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Depositional Controls on the Quality of Clastic Reservoirs: A Review

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Abstract: A comprehensive review of important data from eighty-one clastic reservoirs across the world has yielded important conclusions on the relationship between the depositional environments and clastic reservoir quality. High porosity and permeability have significant controls on the amount of hydrocarbon recoverable in clastic reservoirs, but they may not necessarily guarantee the highest possible recoverable. Permeability can vary very significantly with the same porosity and sometimes the highest permeability does not necessarily occur with the highest porosity. There is a drastic reduction in porosity at depth greater than 3450m regardless of the depositional environment. Gas reservoirs have tendency to recover higher amount of hydrocarbon at relatively lower porosity and permeability when compared to oil reservoirs. The present review suggests that an oil reservoir with porosity of about 20% and a permeability of around 1100mD may recover about 43.6% of oil in place provided all other necessary geologic factors are in place. Gas reservoirs are likely to recover more than 43.6% with similar or lower porosity and permeability. This review will serve as a useful guide to petroleum geologists and sedimentologists in understanding the quality of clastic reservoirs in different environments.

Keywords: Clastic Reservoirs, Porosity, Permeability, Hydrocarbon, Depositional Environments

1. Introduction

Depositional environments exert significant controls on the quality of clastic reservoirs and have significant influence on many factors including overall architecture, geometry, heterogeneity, facies, grain composition and size, sorting, pay thickness, and net to gross of reservoirs [1-3, 51, 54, 62, 67]. These factors in turn control porosity, permeability, and the amount of hydrocarbon recoverable in sandstone reservoirs. Porosity and permeability exert substantial controls on the quality of hydrocarbon reservoirs [11, 12, 54] because they define the amount of hydrocarbon that can be recovered from any reservoir [13, 45] The quality of clastic hydrocarbon reservoirs is of great economic importance because this determines the amount of hydrocarbons that can be recovered at any given time.

The aim of this paper is to review the relationship between depositional environments and the quality of clastic reservoirs and examine the influence and controls of depositional environments on the quality of clastic reservoirs. This relationship will be useful to petroleum geologists and sedimentologists in predicting and understanding the quality of clastic reservoirs in different depositional environments.

2. Methodology

In this review, important reservoir data from over eighty clastic reservoirs across major depositional environments are reviewed. The reservoir data include porosity, permeability, depth, pay thickness, net to gross, area, hydrocarbon type, hydrocarbon in place and recoverable, depositional environment, stratigraphic unit and age, name of field, basin, and the country of location and are presented in Tables 1-6. The data were sourced from the literature and analysed using Microsoft Excel spreadsheet. Additional details including the depositional environments and the measurements details on the reservoir analysed are available in their original sources, which are available in the reference list.

3. Results and Interpretations

3.1. Fluvial Reservoirs

From thirty-two fluvial reservoirs (Table 1), the average porosity is 19.4%. The relationship between porosity and depth is not straightforward (Figure 1a). The highest porosity (35%) occurs at a depth of 152m while the third highest porosity of 29% occurs at a depth of 2779m. On the other hand, the second lowest porosity of 10% occurs at a depth of 2195m while the deepest reservoir at the depth of 3450m has porosity of 21.5% which is higher than the average porosity. About 85.7% of the data points plots within porosity range of 15 and 29% while 78.5% plots within 15 and 24%. These porosity values point to an important range for the average porosity in fluvial reservoirs. This porosity range of 15 and 29% may also have other important implications for clastic reservoirs. The reservoir with the highest porosity of 35% occurs at a shallow depth of 152m and is located in an onshore field. Many factors may be responsible for this high porosity. The shallow depth of the reservoir may be an important factor, which may also facilitate a negligible diagenetic destruction of the primary porosity.

