	-	627	2.64	2.02	1.31
94	22.5	23.8	-1.3	840	2.63	2.04	1.29
96	27.8	20.5	7.3	1565	2.63	1.90	1.39
98	27.1	23.5	3.6	949	2.64	1.93	1.37
99	-	19.5	-	-	-	-	-
100	25.3	21.8	3.5	2541	2.64	1.97	1.34
101	24.0	-	-	4056	2.64	2.01	1.32
102	23.8	19.8	4.1	4647	2.63	2.01	1.31
103	24.2	-	-	2823	2.64	2.00	1.32
104	24.2	21.3	2.9	10075	2.64	2.00	1.32
106	22.7	19.5	3.2	2753	2.64	2.04	1.29
108	24.6	-	-	6643	2.65	1.99	1.33
110	24.1	26.3	-2.2	19526	2.64	2.01	1.32
111	23.0	17.0	6.0	11719	2.64	2.03	1.30
Max	27.8	27.8	14.7	19526	2.65	2.33	1.39
Min	8.3	0.0	1.5	1	2.42	1.89	1.09
Avg	23.1	17.7	6.1	2818	2.61	2.01	1.30

P Ø =Helium porosity, Ph Ø =Horizontal helium porosity, Pv Ø =Vertical helium porosity, Ts Ø =Thin-section porosity, Micro Ø =Microporosity, K =Permeability, Kh =Horizontal permeability, Kv =Vertical permeability, σb =Bulk density, σg =Grain density, PI=Packing index

Table 6.2: Petrophysical parameters of the studied subsurface sandstone.

S No	Ph Ø%	Pv Ø%	Kh (md)	Kv (md)	ρg (g/cc)
1	2.50	-	0.02	-	2.68
2	4.30	5.90	0.22	1.02	2.65
3	6.70	8.40	2.10	1.40	2.65
4	8.90	7.80	48.00	15.00	2.65
5	8.86	7.90	8.20	2.70	2.66
6	6.60	5.10	1.80	0.54	2.66
7	8.80	6.70	7.70	19.00	2.66
8	4.80	4.50	2.30	0.72	2.66
9	2.70	6.50	0.09	1.40	2.66
10	1.90	1.80	11.00	0.07	2.62
11	4.90	3.90	0.71	0.22	2.64
12	4.70	4.00	0.14	0.12	2.64
13	3.30	7.00	0.47	2.80	2.59
14	3.60	2.80	0.89	0.28	2.57
15	4.70	4.10	2.00	0.15	2.67
16	4.40	4.60	0.35	0.31	2.68
17	7.80	6.60	0.62	0.33	2.67
18	7.20	9.20	0.68	1.30	2.66
19	4.20	1.60	0.23	0.24	2.65
20	4.90	2.00	9.30	8.50	2.65
21	2.20	5.00	6.50	4.00	2.65
22	4.40	6.40	1.40	5.10	2.65
23	-	3.90	-	1.50	-
24	2.90	3.60	0.21	0.19	2.65
25	11.00	-	27.00	54.00	2.64
26	11.00	-	20.00	7.20	2.65
27	10.00	-	14.00	6.10	2.65
28	10.00	-	17.00	21.00	2.63
29	10.00	-	310.00	13.00	2.64
30	11.00	-	190.00	29.00	2.65
31	12.00	-	390.00	100.00	2.65
32	12.00	-	350.00	250.00	2.65
33	10.00	-	110.00	230.00	2.65
34	12.00	-	290.00	-	2.65
35	11.00	-	93.00	54.00	2.65
36	11.00	-	130.00	120.00	2.65
37	11.00	-	120.00	180.00	2.65
38	11.00	-	220.00	-	2.65
39	12.00	-	69.00	58.00	2.65
40	11.00	-	40.00	46.00	2.65
41	11.00	-	83.00	57.00	2.65
42	11.00	-	74.00	65.00	2.65
43	11.00	-	81.00	140.00	2.65
44	11.00	-	100.00	140.00	2.65
45	11.00	-	120.00	180.00	2.65
46	11.00	-	110.00	150.00	2.67
47	10.00	-	23.00	26.00	2.64
48	11.00	-	36.00	24.00	2.64
49	11.00	-	25.00	26.00	2.65
50	11.00	-	62.00	98.00	2.65
51	11.00	-	34.00	24.00	2.65
52	8.80	-	19.00	24.00	2.64
53	8.70	-	24.00	9.80	2.64
54	11.00	-	50.00	24.00	2.65
55	11.00	-	77.00	74.00	2.65
56	12.00	-	84.00	130.00	2.65
57	11.00	-	66.00	75.00	2.65
58	11.00	-	87.00	110.00	2.65
59	12.00	-	41.00	47.00	2.65
60	11.00	-	66.00	83.00	2.65
61	9.90	-	9.80	19.00	2.65
62	11.00	-	27.00	36.00	2.66
63	10.00	-	10.00	7.80	2.64
64	12.00	-	53.00	57.00	2.68
65	10.00	-	2.50	4.80	2.65
66	11.00	-	62.00	42.00	2.64
67	11.00	-	140.00	180.00	2.65
68	10.00	-	89.00	300.00	2.65
69	8.70	-	13.00	13.00	2.65
70	12.00	-	81.00	29.00	2.65
71	11.00	-	31.00	17.00	2.65
72	11.00	-	13.00	6.50	2.65
73	11.00	-	19.00	21.00	2.65
74	11.00	-	59.00	50.00	2.65
75	13.00	-	44.00	30.00	2.76
76	10.00	-	19.00	41.00	2.66
77	11.00	-	63.00	37.00	2.65
78	11.00	-	40.00	60.00	2.65
79	11.00	-	49.00	20.00	2.64
80	11.00	-	47.00	28.00	2.64
81	11.00	-	53.00	38.00	2.65
82	11.00	-	50.00	46.00	2.64
83	11.00	-	41.00	19.00	2.64
84	10.00	-	31.00	21.00	2.64
85	12.00	-	23.00	55.00	2.65
86	11.00	-	56.00	33.00	2.65
87	11.00	-	64.00	73.00	2.65
88	10.00	-	17.00	13.00	2.68
89	12.00	-	22.00	100.00	2.63
90	11.00	-	110.00	86.00	2.66
91	7.30	-	56.00	17.00	2.70

S No	Ph Ø%	Pv Ø%	Kh (md)	Kv (md)	ρg (g/cc)
92	9.70	-	12.00	17.00	2.66
93	10.00	-	15.00	25.00	2.66
94	9.20	-	10.00	13.00	2.66
95	9.90	-	40.00	0.82	2.66
96	1.40	-	0.05	0.06	2.68
97	13 00	-	71.00	140.00	2.65
98	11.00	-	93.00	79.00	2.65
99	4.80	-	0.12	0.11	2.65
100	6.20	-	0.15	0.13	2.65
101	11.00	-	0.94	0.73	2.64
102	2.70	-	0.13	0.12	2.64
103	10.00	-	34.00	43.00	2.65
104	10.00	-	24.00	23.00	2.64
105	6.30	-	0.26	0.54	2.64
106	2.80	-	0.29	1.60	2.65
107	12.00	-	410.00	12.00	2.66
108	11.00	-	32.00	14.00	2.64
109	12.00	-	150.00	110.00	2.64
110	8.20	-	27.00	-	2.63
111	8.10	-	19.00	-	2.64
112	7.50	-	17.00	36.00	2.64
113	6.50	-	24.00	28.00	2.63
114	8.40	-	140.00	29 00	2.64
115	8.20	-	120.00	41.00	2.64
116	9.20	-	64.00	50.00	2.65
117	9.00	-	43.00	40.00	2.64
118	8.30	-	37.00	83.00	2.62
119	10.00	-	92.00	68.00	2.66
120	8.30	-	2.60	20.00	2.65
121	10.00	-	20.00	40.00	2.65
122	12.00	-	250.00	210.00	2.63
123	11.00	-	110.00	90.00	2.64
124	12.00	-	31.00	27.00	2.65
125	10.00	-	57.00	28.00	2.64
126	9.30	-	34.00	52.00	2.64
127	11.00	-	130.00	290.00	2.65
128	12.00	-	85.00	70.00	2.65
129	12.00	-	-	50.00	2.64
130	11.80	-	102.00	77.00	2.62
131	11.00	-	161.00	138.00	2.62
132	9.50	-	89.00	221.00	2.63
133	10.40	-	65.00	59.00	2.61
134	16.20	-	98.00	124.00	2.61
135	10.60	-	87.00	28.00	2.63
136	11.10	-	270.00	391.00	2.62
137	12.70	-	372.00	956.00	2.61
138	7.30	-	1.50	7.70	2.61
139	2.50	-	16.00	12.00	2.62
140	9.40	-	14.00	16.00	2.62
141	5.50	-	1.30	3.10	2.62
142	8.90	-	10.00	7.70	2.61
143	8.80	-	13.00	12.00	2.62
144	8.60	-	7.00	10.50	2.63
145	10.30	-	40.00	41.00	2.60
146	10.80	-	53.00	60.00	2.61
147	10.40	-	39.00	66.00	2.62
148	10.70	-	55.00	45.00	2.62
149	10.40	-	25.00	24.00	2.62
150	8.50	-	5.50	4.90	2.61
151	9.40	-	10.40	7.40	2.62
152	6.20	-	5.70	23.00	2.59
153	11.10	-	42.00	20.00	2.65
154	9.70	-	18.00	-	2.62
155	11.00	-	137.00	156.00	2.61
156	9.90	-	44.00	430.00	2.61
157	7.50	-	8.10	138.00	2.62
158	9.80	-	65.00	-	2.62
159	9.40	-	10.90	12.00	2.62
160	9.40	-	17.00	-	2 62
161	9.70	-	68.00	11.00	2.61
162	9.50	-	36.00	58.00	2.62
163	9.30	-	46.00	21.00	2.62
164	9.70	-	73.00	100.00	2.61
165	17.70	-	12.00	103.00	2.62
166	11.20	-	-	231.00	2.64
167	17.60	-	67.00	-	2.61
168	10.00	-	526.00	1.20	2.61
169	11.50	-	510.00	391.00	2.62
170	3.40	-	3.30	0.80	2.62
171	3.60	-	1.01	-	2.61
172	5.20	-	-	2.80	2.62
173	6.20	-	1.80	0.00	2.61
174	4.20	-	1.30	0.62	2.61
175	11.50	-	41.00	111.00	2.61
176	10.10	-	89.00	-	2.62
177	9.10	-	210.00	105.00	2.62
178	9.70	-	101.00	51.00	2.62
179	9.60	-	58.00	146.00	2.62
180	10.20	-	60.00	82.00	2.62
181	10.80	-	93.00	68.00	2.62
182	10.20	-	49 00	-	2.62

S No	Ph Ø%	Pv Ø%	Kh (md)	Kv (md)	ρg (g/cc)
183	9.60	-	36.00	38.00	2.62
184	10.30	-	34.00	24.00	2.62
185	8.70	-	67.00	80.00	2.58
186	12.20	-	143.00	182.00	2.64
187	12.10	-	202.00	196.00	2.64
188	11.30	-	167.00	163.00	2.64
189	11.70	-	106.00	159.00	2.64
190	12.00	-	93.00	89.00	2.64
191	11.70	-	123.00	211.00	2.64
192	11.70	-	140.00	106.00	2.64
193	11.40	-	72.00	62.00	2.64
194	11.30	-	69.00	72.00	2.64
195	12.00	-	177.00	127.00	2.64
196	12.20	-	213.00	192.00	2.64
197	12.40	-	136.00	72.00	2.64
198	13.10	-	91.00	62.00	2.64
199	10.40	-	39.00	100.00	2.64
200	11.40	-	87.00	134.00	2.64
201	10.60	-	82.00	99.00	2.64
202	11.80	-	110.00	175.00	2.64
203	11.50	-	144.00	3.50	2.64
204	11.60	-	108.00	187.00	2.64
205	15.00	-	73.00	197.00	2.65
206	12.50	-	109.00	144.00	2.64
207	12.10	-	87.00	108.00	2.65
208	12.20	-	199.00	122.00	2.64
209	12.50	-	175.00	227.00	2.64
210	13.20	-	128.00	188.00	2.64
211	13.10	-	113.00	282.00	2.64
212	12.90	-	83.00	111.00	2.64
213	13.20	-	262.00	120.00	2.64
214	12.80	-	109.00	168.00	2.64
215	11.80	-	15.00	29.00	2.64
216	12.20	-	95.00	112.00	2.64
217	12.40	-	95.00	208.00	2.64
218	12.80	-	73.00	176.00	2.64
219	12.10	-	191.00	245.00	2.64
220	11.60	-	87.00	119.00	2.64
221	12.90	-	106.00	256.00	2.64
222	12.50	-	73.00	116.00	2.64
223	13.20	-	93.00	183.00	2.65
224	12.60	-	60.00	99.00	2.65
225	13.40	-	109.00	194.00	2.65
226	13.20	-	235.00	162.00	2.65
227	13.10	-	114.00	231.00	2.65
228	13.10	-	93.00	186.00	2.65
229	11.50	-	58.00	55.00	2.65
230	9.90	-	46.00	64.00	2.66
231	12.30	-	172.00	85.00	2.65
232	8.80	-	18.00	59.00	2.67
233	12.80	-	151.00	120.00	2.64
234	11.20	-	94.00	104.00	2.64
235	12.40	-	94.00	70.00	2.64
236	12.40	-	121.00	148.00	2.64
237	11.80	-	51.00	85.00	2.65
238	12.10	-	112.00	131.00	2.65
239	11.60	-	67.00	131.00	2.65
240	8.60	-	-	-	2.65
241	11.70	-	90.00	141.00	2.64
242	12.40	-	80.00	75.00	2.64
243	12.10	-	80.00	224.00	2.63
244	10.90	-	11.00	73.00	2.64
245	12.80	-	101.00	15.00	2.65
246	11.10	-	6.40	5.60	2 65
247	11.00	-	6.30	3.50	2.65
248	10.40	-	5.70	5.90	2.65
249	11.10	-	8.60	7.20	2.64
250	5.70	-	0.48	0.38	2.63
251	10.00	-	2.70	1 50	2.65
252	10.30	-	4.70	2.00	2.65
253	10.80	-	5.10	1.90	2.65
254	10.70	-	3.60	5.70	2.65
255	8.10	-	13.00	20.00	2.65
256	5.40	-	8.20	3.40	2.65
257	3.00	-	-	0.53	2.65
258	9.10	-	2.10	3.60	2.65
259	5.90	-	1.40	2.50	2.67
260	12.20	-	122.00	210.00	2.65
261	8.70	-	62.00	115.00	2.65
262	11.50	-	88.00	110.00	2.65
263	11.60	-	-	27.00	2.65
264	11.80	-	154.00	20.00	2.64
265	11.80	-	209.00	187.00	2.65
266	12.60	-	184.00	523 00	2.65
267	11.30	-	108.00	275.00	2.66
268	12.50	-	397.00	532.00	2.66
269	12.00	-	115.00	222.00	2.66
270	12.60	-	160.00	164.00	2.64
271	12.10	-	111.00	540.00	2.65
272	12.40	-	138.00	403.00	2.65
273	12.10	-	163.00	266.00	2.65

Table 6.2 *(continued)*: Petrophysical parameters of the studied subsurface sandstone.

S No	Ph Ø%	Pv Ø%	Kh (md)	Kv (md)	σg (g/cc)	S No	Ph Ø%	Pv Ø%	Kh (md)	Kv (md)	σg (g/cc)	S No	Ph Ø%	Pv Ø%	Kh (md)	Kv (md)	σg (g/cc)
274	12.80	-	221.00	-	2.64	364	11.90	-	108.00	116.00	2.64	454	0.20	-	0.04	-	2.69
275	12.00	-	42.00	196.00	2.64	365	8.00	-	151.00	110.00	2.64	455	8.90	-	4.00	21.00	2.61
276	12.40	-	186.00	209.00	2.64	366	7.70	-	63.00	131.00	2.64	456	10.70	-	47.00	-	2.64
277	12.00	-	196.00	420.00	2.65	367	9.30	-	98.00	111.00	2.64	457	13.40	-	7.90	22.00	2.61
278	12.40	-	-	108.00	2.64	368	9.00	-	72.00	102.00	2.64	458	8.43	-	15.00	0.58	2.58
279	11.50	-	82.00	35.00	2.64	369	8.70	-	149.00	25.00	2.64	459	3.80	-	0.18	0.16	2.64
280	12.40	-	84.00	93.00	2.65	370	11.90	-	44.00	62.00	2.64	460	12.40	-	668.00	639.00	2.64
281	13.10	-	50.00	93.00	2.64	371	11.50	-	65.00	59.00	2.64	461	15.30	-	1270.00	1340.00	2.66
282	12.40	-	33.00	26.00	2.65	372	8.50	-	75.00	45.00	2.64	462	13.80	-	1170.00	396.00	2.64
283	11.30	-	65.00	54.00	2.64	373	12.90	-	39.00	23.00	2.64	463	13.20	-	191.00	407.00	2.64
284	11.90	-	123.00	108.00	2.64	374	10.90	-	92.00	59.00	2.64	464	13.20	-	474.00	151.00	2.65
285	12.20	-	113.00	168.00	2.65	375	10.80	-	57.00	34.00	2.64	465	11.60	-	123.00	306.00	2.66
286	8.40	-	-	-	2.65	376	10.80	-	58.00	50.00	2.64	466	2.80	-	0.07	-	2.77
287	10.00	-	19.00	-	2.64	377	12.60	-	66.00	65.00	2.64	467	0.40	-	0.04	-	2.68
288	11.00	-	49.00	48.00	2.65	378	12.60	-	64.00	79.00	2.64	468	5.70	-	0.16	0.17	2.63
289	11.70	-	67.00	-	2.64	379	10.70	-	84.00	85.00	2.64	469	8.00	-	0.19	0.14	2.66
290	12.10	-	-	-	2.65	380	11.80	-	44.00	25.00	2.64	470	3.80	-	0.08	-	2.65
291	10.00	-	27.00	-	2.64	381	11.80	-	54.00	51.00	2.64	471	3.30	-	0.13	-	2.61
292	10.50	-	35.00	-	2.63	382	11.90	-	51.00	69.00	2.64	472	4.20	-	0.22	-	2.63
293	8.40	-	5.50	-	2.65	383	12.60	-	50.00	72.00	2.64	473	5.00	-	0.09	-	2.62
294	11.60	-	92.00	-	2.64	384	11.60	-	37.00	34.00	2.64	474	7.40	-	0.19	0.38	2.63
295	11.90	-	4.80	-	2.63	385	11.20	-	312.00	5.70	2.64	475	7.00	-	0.59	0.68	2.59
296	9.80	-	7.30	-	2.64	386	12.10	-	62.00	48.00	2.64	476	8.00	-	1.01	0.52	2.61
297	11.40	-	-	131.00	2.65	387	11.30	-	39.00	46.00	2.65	477	13.90	-	80.00	66.00	2.63
298	6.90	-	1.90	2.90	2.65	388	9.90	-	45.00	40.00	2.63	478	13.80	-	52.00	33.00	2.64
299	9.20	-	10.00	0.50	2.64	389	9.80	-	71.00	28.00	2.64	479	5.60	-	0.43	0.31	2.63
300	9.80	-	86.00	107.00	2.64	390	11.90	-	105.00	32.00	2.64	480	15.00	-	246.00	257.00	2.64
301	11.50	-	40.00	-	2.64	391	11.70	-	81.00	45.00	2.65	481	15.80	-	674.00	700.00	2.64
302	11.00	-	78.00	-	2.64	392	12.70	-	156.00	297.00	2.64	482	14.00	-	127.00	109.00	2.64
303	11.40	-	443.00	561.00	2.64	393	12.50	-	71.00	48.00	2.64	483	14.60	-	261.00	400.00	2.64
304	10.60	-	22.00	-	2.65	394	12.90	-	75.00	75.00	2.64	484	15.80	-	542.00	443.00	2.64
305	10.10	-	212.00	196.00	2.64	395	10.80	-	109.00	141.00	2.64	485	14.50	-	215.00	261.00	2.65
306	10.90	-	609.00	829.00	2.65	396	10.90	-	135.00	234.00	2.64	486	3.80	-	0.83	-	3.34
307	12.90	-	809.00	475.00	2.64	397	11.10	-	110.00	76.00	2.64	487	0.81	-	-	0.04	2.65
308	12.20	-	-	222.00	2.65	398	10.60	-	202.00	54.00	2.64	488	5.10	-	0.07	-	2.70
309	10.40	-	407.00	137.00	2.65	399	11.60	-	58.00	54.00	2.64	489	3.60	-	0.05	-	2.66
310	12.10	-	162.00	133.00	2.64	400	11.90	-	135.00	90.00	2.64	490	3.50	-	0.04	-	2.68
311	12.40	-	140.00	165.00	2.64	401	13.00	-	86.00	55.00	2.64	491	0.80	-	0.07	-	2.64
312	8.90	-	49.00	46.00	2.63	402	12.60	-	71.00	57.00	2.64	492	5.50	-	0.55	0.84	2.63
313	11.00	-	37.00	51.00	2.63	403	12.70	-	76.00	73.00	2.64	493	12.60	-	110.00	67.00	2.64
314	10.10	-	337.00	41.00	2.64	404	12.60	-	60.00	41.00	2.64	494	11.90	-	40.00	33.00	2.69
315	10.10	-	6.00	39.00	2.63	405	12.70	-	45.00	106.00	2.63	495	2.70	-	1.04	0.38	2.65
316	12.90	-	65.00	59.00	2.64	406	12.80	-	54.00	90.00	2.64	496	11.20	-	72.00	222.00	2.64
317	12.90	-	64.00	53.00	2.64	407	11.50	-	60.00	46.00	2.64	497	12.40	-	40.00	369.00	2.64
318	13.00	-	112.00	98.00	2.63	408	12.60	-	110.00	54.00	2.64	498	13.60	-	323.00	143.00	2.65
319	12.80	-	28.00	23.00	2.64	409	13.40	-	88.00	51.00	2.64	499	12.90	-	342.00	184.00	2.64
320	10.50	-	10.00	4.60	2.63	410	12.90	-	92.00	53.00	2.65	500	0.60	-	0.04	-	2.67
321	13.20	-	199.00	47.00	2.64	411	12.00	-	39.00	32.00	2.64	501	4.70	-	0.38	0.54	2.65
322	12.10	-	66.00	63.00	2.64	412	12.00	-	58.00	52.00	2.64	502	9.30	-	7.90	8.90	2.64
323	9.70	-	90.00	84.00	2.64	413	12.20	-	34.00	75.00	2.64	503	12.60	-	107.00	45.00	2.65
324	12.10	-	50.00	44.00	2.64	414	11.80	-	96.00	85.00	2.63	504	10.20	-	35.00	243.00	2.64
325	13.50	-	35.00	24.00	2.64	415	12.00	-	59.00	39.00	2.64	505	12.70	-	83.00	247.00	2.64
326	12.20	-	38.00	24.00	2.64	416	12.00	-	70.00	56.00	2.64	506	3.40	-	0.34	-	2.64
327	13.20	-	48.00	46.00	2.65	417	11.40	-	55.00	42.00	2.64	507	11.20	-	8.40	39.00	2.65
328	12.70	-	54.00	50.00	2.63	418	11.80	-	73.00	63.00	2.64	508	10.90	-	97.00	65.00	2.64
329	11.70	-	32.00	32.00	2.64	419	12.10	-	149.00	36.00	2.64	509	3.50	-	1.12	0.39	2.64
330	11.20	-	50.00	39.00	2.64	420	12.10	-	37.00	35.00	2.64	510	1.30	-	0.12	0.31	2.63
331	12.10	-	43.00	30.00	2.64	421	12.20	-	29.00	20.00	2.64	511	10.10	-	46.00	2.30	2.61
332	12.80	-	40.00	54.00	2.64	422	12.30	-	36.00	24.00	2.64	512	7.10	-	1.60	1.30	2.60
333	12.90	-	26.00	4.50	2.63	423	12.30	-	29.00	22.00	2.67	513	11.40	-	63.00	31.00	2.66
334	13.00	-	67.00	51.00	2.64	424	12.10	-	35.00	31.00	2.64	514	12.60	-	313.00	332.00	2.65
335	11.20	-	84.00	31.00	2.64	425	12.90	-	50.00	42.00	2.64	515	11.60	-	36.00	86.00	2.66
336	12.10	-	46.00	49.00	2.63	426	13.30	-	30.00	1.80	2.64	516	6.82	-	-	1.40	2.59
337	12.20	-	37.00	50.00	2.64	427	13.40	-	215.00	61.00	2.64	517	7.60	-	7.50	1.80	2.61
338	12.80	-	46.00	55.00	2.64	428	12.30	-	20.00	121.00	2.64	518	4.80	-	1.80	-	2.63
339	13.20	-	47.00	56.00	2.63	429	12.90	-	98.00	438.00	2.63	519	6.00	-	1.90	0.78	2.65
340	13.40	-	65.00	56.00	2.63	430	12.10	-	152.00	15.00	2.63	520	11.20	-	55.00	21.00	2.65
341	12.80	-	60.00	38.00	2.64	431	11.90	-	326.00	292.00	2.64	521	11.50	-	7.70	124.00	2.65
342	12.60	-	62.00	74.00	2.63	432	13.20	-	170.00	372.00	2.63	522	10.20	-	51.00	36.00	2.64
343	12.10	-	53.00	46.00	2.63	433	13.40	-	220.00	365.00	2.63	523	5.90	-	0.79	0.87	2.65
344	12.50	-	56.00	72.00	2.63	434	20.20	-	49.00	13.00	2.63	524	8.70	-	123.00	64.00	2.58
345	12.30	-	64.00	39.00	2.64	435	12.80	-	220.00	292.00	2.64	525	12.30	-	226.00	181.00	2.67
346	11.90	-	70.00	63.00	2.63	436	12.10	-	127.00	42.00	2.64	526	12.80	-	328.00	169.00	2.66
347	12.20	-	65.00	72.00	2.63	437	5.40	-	1.30	1.50	2.63	527	14.50	-	451.00	291.00	2.67
348	12.30	-	69.00	59.00	2.64	438	14.20	-	241.00	256.00	2.64	528	12.60	-	225.00	89.00	2.66
349	12.40	-	54.00	40.00	2.64	439	14.00	-	236.00	70.00	2.64	529	0.80	-	0.03	0.03	2.63
350	12.40	-	71.00	73.00	2.64	440	13.90	-	267.00	237.00	2.64	530	0.22	-	-	0.04	2.62
351	12.90	-	54.00	51.00	2.64	441	13.60	-	415.00	465.00	2.64	531	0.63	-	0.05	-	2.60
352	12.40	-	84.00	72.00	2.64	442	12.40	-	422.00	285.00	2.64	532	4.20	-	0.68	-	2.61
353	11.80	-	42.00	56.00	2.64	443	12.90	-	374.00	275.00	2.64	533	10.10	-	5.00	22.00	2.65
354	12.40	-	61.00	43.00	2.64	444	13.80	-	271.00	356.00	2.65	534	4.90	-	0.24	-	2.66
355	12.50	-	45.00	45.00	2.64	445	13.50	-	283.00	378.00	2.64	535	14.60	-	1.09	-	2.61
356	12.30	-	40.00	37.00	2.64	446	12.80	-	186.00	269.00	2.64	536	12.00	-	167.00	142.00	2.65
357	8.50	-	43.00	134.00	2.64	447	13.40	-	186.00	417.00	2.65	537	12.00	-	86.00	35.00	2.65
358	12.40	-	42.00	54.00	2.64	448	12.20	-	153.00	546.00	2.64	538	12.30	-	18.00	37.00	2.65
359	12.10	-	64.00	104.00	2.64	449	12.40	-	299.00	341.00	2.64	539	13.10	-	101.00	160.00	2.65
360	10.80	-	67.00	54.00	2.64	450	12.30	-	412.00	382.00	2.64	540	12.80	-	83.00	-	2.66
361	10.50	-	353.00	17.00	2.64	451	13.50	-	364.00	228.00	2.64	541	11.30	-	124.00	-	2.64
362	11.10	-	98.00	283.00	2.64	452	10.90	-	43.00	9.70	2.63	542	7.80	-	7.80	-	2.64
363	12.10	-	144.00	102.00	2.64	453	0.20	-	0.05	0.04	2.63						
												Max	20.2	9.2	1270.0	1340.0	3.34
												Min	0.2	1.6	0.0	0.0	2.57
												Avg	10.4	5.2	92.4	100.3	2.64