Table 1. *Details of fluvial reservoirs. Abbreviations for Tables 1-5: L: Lower, M: Middle, U: Upper, E: Early, Lt: Late, Cam: Cambrian, Sil: Silurian, Dev: Devonian, Carb: Carboniferous, Per: Permian, Tr: Triassic, Ju: Jurassic, Cr: Cretaceous, Pal: Palaeocene, Eo: Eocene Olig: Oligocene, Mio: Miocene, Pli: Pliocene, Ple: Pleistocene, Ss: Sandstone, O: Oil, G: Gas. MMBO: Million Barrels of Oil, BCFG: Billion Cubic Feet Gas. Average values in brackets.*

Field	Basin	Location	Strat Unit	Age	Depositional Environment
Messla	Sirte	Libya	Sarir Ss	L. Cr	Stacked braided channels
McArthur River		USA	Hemlock Ss-	Olig	Alluvial-fluvial
October		Egypt	Nubia Ss	Carb-Cr	Stacked fluvial channels, blanket sandstone
Hassi Messaoud		Algeria	Ra Ss	Cam	Blanket sandstone
Brent		UK	Statfjord	U. Tr- L. Ju	Braided/meandering
Buchan		UK	Old Red Sandstone	Dev-Carb	Braided
Caister B		UK	Bunter Ss	Tr	Channel/sheet flood
Caister C		UK	Coal Measures	Carb	Braided/low sinuosity
Esmond Complex		UK	Bunter Ss	Tr	Braided/alluvial fan
Heidrum		Norway	Garn	M. Ju	Braided/meandering
Hewett		UK	Bunter Ss	Tr	Alluvial plain
Morecambe		UK	Sherwood Ss	Tr	Braided
Snorre		Norway	Lunde Ss	L. Tr	Braided channels
Snorre		Norway	Statfjord	L. Tr	Braided/low sinuosity
Statfjord		UK/Norway	Statfjord	U. Tr-L. Ju	Braided/meandering?
Azal		Yemen	Alif	Cr	Braidplain/channel fill
Bu Attifel		Libya	Sarir Ss	L. Cr	Braided
North Rankin		Australia		Tr- L. Ju	Braided
Peco	Western Interior	Canada	Belly River	L. Cr	Braided/ single channel
Prudhoe Bay	Colville Trough	Alaska	Ivishak Ss	Per-Tr	Braided, fluvio-deltaic
South Belridge	San Joaquin Valley	USA	Tulare	Ple	Braided, fluvio-deltaic
Ninian		UK	Brent	Ju	Fluvio-deltaic
Tiajuana		Venezuela	Misoa Ss	Eo	Fluvio-deltaic
	Gulf of Mexico	USA	Wilcox	Pal- Eo	Fluvio-deltaic
Weixing	Songliao	NE China	Putaohua	L. Cr	Fluvio-deltaic
Main Consolidated	Illinois	USA	Caseyville	L. Carb	Fluvio-estuarine
Sarir C-Main		Libya	Sarir Ss	L. Cr	Braided
Vacas Muertas		Argentina	Barancas	Cr	Alluvial fan
Rocky Ridge	Williston	USA	Tyler	L. Carb	Meander belt
Little Creek	Mississippi Salt	USA	Lower Tuscaloosa	L. Cr	Meander belt
Greater Burgan		Kuwait	Burgan	L. Cr	Fluvial and tidal dominated
Crawford		UK		Tr-Cr	Fluvial channel fills
Wytch Farm		UK	Sherwood Ss	Tr	Braided
Barryroe	Celtic Sea	Ireland	Wealden	L. Cr	Fluvial?
Crystal	Western Interior	Canada	Viking	E. Cr	Estuary
Senlac	Western Canada	Canada	Lloydminster/ Mannville	E. Cr	Estuary

Table 1. *Continued.*

Depth (m)	Porosity (%)	Permeability (mD)	Thickness of Pay (m)	Net/Gross (%)	Area (Sq Km)	Type	In Place (MMBO/BCFG)	Recoverable (MMBO/ BCFG)	References
2644	17	500	300		230	O	3000	1000-1500 (33-50%)	Clifford et al. [18]
2560	17	80				O	570		Morse [54]

Depth (m)	Porosity (%)	Permeability (mD)	Thickness of Pay (m)	Net/Gross (%)	Area (Sq Km)	Type	In Place (MMBO/BCFG)	Recoverable (MMBO/ BCFG)	References
3350	17	236	135						Lelek et al. [42]
3350	2-12		120			O	25000	9000 (36%)	Balducchi and Pommier [7]
	16-29	20-10000		35-90	39	G,O	580/3241	313 (54%)/1215 (37.5%)	Martin [45]
	7-11	0.1-2			14	O	466	83.8 (18%)	Martin [45]
	11-30	1-1000		84-100	7.5	G	156	75%	Ritchie and Pratsides [60]
	6-15	0.1-400		67-80	15	G	230	186.3 (81%)	Ritchie and Pratsides [60]
	9-24			70-95	39	G		533	Ketter (38]
	27-35	9000			40	O.G	1000 BCFG		Harris [28]
	19-23	250-1000		88-98	190	G			Cooke-Yarborough (19]
	14-15	1-100		56-85	170	G	6750	5400 (80%)	Bushell [14]
2526	19-29	320-535		35-68	50	O	2080-3000	770-2,080; (21-41%)	Martin [45], Morse [54]
	19-29	1300-2000		4-6.3	30	O	2,080	665.6-873.6 (32-42%)	Martin [45]
	18-23	1500		50-72	35	O	1,500	630 (42%)	Morse [54]
	16-18	500-1200			13	O,G		142/5.7	Huurdeman et al. [34]
	8-16	1-1000			55	O		15%	Martin [45]
	17-21	500-1500		75-83	50	G		7700	Martin [45]
2195	6-13 (10)	1-150 (5)	5.5	30	91.2	O,G	34	3.4 (10%)	Gardiner et al. [24]
2440-2800	10-30 (22)	20-4000 (400)	148-174	87	1140	O,G	21500/46,500	12040 (56%)	Atkinson et al. [5]
152	32-42 (35)	100-10000 (3000)	15-84	30-70	51.2	O		1,200	Miller et al. [52]
2779	29	1000	110			O		1,200	Albright et al. [4]
750-4850	12-28	240				O		5,000	Talukdar and Marcano [68]
200-6700	10-33	0.08-185				O,G			Dutton and Loucks [21]
1150-1490	15-26	0.01-400				O,G			Sun et al. [67]
380	6-25 (15)	0-3570 (670)	5.8	40	2.56	O,G	4.6 MMBO	1.5 (33%)	Howard and Whitaker [33]
	13-17	30-600		50-95	800	O	8000	2000 (25%)	Martin [45]
	17.5	217				O	400	38.5 (9.6%)	Martin [45]
2470	13-25 (16)	60-780 (115)	7.6	83	20.8	O	11.4	3.4 (30%)	Hastings [29]
3283	10-35 (24)	0.1-1000 (100)	9.1	75	46.6	O	102	68 (67%)	Werren et al. [70]
	19-25	10-1600	380			O		>10000	Strohmenger et al. [65]
	20-25	10-2500	7-181	30-50		O	130-1000	9 (6.9%)	Gluyas and Swarbrick [25]
	5-30	0.01-1000			34	O	350		Martin [45]
	16	50							Gluyas and Swarbrick [25]
100	15	100-600	12.5			O,G	1043-1612 MMBO	300 (18.6-28.7%)	Providence [57]
1750	6-25 (10.5)	0.01-2500 (200)	3-30.5	95	92.8	O	102	34.6 (34%)	Clark and Reinson [16]
775-805	25-31 (27.5-30)	2500-4000 (2500-3000)	3-7	100	17.9	O	84.37	6.4 (7.5%)	Zaitlin and Shultz [71]
1750	6-25 (10.5)	0.01-2500 (200)	3-30.5	95	92.8	O	102	34.6 (34%)	Clark and Reinson [16]
775-805	25-31 (27.5-30)	2500-4000 (2500-3000)	3-7	100	17.9	O	84.37	6.4 (7.5%)	Zaitlin and Shultz [71]