sandstones, by assessing the effect of diagenetic processes whether reduce or enhance porosity and permeability.

6.1 Petrophysical parameters

Petrophysical measurements yielded fundamental information about the storage capacity for reservoir fluids (porosity), flow capacity (permeability) and the density properties of the studied sandstones. A brief description of these parameters is given below.

6.1.1 Porosity

Porosity in sandstones is the aggregate total of all the openings or interstices in a rock framework and within grains. The interstices are individually referred to as pores. Porosity is normally expressed as percentage (or fraction) of the bulk rock volume. In the present study, porosity was measured petrophysically by using a helium porosimeter and also in thin sections by point counting.

Helium porosity of the studied sandstones was measured at surface pressure conditions. In Naqus Sandstone, helium porosity ranges from 8.3 % to 27.8 % with an average of 23.1 % (Table 6.1). About 84 % of Naqus samples have porosity greater than 20 %. Sandstone of this porosity magnitude makes it as an excellent reservoir rock. In Araba Sandstone, helium porosity ranges from 11.0 % to 24.7 % with an average of 17.8 % (Table 6.1). This sandstone has a high content of kaolinite cement (Table 4.1) and its porosity is usually intercrystalline. On the other hand, helium porosity in the subsurface sandstone ranges from 0.2 % to 20.2 % with an average of 10.4 % (Table 6.2).

In thin sections, porosity was also evaluated by point counting. Thin section porosity in Naqus Sandstone ranges from 0.0 % to 27.8 % with an average of 17.7 %, while in Araba Sandstone it varies from 0.0 % to 11.5 % with a mean value of 3.6 % (Table 6.1). On the other hand, thin section porosity in the subsurface sandstone ranges from 0.0 % to 14.8 % with an average of 4.9 % (Table 6.2).

6.1.2 Microporosity

In the studied thin sections, only relatively large pores were observed (macropores). Many pores, such as those within authigenic clay crystals, are only several microns in size, and go unnoticed in thin section. These small pores are called micropores. When these areas of clay-filled microporosity were intersected on a point-counting traverse, they were counted as authigenic clay. This microporosity was measured by porosimeter. Therefore, helium porosity is almost greater than thin section porosity for the same sample. Microporosity was calculated by subtracting macroporosity measured in thin sections from helium porosity measured by porosimeter (Table 6.1).

In the investigated Naqus samples, microporosity ranges from 1.5 % to 14.7 % with an average of 6.1 % and from 12.3 % to 20.3 % with an average of 15.8 % in the studied Araba samples (Table 6.1). Negative microporosity values result from the calculation procedure and are unreasonable values. Slight sample heterogeneities explain these values. Micropores are, predictably, more abundant in samples with kaolinite cement. A cross plot of microporosity versus kaolinite shows a good positive linear relationship (correlation coefficient $r = 0.76$ and 0.75 for Naqus and Araba sandstones, respectively, Fig. 6.1A). No attempt was made to calculate the microporosity of the subsurface sandstone because most of the thin sections were made from rocks few centimeters from the place where helium porosity was measured.

Clay microporosity data are used to calculate effective pore volumes and volumes of clay-bound water (irreducible water) for clay minerals in sandstones. Converting from weight percent clay to volume percent clay is important. Microporosity data are valuable input to shale volume (V_{shale}) evaluation where water saturation is associated with clay mineral type, texture and volume. In a reservoir, one needs to consider possible capillary pressure characteristics of microporosity, because the water preserved in reservoir pore systems is a function of what the buoyant force of the hydrocarbon phase can displace. Clay micropores that are entirely water-bearing in an oil reservoir may contain gas in reservoirs with large hydrocarbon columns. Independent of which phase is saturating the micropores, quantification of clay microporosity provides valuable information for evaluating fluid saturation and reservoir performance characteristics (cf. Hurst and Nadeau, 1995).

6.1.3 Permeability

Permeability is the ability of fluids to pass through a porous material. Reservoir quality of a target sandstone reservoir (as controlled by permeability K in millidarcy) has been classified by Levorsen (1967) into:

1- Poor $K < 1$

2- Fair $1 < K < 10$

3- Moderate $10 < K < 50$

4- Good $50 < K < 250$

5- Very good $K > 250$

Air permeability of the studied sandstones was measured at surface pressure conditions. In Naqus Sandstone, permeability ranges from 1 md to 19526 md with an average of 2818 md (Table 6.1). About 46 % of Naqus samples have permeability greater than 1000 md. Sandstone having this permeability magnitude makes an excellent reservoir rock. Likewise, in Araba Sandstone, permeability ranges from 3 md to 162 md with an average of 50 md (Table 6.1). 50 % of Araba samples have permeability values between 10 and 50 md indicating moderate reservoir quality. The subsurface sandstone has a horizontal permeability ranging from 0.0 md to 1270 md and averaging 92 md. On the other hand, vertical permeability in the subsurface sandstone varies from 0.0 md to 1340 md with an average of 100 md (Table 6.2). Sandstone having this permeability magnitude makes a good reservoir rock. In the subsurface sandstone, average vertical permeability is slightly higher than average horizontal permeability. This slight difference is probably due to the presence of small-scale open vertical fractures (PL. 3.4F), which enhance vertical permeability. These fractures are sometimes only detectable in thin section (hairline fractures).

6.1.4 Rock density properties

Density of any solid phase is the mass of its unit volume. Rocks, in addition to their mineral contents, contain a certain quantity of voids or spaces filled by fluids. A new term called apparent specific gravity, which is the mass of a unit volume of an absolutely dry rock of known porosity, has been introduced to describe the density properties of a rock.

Rock density is controlled by many factors, among them are: mineral composition, porosity and fluid saturation. The density of a rock can be classified into two main types, bulk density and grain density.

6.1.4.1 Bulk density (σb, gm/cc)

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

$\sigma b = m / v$

where

σb = bulk density

m = mass of the sample

v = volume of the sample

Bulk density of Naqus Sandstone varies from 1.89 gm/cc to 2.33 gm/cc with 2.01 gm/cc as a mean value, while in Araba Sandstone it ranges from 1.97 gm/cc to 2.38 gm/cc with an average of 2.16 gm/cc (Table 6.1).

6.1.4.2 Grain density (σg, gm/cc)

The grain density of a rock is defined as the mass of a unit volume of the solid phase of the rock (grains and/or crystals). The grain density is a sensitive measure to indicate the mineral composition of a rock. It also helps evaluation of the cement materials and indicates the presence of impurities. Grain density can be expressed as:

ρg = wd / vg

where

ρg = grain density

wd = sample dry weight

vg = grain volume

Grain density of Naqus Sandstone varies from 2.42 gm/cc to 2.65 gm/cc with a mean value of 2.61 gm/cc, while in Araba Sandstone it ranges from 2.57 gm/cc to 2.69 gm/cc with a mean value of 2.63 gm/cc (Table 6.1). On the other hand, grain density in the subsurface sandstone ranges from 2.57 gm/cc to 3.34 gm/cc with an average of 2.64 gm/cc (Table 6.2). The high values of grain density of some samples are attributed to the presence of iron minerals (mostly hematite), while the low values of others may be attributed to the presence of clay minerals (particularly kaolinite).

6.1.4.3 Packing index

Packing Index (PI) is defined as the ratio between grain density and bulk density. It can be expressed as:

PI = σg / σb

where

PI = packing index

σg = grain density, gm/cc

σb = bulk density, gm/cc

Packing index in Naqus Sandstone varies from 1.09 to 1.39 with a mean value of 1.30, while in Araba Sandstone it ranges from 1.12 to 1.33 with an average of 1.22 (Table 6.1).

6.2 Statistical distributions and correlations of petropysical parameters

Statistical distributions and correlations of petrophysical parameters such as porosity and permeability give significant insights about a reservoir rock. Spatial patterns of porosity and permeability are generally dependent on lithology. Therefore, each zone and/or layer in a reservoir may provide a distinct set of porosity and permeability values with a characteristic statistical distribution (Saner and Sahin, 1999). It may be possible to refine a reservoir's zonation and to identify lithologies using these statistical distributions, which should be analyzed at an early stage of a reservoir characterization study (Busch et al., 1987; Jensen et al., 1987).

In the present work, statistical analyses were conducted on both thin section and core data for the studied surface and subsurface samples. Statistical parameters, including central tendency (mean, median and mode), dispersion (minimum, maximum, standard deviation and variance) and distribution (skewness and kurtosis) for the measured petrophysical data, together with the number of samples, are listed in Table 6.3. Histograms are constructed to determine the pattern of data distributions within each studied unit (Figs. 6.1B-6.1D; 6.2A-6.2D). The relationships between the measured petrophysical parameters are illustrated in Figures 6.3-6.6.

Cross plot of helium versus thin section porosity for Naqus Formation yield a strong positive correlation (correlation coefficient r = 0.88, Fig. 6.3A) commensurate with samples dominated by macroporosity. In Araba Formation, helium porosity has no correlation with thin section porosity (correlation coefficient r = -0.06, Fig. 6.3A). Measured helium porosity is higher than point-counted thin section porosity by approximately five orders of magnitude (Table 6.1). The higher helium porosity values are attributed to the abundance of micropores in the recorded diagenetic clays (mainly kaolinite). This is particularly evident in samples that have low modal porosity but high helium porosity. The regression line equations controlling this linear relation are:

Thin section porosity = 1.7689Ø -22.993 for Naqus Formation

Thin section porosity = -0.0494Ø + 4.5226 for Araba Formation

where Ø is the helium porosity

6.2.1 Relationship between horizontal and vertical porosity

A cross plot of 22 subsurface samples, for which both horizontal and vertical porosity are available shows a moderate positive correlation (correlation coefficient r = 0.6, Fig. 6.3B). The regression line equation controlling this linear relation is:

Vertical porosity = 0.6141Ø + 2.0978

where Ø is the horizontal porosity

6.2.2 Relationship between helium porosity and bulk density

The relationship between helium porosity and bulk density for Naqus and Araba formations is shown in Figure 6.3C. This relation is represented by a linear regression line and exhibits an increase in porosity with decrease of bulk density. The calculated relation is controlled by the equations:

$\rho b = -0.0219Ø + 2.5113$ for Naqus Formation

$\rho b = -0.0306Ø + 2.7075$ for Araba Formation

where

ρb = bulk density g/cc

Ø = porosity %

This relation is characterized by a correlation coefficient equal to -0.92 and -0.98 for Naqus and Araba samples, respectively. These two equations are very reliable to calculate porosity from bulk density and vice versa.

6.2.3 Relationship between helium porosity and packing index

The plot of helium porosity versus packing index has an excellent positive correlation (correlation coefficient r = 0.997 and 0.999 for Naqus and Araba samples, respectively, Fig. 6.3D). The regression line equations controlling this linear relation are:

$PI = 0.0155Ø + 0.9453$ for Naqus Formation

$PI = 0.015Ø + 0.9534$ for Araba Formation

where:

PI = packing index

ϕ = porosity %

Porosity can be predicted (PI) with a great precision.

6.2.4 Relationship between porosity and permeability

Porosity versus permeability relationships have been reviewed by Nelson (1994 and 2000). He went on to query the reasons for different data distributions on a porosity versus permeability cross-plot. In particular, there is a little initial dependence of permeability on porosity in newly deposited sands, where grain-packing and sorting effects predominate. An apparent dependence emerges through diagenesis, the effects of which are impacted by compaction (Worthington, 2003).

In the present study, a graph of helium porosity (arithmetical scale) versus permeability (logarithmic scale) shows a good positive correlation between the two parameters (correlation coefficient r = 0.82, 0.81 and 0.82 for Naqus, Araba and subsurface samples, respectively, Fig. 6.4A, B) indicating that microporosity, even though locally important, does not significantly influence reservoir quality. However, the relationship is not a simple one. For any giving porosity, there is a wide range of permeability, which is attributed to variations in the amount and distribution pattern of interstitial clay minerals (mainly kaolinite), variations in the amount of cement, variations in grain size, sorting and packing and, to a lesser extent, to the presence of intragranular pores that are poorly connected to the intergranular pore conduits in the sandstones (Ketzer, et al., 2003). The regression line equations controlling this non-linear relation are:

$\text{Permeability} = 0.0227e^{0.4504Ø}$	for Naqus Formation
$\text{Permeability} = 0.8423e^{0.2028Ø}$	for Araba Formation
$\text{Permeability} = 0.0765e^{0.5751Ø}$	for the subsurface sandstone

On the other hand, cross plot of thin section porosity (arithmetical scale) versus permeability (logarithmic scale) for Naqus Formation shows a good positive correlation (Fig. 6.4C) with a correlation coefficient r = 0.80, while that for Araba Formation yield a near-random pattern (correlation coefficient r = 0.29, Fig. 6.4C). The regression line equations controlling this non-linear relation are:

$\text{Permeability} = 12.733e^{0.2337Ø}$	for Naqus Formation
$\text{Permeability} = 22.483e^{0.0903Ø}$	for Araba Formation

A plot of vertical porosity versus vertical permeability for 22 subsurface samples is shown in Figure 6.4D. It shows a moderate positive correlation between the two parameters (correlation coefficient r = 0.52). The regression line equation controlling this non-linear relation is:

Vertical permeability = $0.1283e^{0.3826Ø}$

where Ø is the vertical porosity

6.2.5 Relationship between horizontal and vertical permeability

A plot of horizontal versus vertical permeability for 492 subsurface samples shows a strong positive correlation (correlation coefficient r = 0.86, Fig. 6.5A) that indicates an overall low permeability anisotropy and, hence, pore fluids migration (including hydrocarbons) occurred equally well both vertically and horizontally. The regression line equation controlling this non-linear relation is:

Vertical permeability = $1.1518Kh^{0.9354}$

where Kh is the horizontal permeability

6.3 Controls on reservoir quality of the studied sandstones

Reservoir quality of the studied sandstones may be a function of many controls including the depositional control of grain size and sorting and the diagenetic control of compaction, cementation and dissolution (cf. Cade, et al., 1994).

6.3.1 The depositional control

6.3.1.1 Effect of grain size on porosity

Theoretically, porosity is independent of grain size for uniformly packed and graded sands (Rogers and Head, 1961). In practice, however, coarser sands sometimes have higher porosities than do finer sands or vice versa (Lee, 1919; Sneider et al., 1977). This disparity may be due to separate but correlative factors such as sorting and/or cementation (Selley, 1985).

In the present study, Naqus samples indicate a moderate positive relation between porosity and grain size (correlation coefficient r = 0.55 and 0.50 for helium and thin section porosity, respectively, Fig. 6.5B, C). On the other hand, Araba samples show low correlation between porosity (both helium and thin section) and grain size (correlation coefficient r = -0.25 and 0.19 for helium and thin section porosity, respectively, Fig. 6.5B, C).

6.3.1.2 Effect of grain size on permeability

At the reservoir scale, grain size is the primary control of permeability, and a decrease in grain size is generally accompanied by decreasing permeabilities because pore diameter decreases and hence capillary pressure increases (Krumbein and Monk, 1942).

Herein, Naqus samples indicate a moderate positive non-linear relation between the two parameters (correlation coefficient r = 0.68, Fig. 6.5D). On the other hand, Araba samples show no correlation between permeability and grain size (correlation coefficient r = -0.11, Fig. 6.5D). Absence of relationship is attributed to extensive diagenesis. The average grain size of the studied samples is chiefly fine to medium, but is locally coarse. Most samples are unimodal, but some have a bimodal size distribution of the fine and coarse modes. Occasionally, grain size bimodality is a major control of porosity and permeability. Clarke (1979) pointed out that "the effects of bimodality are more important than diagenesis in determining the quality of some oil-field reservoirs".

6.3.1.3 Effect of grain sorting on porosity and permeability

Grain sorting significantly influences reservoir quality of the sandstones. Porosity increases with improved sorting. As sorting decreases, the pores between the larger, framework-forming grains are infilled by the smaller particles. Permeability decreases with sorting for the same reason (Fraser, 1935; Rogers and Head, 1961; Beard and Weyl, 1973).

Porosity and permeability of Naqus Formation have a moderate positive relation with grain sorting (correlation coefficient r = 0.54 and 0.56, respectively, Fig. 6.6A, B). A plot of porosity and permeability versus grain sorting for Araba samples is shown in Figure 6.6A, B. It shows a good positive correlation between the two parameters and grain sorting (correlation coefficient r = 0.76 for both).

6.3.2 The diagenetic control

Sandstone reservoir quality is largely determined by diagenetic processes that either reduce or enhance porosity and permeability. Mechanical compaction, intergranular pressure solution, cementation, framework grain and cement dissolution have all been documented as playing significant roles in modifying porosity of various sandstones.

In contrast to the other diagenetic processes, mechanical compaction and intergranular pressure solution (isochemical diagenesis) reduce the intergranular volume (minus cement porosity) of sands and sandstones.

Cementation (allochemical diagenesis) occludes intergranular volume by the precipitation of authigenic minerals, with no directly related reduction of bulk volume. It always results in the reduction of intergranular porosity (cf. Houseknecht, 1987). Iron minerals (mostly hematite), clays (mainly kaolinite) and quartz are the main authigenic minerals that influence reservoir quality in the studied surface and subsurface sandstones. Other cements (calcite, halite and gypsum) have uneven distribution, thus their influence on reservoir quality varies from bed to bed.

6.3.2.1 Effect of iron minerals cement

The iron minerals cement tends to sit in pores, blocking pore throats and hence reduce porosity and permeability. However, iron minerals also occurred as grain coats and may have helped in the preservation of porosity by inhibiting the precipitation of quartz overgrowths. Due to its high abundance, iron minerals cement played an important role in lowering the reservoir quality of the studied surface and subsurface sandstones.

6.3.2.2 Effect of clay cement

Clay minerals cement is important component in sandstones, because of the enormous effect it has on porosity and permeability (cf. Wilson and Pittman, 1977; Howard, 1992, McBride et al., 1996). Clay minerals are thus a vital consideration in studies involving the movement of fluids through pore spaces. In this study, authigenic clays are represented by kaolinite together with traces to minor proportions of illite, smectite, illite-smectite mixed layer and chlorite. Many scientists consider authigenic kaolinite to be potentially deleterious cement because of its high microporosity, which causes high residual water saturation, and because its small crystals can break loose during hydrocarbon production and block pore throats and perforations (Almon and Davies, 1978; Neasham, 1977; Pittman, 1989). Howard (1992), however, believed that kaolinite has little tendency to migrate through pores. Kaolinite dispersion and migration may also potentially result in damage to reservoir formations during recovery enhancement using techniques that require the injection of reactive chemicals into the pore space of sandstones. Furthermore, the dispersion of kaolinite cement can cause weakening of the formation around the well bore.

In the present study, a graph of helium porosity versus kaolinite in Naqus Formation shows a good negative correlation (correlation coefficient r = -0.77, Fig. 6.6C), while that in Araba Formation shows unreasonable moderate positive correlation (correlation coefficient r = 0.62, Fig. 6.6C). Such trend may be attributed to the fact that most of the measured porosity in Araba samples is micropores, which proportionate with the kaolinite content (Fig. 6.1A). Likewise, the plot of permeability versus kaolinite for Naqus Formation shows a good negative non-linear relation (correlation coefficient r = -0.83, Fig. 6.6D), while that for Araba Formation shows unreasonable poor non-linear positive correlation (correlation coefficient r = 0.29, Fig. 6.6D).

6.3.2.3 Effect of quartz cement

Quartz cementation, more specifically quartz overgrowth, has been recognized as the main cause of porosity-loss in many deeply buried quartzose sandstone reservoirs in various basins (cf. Blatt, 1979; McBride, 1989; Ehrenberg, 1990; Worden and Morad, 2003). Quartz cement in the studied surface and subsurface sandstones occurs mainly as syntaxial overgrowths and less commonly as prismatic outgrowths projected into and completely fill adjacent pores. However, thin sections show that some samples with good porosities have abundant quartz overgrowth. A possible explanation is that in certain parts of the reservoir, quartz cementation took place in a relatively early phase of the diagenetic history, thus preventing further porosity reduction by compaction.

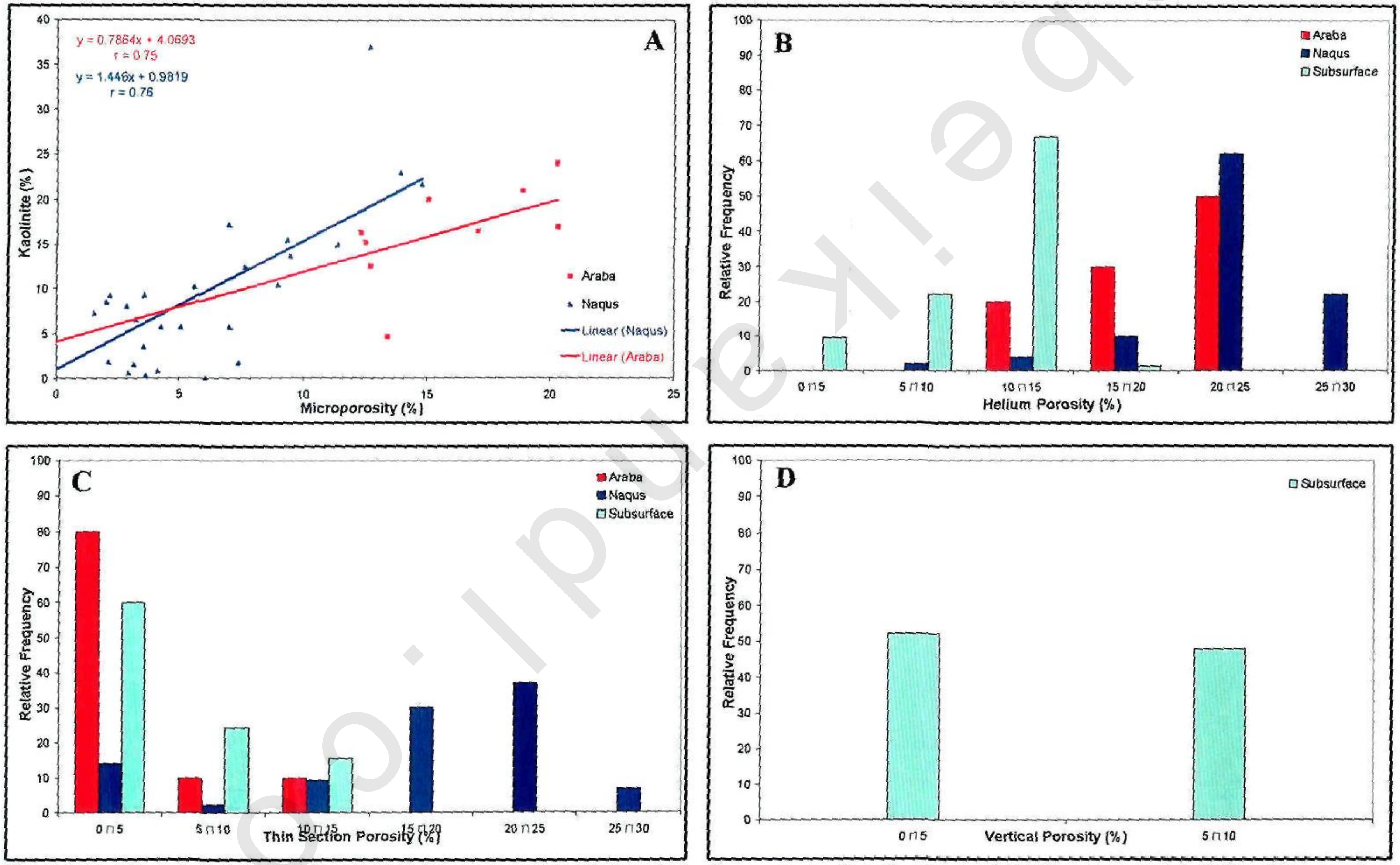

Fig. 6.1: Cross plots of microporosity versus kaolinite (A), frequency distribution of Helium porosity (B), thin section porosity (C) and vertical porosity (D).

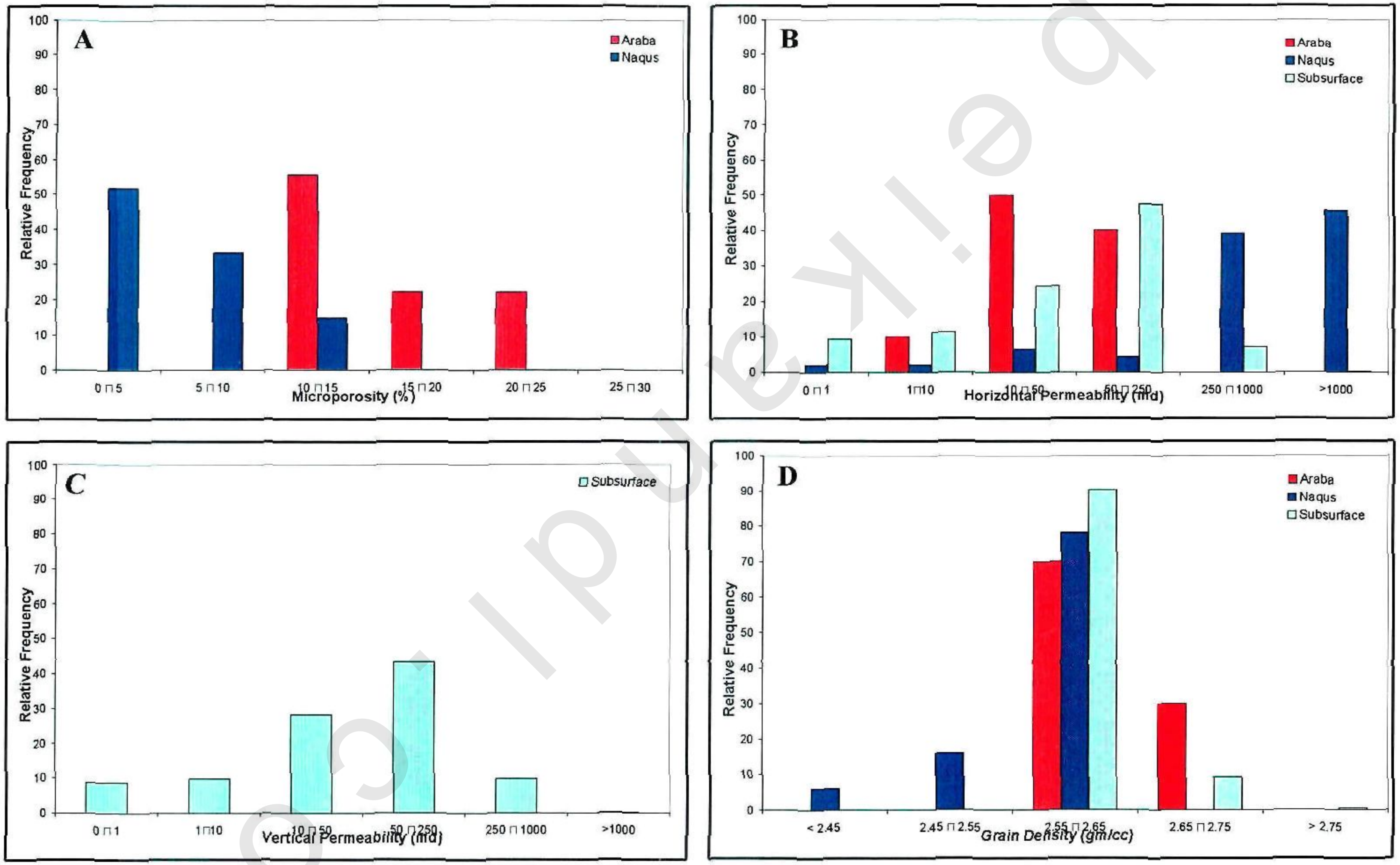

Fig. 6.2: Frequency distribution of microporosity (A), horizontal permeability (B), vertical permeability (C) and grain density (D).

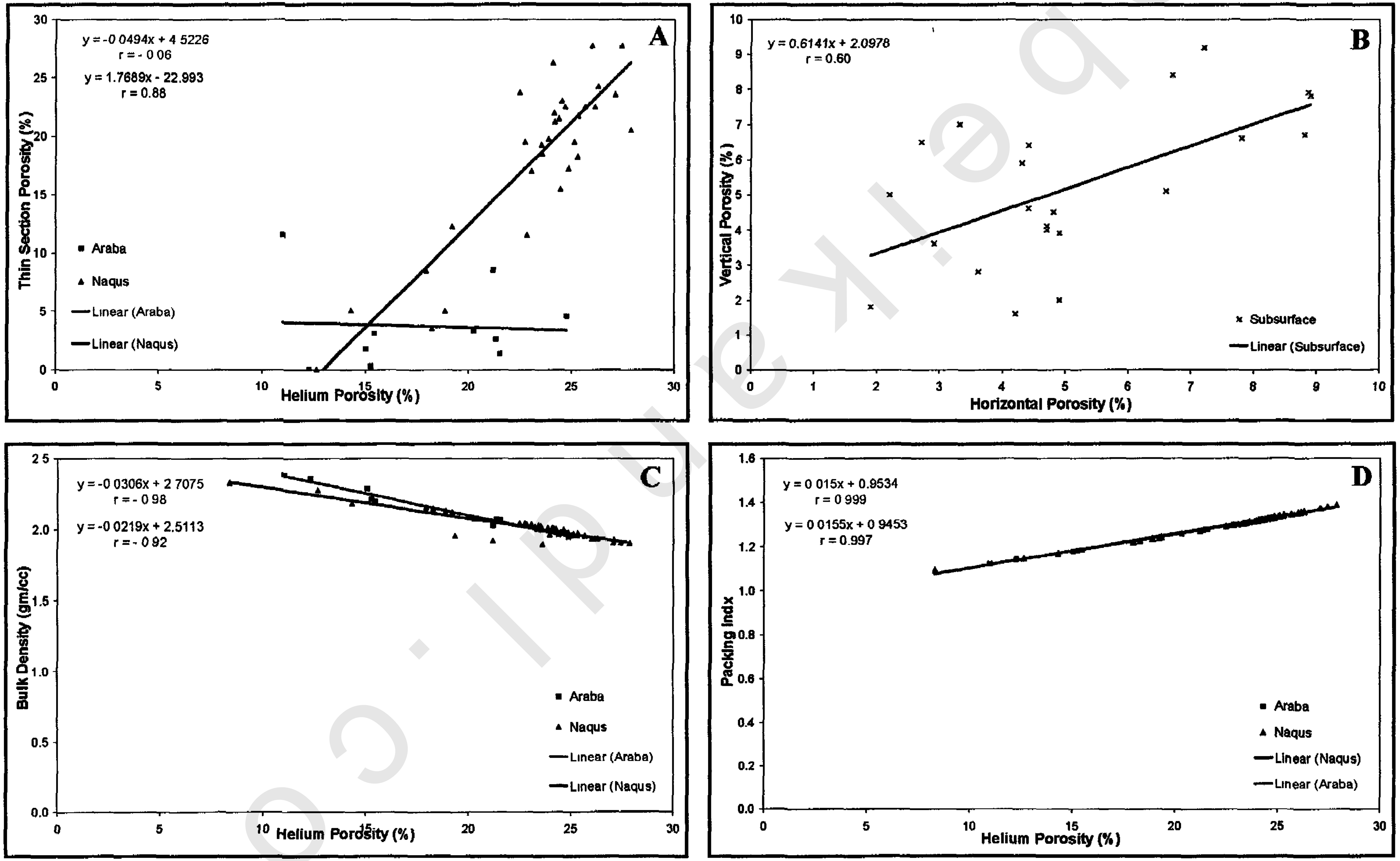

Fig. 6.3: Cross plots of Helium porosity versus thin section porosity (A), horizontal porosity versus vertical porosity (B), Helium porosity versus bulk density (C) and Helium porosity versus packing index (D).

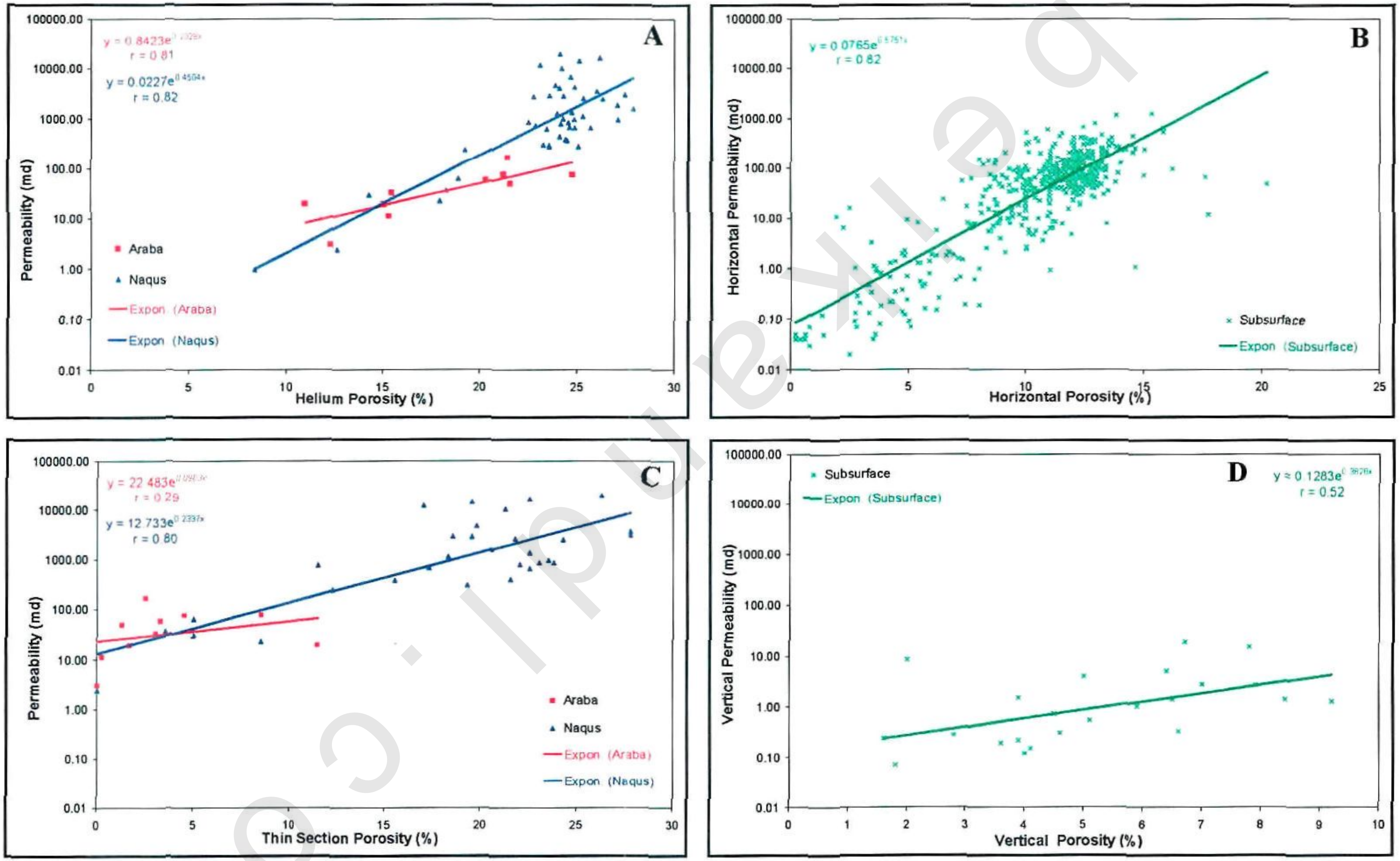

Fig. 6.4: Cross plots of Helium porosity versus permeability (A), horizontal porosity versus horizontal permeability (B), thin section porosity versus permeability (C) and vertical porosity versus vertical permeability (D).

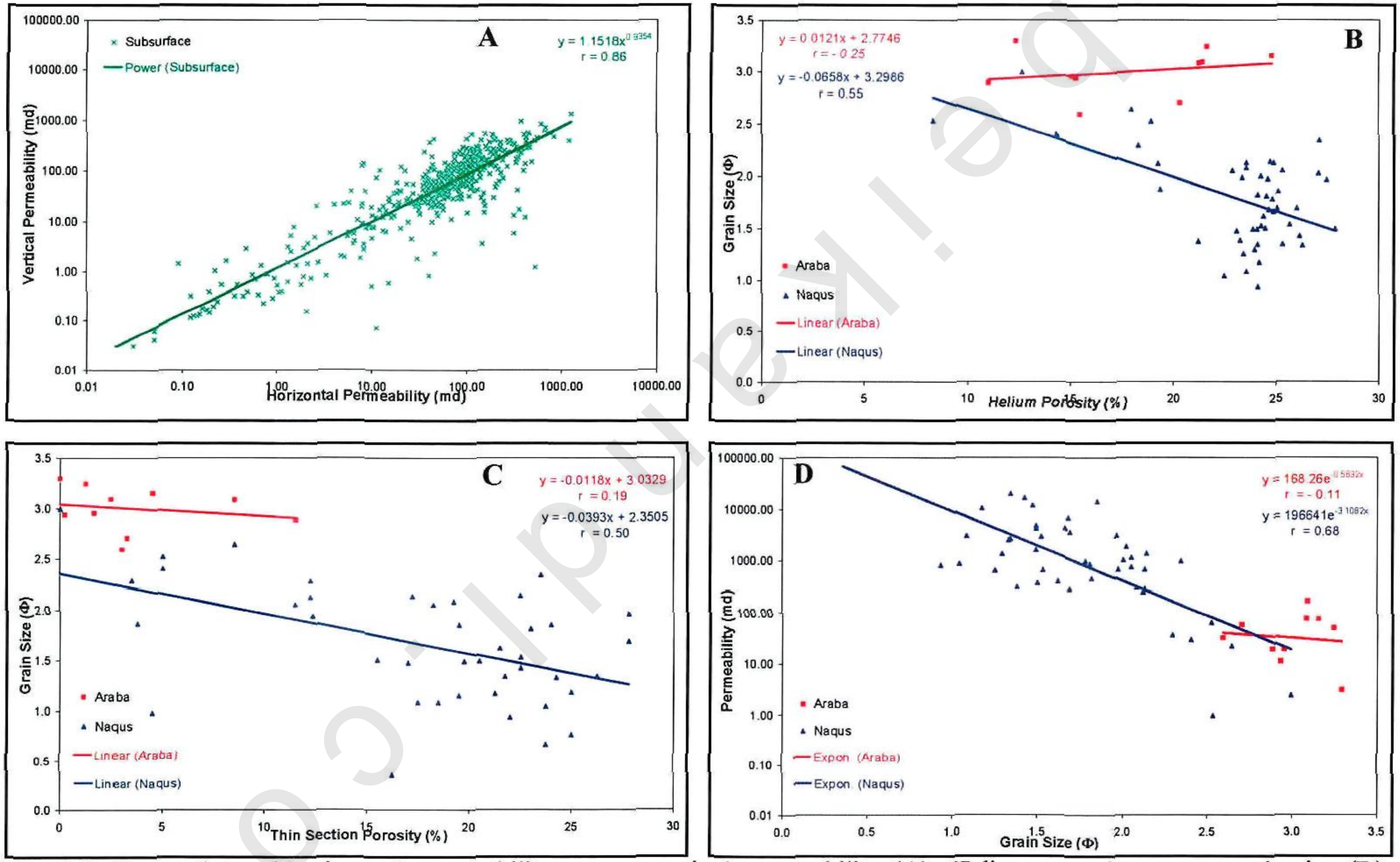

Fig. 6.5: Cross plots of horizontal permeability versus vertical permeability (A), Helium porosity versus grain size (B), thin section porosity versus grain size (C) and grain size versus permeability (D).

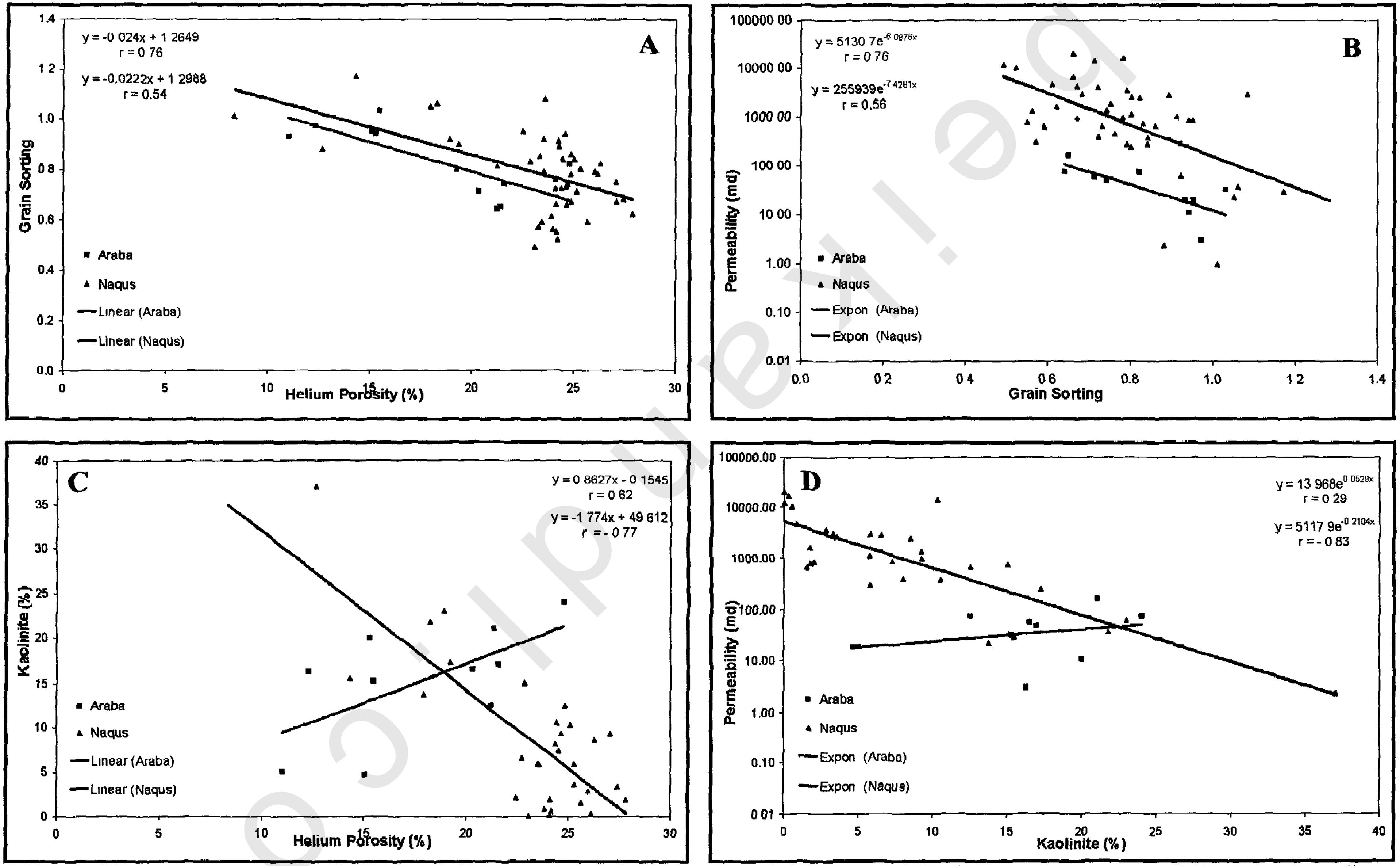

Fig. 6.6: Cross plots of Helium porosity versus grain sorting (A), grain sorting versus permeability (B), Helium porosity versus kaolinite (C) and kaolinite versus permeability (D).

Table 6.3: Statistical parameters of the petrophysical data of the studied sandstones.

Statistics		Surface sandstone														Subsurface sandstones					
		Araba							Naqus												
		P Ø%	Ts Ø%	Micro Ø%	K (md)	σg (g/cc)	σb (g/cc)	PI	P Ø%	Ts Ø%	Micro Ø%	K (md)	σg (g/cc)	σb (g/cc)	PI	Ph Ø%	Pv Ø%	Ts Ø%	Kh (md)	Kv (md)	σg (g/cc)
Central Tendency	Mean	17.82	3.66	15.81	50.00	2.63	2.16	1.22	23.14	17.70	6.09	2818.20	2.61	2.01	1.30	10.41	5.19	4.86	92.41	100.27	2.64
	Median	17.90	2.75	15.00	40.50	2.63	2.14	1.22	24.10	19.50	5.00	954.00	2.62	1.99	1.32	11.10	5.00	4.00	59.00	54.00	2.64
	Mode	11.00	0.00	12.30	19.00	2.60	2.07	1.18	23.50	12.30	3.60	276.00	2.64	1.98	1.32	11.00	3.90	0.00	40.00	24.00	2.64
Dispersion	Minimum	11.00	0.00	12.30	3.00	2.57	1.97	1.12	8.30	0.00	1.50	1.00	2.42	1.89	1.09	0.20	1.60	0.00	0.02	0.00	2.57
	Maximum	24.70	11.50	20.30	162.00	2.69	2.38	1.33	27.80	27.80	14.70	19526.00	2.65	2.33	1.39	20.20	9.20	14.75	1270.00	1340.00	3.34
	Std. Dev	4.57	3.68	3.35	46.81	0.04	0.14	0.07	3.68	7.22	3.79	4453.14	0.05	0.09	0.06	3.06	2.15	3.91	128.63	136.49	0.03
	Variance	20.88	13.51	11.23	2191.56	0.00	0.02	0.00	13.52	52.12	14.39	19830448.38	0.00	0.01	0.00	9.34	4.61	15.29	16546.71	18628.75	0.001
Distribution	Skewness	-0.09	1.36	0.35	1.63	0.30	0.32	0.07	-2.19	-0.90	0.89	2.45	-2.84	1.86	-1.85	-1.30	0.05	0.77	4.11	3.48	15.30
	Kurtosis	-1.35	1.26	-1.87	3.26	-0.85	-1.36	-1.14	5.74	-0.07	-0.15	5.63	8.17	4.08	4.17	1.80	-0.81	-0.24	26.02	19.58	306.76
	Count	10	10	9	10	10	10	10	50	43	27	46	50	50	50	541	23	45	527	492	541

P Ø =Helium porosity, Ph Ø =Horizontal helium porosity, Pv Ø =Vertical helium porosity, Ts Ø =Thin-section porosity, Micro Ø =Microporosity, K =Permeability, Kh =Horizontal permeability, Kv =Vertical permeability, σb =Bulk density, σg =Grain density, PI=Packing index

6.3.3 Effect of fractures

Silica infilled fractures and quartz veins are common in the subsurface sandstone (PLs. 3.3D, 3.4A, B). The permeability of theses structures is substantially less than 10 % of the permeability of the surrounding reservoir sandstone. Consequently, it was concluded that the filled fractures represent significant barriers to fluid flow and are responsible for the low productivity index and the high positive skin factor characteristic of wells producing from the Paleozoic Sandstone (Harper, 1984). Fractures without filling (open or conductive) are also observed in the subsurface sandstone (PL. 3.4F) and have contributed to its porosity and permeability, but filled fractures were almost four times as numerous as the open fractures.

6.4 Quantitative estimation of porosity loss due to compaction and cementation

At the time of deposition, an initial porosity of approximately 45 % was assumed for the studied sandstones. That value was also suggested by many researchers for sands that are well sorted or better (cf. Pryor, 1973; Atkins, 1989; McBride et al., 1991; Atkins and McBride, 1992). During burial diagenesis, that porosity was reduced by mechanical compaction, chemical compaction and cementation. In fact, compactional processes irreversibly reduce the intergranular volume of sand, whereas, cementation occludes, but does not reduce, intergranular volume.

Proper assessment of the relative importance of porosity loss by compaction and cementation is important to the prediction of porosity in sandstones, studies of mass transport during diagenesis and the modeling of basin fluid flow. Quantitative estimation of the amounts of porosity loss by compaction and cementation can be made from standard point-count data on cement and pore space abundance (Lundegard, 1992). The average total volume of porosity lost by compaction and cementation can be computed from the following formula (Ehrenberg, 1989):

$$\text{Total Ø lost by compaction} = \text{Initial Ø} - \frac{(100 \times PCP) - (\text{Initial Ø} \times PCP)}{(100 - PCP)}$$

$$\text{Total Ø lost by cementation} = (\text{Initial Ø} - \text{Compactional porosity loss}) \times \frac{PFC}{PCP}$$

Where PCP is the average pre-cement porosity or the intergranular volume, PFC is the pore-filling cement and Initial Ø is the inferred average initial porosity of the studied sandstones.

The term intergranular volume that is synonymous with pre-cement porosity or minus-cement porosity is easily quantified (by point counting) as the sum of intergranular porosity (exclusive of oversize grain dissolution pores) plus all cements that occupy intergranular space (exclusive of oversized cement patches).

Assuming an initial porosity of 45 % and using the average values for PCP of 19.10, 31.62 and 17.00 % for Naqus, Araba and subsurface sandstones, respectively, in Ehrenberg's equation, then the average Naqus, Araba and subsurface sandstones lost 31.69, 19.03 and 33.66 % porosity, respectively, by compaction prior to cementation (Table 4.4). That is, the intergranular volume of Araba, Naqus and subsurface sandstones was reduced to an average of 13.31, 25.97 and 11.34 %, respectively, by compaction alone.

Applying the calculated compactional porosity loss and using the average value for PFC of 7.98, 29.27 and 12.47 % for Naqus, Araba and subsurface sandstones, respectively, in Ehrenberg's equation, then the average Naqus, Araba and subsurface sandstones lost 5.45, 24.16 and 8.33 % porosity, respectively, by cementation (Table 4.4). This means that Naqus Sandstone lost about 70.42 % of the original 45 % porosity by compaction and 12.11 % by cementation, while Araba Sandstone lost about 42.28 % of the original 45 % porosity by compaction and 53.68 % by cementation. On the other hand, the subsurface sandstone lost about 74.80 % of the original 45 % porosity by compaction and 18.51 % by cementation.

When assessing the diagenetic modification of intergranular porosity, it is useful to separate the effect of compaction from that of cementation. This has been done by applying: 1) modified Houseknecht's (1987) diagram, 2) Lundegard's (1992) diagram and 3) compaction index concept (Lundegard, 1992) on the studied sandstones.

6.4.1 Houseknecht's (1987) diagram

The diagram shown in Figure 6.7 illustrates how intergranular porosity of sandstones depends upon intergranular volume and proportion of intergranular volume that is occupied by cement. This diagram can be used to evaluate the diagenetic processes that are largely influential to intergranular porosity reduction, and to determine why some sandstone retain better reservoir quality than others. The diagram can also be used to calculate intergranular porosity values from point counted data and to reconstruct diagenetic pathways of reservoir sandstones by sequentially plotting discrete paragenetic phases. As shown in the diagram, the volume of intergranular porosity present in a sandstone is a function of how much intergranular volume has been destroyed by compaction (vertical axis), both mechanical and chemical, and how much of that intergranular volume is occluded by cement (horizontal axis). For example, a sandstone that contains 10 % intergranular porosity may plot any where along the 10 % line of the figure. The sandstone's porosity may be predominantly a function of mechanical and chemical compaction (in which case it would plot close to the vertical axis), may be predominantly a function of cementation (in which case it would plot close to the horizontal axis) or

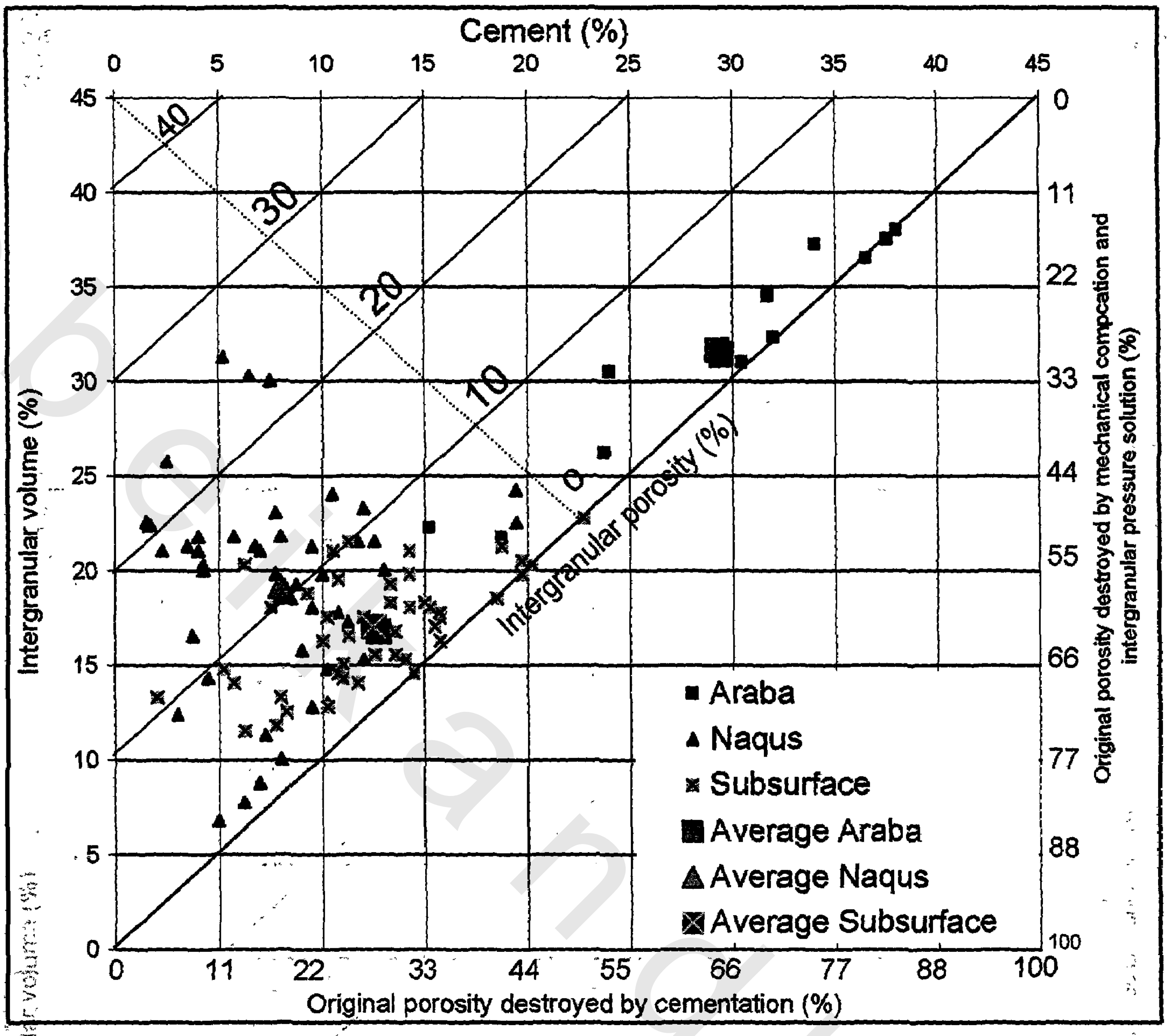

Fig. 6.7: Diagram showing the relative importance of compaction versus cementation to porosity development in the studied sandstones (after Houseknecht, 1987).

may be a function of both compaction and cementation (in which case it would plot at some point between the two axes).

Except for one sample, all of the data points of Naqus and subsurface sandstones cluster in the lower-left portion of the diagram indicating that these samples have undergone significant reduction of intergranular volume by compactional processes and relatively little cementation. Naqus samples are less cemented and have more intergranular porosity than the subsurface samples. The wide range in intergranular volume values may be the result of varied amounts of intergranular pressure solution, which was largely controlled by the variation in grain size and clay content (cf. Healed, 1956). Most of the subsurface samples plot between the 0 and 10 % intergranular porosity lines on Figure 6.7, and the average intergranular porosity for all samples, calculated using point counting is only 4.53 %. The predominance of grain contacts indicative of pressure solution and the small intergranular porosity of subsurface sandstone indicate that it has undergone considerable chemical compaction. Sandstones that have such low intergranular volumes also have very low permeabilities because the remaining porosity tends to be isolated and, therefore, non-effective (Houseknecht, 1987). The five samples that plot between the 10 and 20 % lines on Figure 6.7 contain more intergranular volume and less cement than average. Thus, the best quality reservoir samples are those that have undergone less destruction of intergranular volume by intergranular pressure solution and that contain less cement than average. On the other hand, 82 % of the data points of Araba Sandstone cluster in the upper-right portion of the diagram, indicating that a larger percentage of their original porosity has been destroyed by cementation processes than by compaction. Recognizing samples that fall into the upper-right portion of the diagram is particularly important in dealing with sandstones that contain relatively soluble cements, such as calcite. These cements may allow large volumes of cement-dissolution porosity to be generated if suitable geochemical conditions occur (Houseknecht, 1987). Despite having the highest intergranular volume percent, Araba samples have the lowest reservoir quality among the studied samples. This is simply attributed to extensive cementation that filled most of the intergranular pores.

Two problems with the original Houseknecht's work exist: 1) an incorrect formula was used for analysis of compactional porosity loss, and 2) the assumption of a value of 40 % for the original porosity of sandstone is an unnecessary oversimplification. Nevertheless, neither of these problems significantly alters the fundamental conclusions reported in his work.

Houseknecht (1987) calculated compactional porosity loss as the simple difference between an assumed initial porosity and the present day intergranular volume (pre-cement porosity) as determined by point counting petrographic thin sections. However, such calculation results in an error (cf. Ehrenberg, 1989; Pate, 1989; Lundegard, 1992). The reason that this seemingly straightforward calculation is wrong is that the total volume of the sandstone changes during compaction, such that present percent intergranular volume is a percentage of a different and smaller total rock volume than the original porosity. Subtraction of one from the other, therefore, is meaningless, or, at best, provides a systematically inaccurate approximation (cf. Ehrenberg, 1989). The error in calculations can be inferred in this study (both surface and subsurface sections). Considering that, the studied sandstones were compacted from an original porosity of 45 % to a pre-cement porosity of 19.10, 31.62 and 17.00 % for Naqus, Araba and subsurface sandstones, respectively. Compactional porosity loss calculated as the simple difference between the assumed original and present-day pre-cement porosity is 25.90, 13.38 and 28.00 %, which is 57.55, 29.73 and 62.22 % of the original 45 % porosity for Naqus, Araba and subsurface sandstones, respectively. However, using Ehrenberg's equation (1989), which accounts for bulk volume changes, indicated that the average Naqus, Araba and subsurface sandstones lost 31.69, 19.03 and 33.66 % porosity by compaction, which is 70.42, 42.28 and 74.80 % of the original 45 % porosity. Moreover, analysis of the relative importance of compaction and cementation can not be accurately determined from the diagram due to the aforesaid effect of changing bulk rock volume on the volume percentages of grains and cements. Failure to consider this effect results in significant underestimation of compactional porosity loss.

In the present study, certain corrections to Houseknecht's volume-cement diagram were therefore necessary. First, Ehrenberg's (1989) formula was used to calculate the amount of porosity lost by compaction. This method accounts for the reduction in sediment bulk-volume by compaction. Second, assumed porosity value of 45 % was used throughout this work as the original porosity that is subsequently modified by diagenetic processes during burial. That value is used in Ehrenberg's equation when calculating porosity loss by compaction and cementation and as the maximum intergranular volume possible when constructing the intergranular volume versus cement diagram. These corrections, however, do not completely invalidate Houseknecht's study; they simply show that compaction was even more important than he initially indicated.

6.4.2 Lundegard's (1992) diagram

Plots of compactional porosity loss versus cementational porosity loss are very useful for comparing individual samples (Fig. 6.8). These derived parameters are preferred to primary petrographic parameters such as percent cement and intergranular volume because this approach facilitates analysis of the relative importance of compaction and cementation. Primary petrographic percentages are biased by the decrease in total rock volume that is caused by compaction. The parameters compactional porosity loss and cementational porosity loss account for this effect. On a cross plot of these parameters, samples with equal porosity loss by compaction and cementation lie on a straight line that bisects the coordinates.

Herein, all the data points of the Naqus and subsurface sandstones indicate that these samples have undergone significant reduction of intergranular volume by compactional processes and a relatively little cementation. On the other hand, 64 % of the data points of Araba Sandstone indicate that a larger percentage of their original porosity has been destroyed by cementation processes than by compaction (Fig. 6.8). Generally, these results are similar to what deduced from Houseknecht's diagram, however, they show that compaction was even more important than indicated by modified Houseknecht's diagram. Moreover, analysis of the relative importance of compaction and cementation can be easily and, to a great extent, accurately done using this approach.

6.4.3 Compaction index

A useful parameter for comparing different data sets is what is called the compaction index (Lundegard, 1992), the fractional ratio of compactional porosity loss to the sum of compactional and cementational porosity loss:

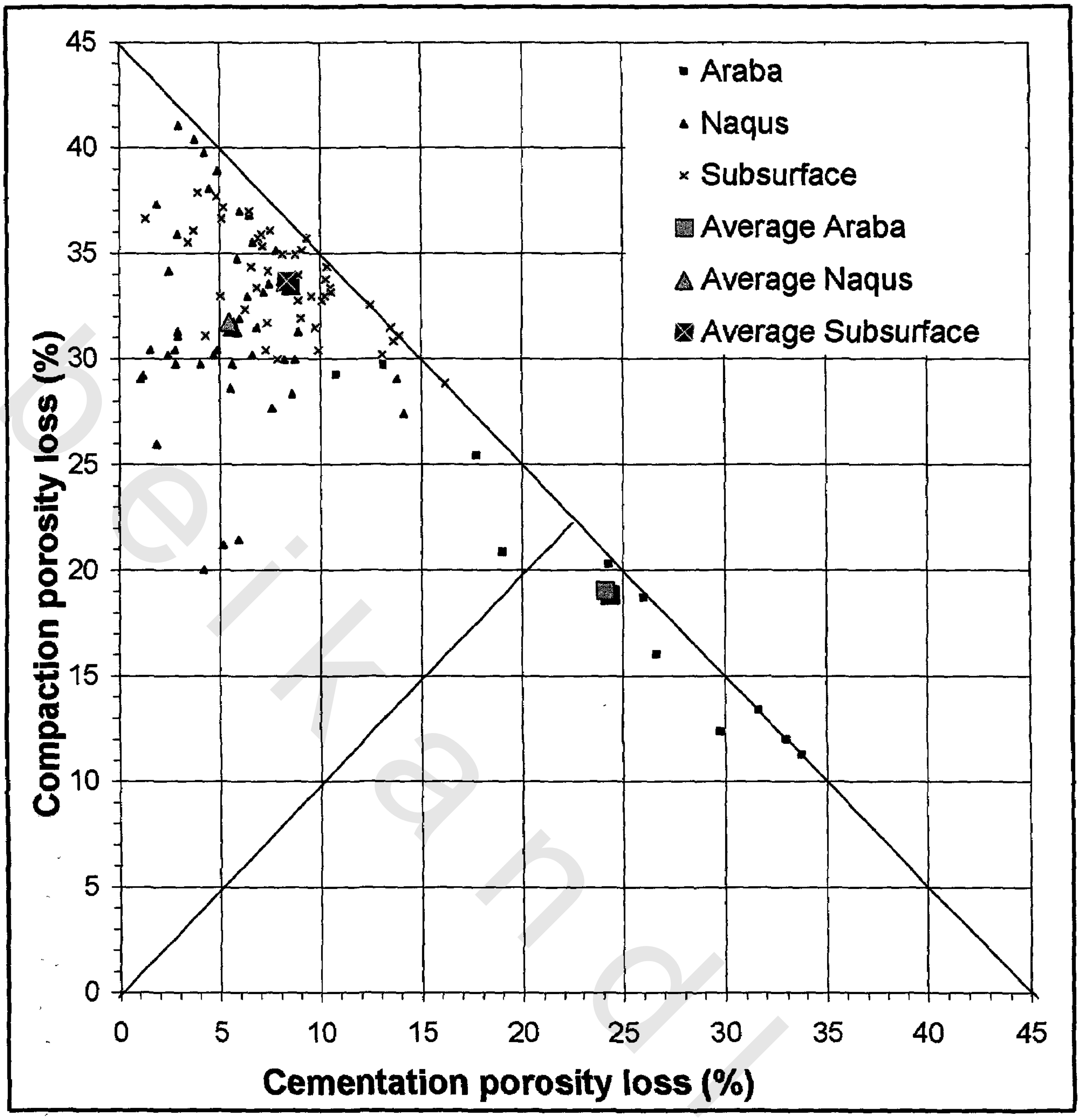

Fig. 6.8: Diagram showing the relative importance of compaction versus cementation to porosity development in the studied sandstones (after Lundegard, 1992).

$$\text{Compaction index} = \frac{\text{compactional porosity loss}}{\text{compactional porosity loss + cementational porosity loss}}$$

The compaction index equals 1.0 when all porosity loss is by compaction, and equals 0.0 when all porosity loss is by cementation. It is important to note that the compaction index does not reflect the magnitude of the porosity loss. Samples with different porosities can have the same compaction indices. The compaction index for Naqus Sandstone ranges from 0.66 to 0.96 with an average of 0.86, while in the subsurface sandstone it varies from 0.64 to 0.97 with an average of 0.80 (Table 4.4). The high average compaction indices for Naqus and subsurface sandstones indicate that these sandstones have on average lost more porosity by compactional processes than by cementation. On the other hand, Araba Sandstone has compaction index that ranges from 0.25 to 0.73 with an average of 0.44 indicating that Araba Sandstone has on average lost more porosity by cementational processes than by compaction. The studied sandstones are almost free of ductile grains. This indicates that compaction is a very significant mechanism of porosity loss even in sands containing few or no ductile grains.

6.5 Development of secondary porosity

In the present study, the term "secondary porosity" refers to the sum of oversized pores, intragranular pores and fracture porosity. Secondary porosity in the studied sandstones are formed mainly by the dissolution of unstable framework grains (FGD) and to a lesser and unknown extent by the dissolution of calcite cement. Schmidt and McDonald (1979) and Shanmuggan (1984) gave criteria for the recognition of secondary porosity in sandstones. They stated that the most common diagenetic secondary porosity resulted from the dissolution of feldspars and carbonate cement. Schmidt et al. (1977) and Burley and Kantorowicz

(1986) have distinguished two types of secondary porosity: porosity formed by dissolution of 1) chemically unstable framework components and 2) soluble cements.

In the investigated samples, oversized pores are formed chiefly by the complete dissolution of feldspar grains. It is possible that a few oversized pores formed where rock fragments and unstable heavy minerals dissolved also. Porosity formed by framework grains dissolution is thus the sum of intragranular pores and oversized pores. It averages 3.73, 1.10 and 0.36 % of the total rock volume of the Naqus, Araba and subsurface sandstones, respectively. Porosity generated by dissolution of unstable framework grains (FGD) averages 24.84 %, 43.02 % and 4.30 % of the total thin section porosity in Naqus, Araba and subsurface sandstones, respectively, thus, it contributes significantly to the present total porosity in the surface sandstone. Framework grains dissolution does not appreciably increase reservoir permeability. However, the amount of framework grains dissolution porosity developed was found to be a function of the sandstone's initial permeability (cf. Siebert, et al., 1984).

Secondary porosity which, results from the dissolution of mineral cements, whether they are replacive or purely pore-filling, is termed cement-dissolution porosity (Burley and Kantorowicz, 1986). Authigenic carbonates are generally corrosive with respect to the stable silicate framework of sandstones and will, therefore, on dissolution, leave behind a record of their former presence (Burley and Kantorowicz, 1986). Ragged, corroded edges (regular v-shaped or spiky patterns) of calcite cement crystals in the studied sandstones indicate that calcite was being dissolved in outcrop and subsurface. Furthermore, micritic calcite cement occurs in some samples as a few widely scattered grains per thin section and some quartz grains in samples uncemented by calcite have notches and embayments on their margins. Both of the latter features are possible clues to the presence of former calcite cement that has been dissolved (Shanmuggan, 1984; Burley and Kantorowicz, 1986). Cement dissolution porosity may be created by the dissolution of calcite cement in outcrop or in the subsurface by pore fluid (meteoric or marine derived formation water) that is undersaturated with respect to carbonates (Bjørlykke, 1984). Although large volumes of meteoric water passed through the studied sandstones when silica for quartz cement was introduced, calcite cement had not yet precipitated. Thus, the meteoric water that precipitated the quartz cement could not have dissolved the calcite cement. Later on, some calcite cement has been dissolved from the studied sandstones, but the exact amount is uncertain. The studied sandstones have a very little calcite cement (0.12, 0.10 and 0.17 %, respectively, of the total rock volume in Naqus, Araba and subsurface samples). Because there is no major source of carbonate (i.e. marine shells, carbonate rock fragments, calcrete) in the studied sandstones, they probably did not contain much more calcite cement originally than they have now and that cement dissolution produced only small amounts of secondary porosity. Secondary porosity in the studied sandstones may have also resulted from fracturing due to tectonic stresses or overpressure (hydrofracturing).