***Table 2.** Details of deltaic reservoirs.*

Field Basin	Location	Strat Unit	Age	Depositional Environment
Senecaville Appalachian	USA	Clinton	E. Sil	Deltaic
Cano Limon Llanos	Colombia	Mirador Ss, Carbonera	Lt. Cr-Oli	River-dominated deltaic, stacked channels, shallow marine
Northwest Hutton/East Shetland	UK	Brent	M. Ju	Shallow marine/ fluvio-deltaic
Burgan	Kuwait	Wasia	Cr	Deltaic and shallow shelf
Safaniya	Saudi Arabia	Khafji	U. Cr	Stacked delta plain, mouth bar and bay fill
Hibernia	Canada	Hibernia	U. Ju	Delta plain, straight channel, fluvial delta
Badak	Indonesia	Balikpapan	Mio-Pli	Stacked delta plain, channel, mouth bar and delta front
Bekapai	Indonesia	Balikpapan	Mio-Pli	Stacked delta plain, channel, mouth bar and delta front
Oseberg	Norway	Oseberg Ness		Delta lobes stacked with delta plain
Smorbukk	Norway	Tilje, Iie, Garn		Tidal influence shoreline and braided delta complex
Statfjord	UK/Norway	Brent and Statfjord	Ju	Delta front, mouth bar and channels
Cambay-Hazard (!)	India	Hazad	M. Mio	Prograding deltaic Sandstone
Prudhoe Bay	USA	Sadlerochit	L. Tr	Deltaic, fluvial
Island Block 300	Gulf of Mexico		Pli-Ple	Delta front Sandstone on marine shelf
Medora/Williston	USA	Tyler	L. Carb	Barrier Island

Table 2. *Continued.*

Depth (m)	Porosity (%)	Permeability (mD)	Thickness of Pay (m)	Net/Gross (%)	Area (Sq Km)	Type	In Place (MMBO/BCFG)	Recoverable (MMBO/BCFG)	References
1710	2-16 (8)	0.01-5 (0.5)	18	32	7.7	G,O		4.2 (60%)	Keltch et al. [37]
2286-2500	12-32 (25)	10.0-8000 (1450)	65-150	23-76	60	O	1940	1050 (54%)	Cleveland and Molina [17]
145	8-24 (18)	0.1-2000 (99)	55	45	48	O,G	670 MMBO	200 (30%)	Scotman and Johnes [61]
300-2500	20-35	250-8000				O		66000	Morse [54]
1500	20-35	250-8000				O	88000	32300 37%	Morse [54]
3720	16	500	68			O		2000.1	Morse [54]
1372	22	200				G,O		3160 BCFG	Morse [54]
1300	25-35	1000							Morse [54]
2120-2700	24	2000				O,G	1420	770 MMBO (51%)	Hagen and Kvalheim [26]
3800-4400	11	10-1000				O,G	1180		Ehrenberg et al. [22]
2585	29	250-1500	300			O	5600	3400 (61%)	Kirk [39]
2750	12-22	250				O	2700		Biswas et al. [10]
2438	20	500				O,G		14900	Morse [54]
1290-3600	30	1000	330					400	Holland et al. [31]
2367	2-22 (12)	0.1-750 (90)	4.3	100	17.8	O	24.8	7.1 (29%)	Barwis [8]

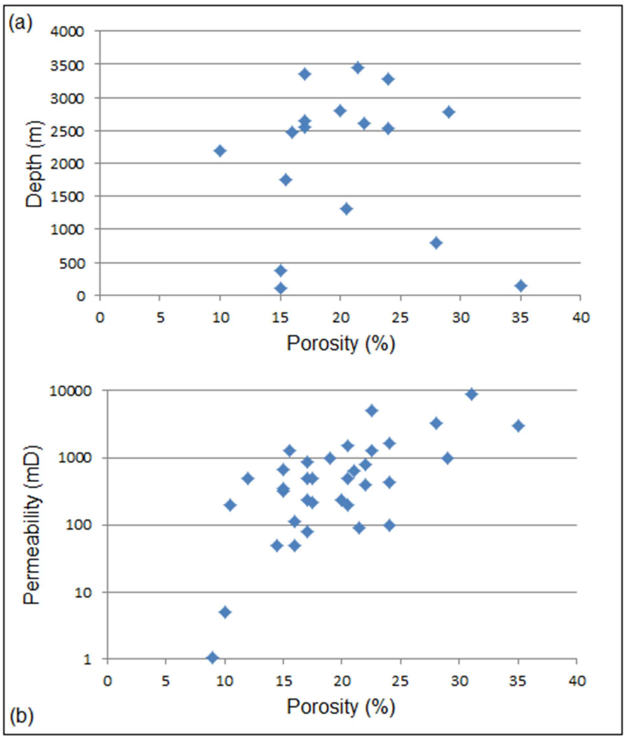

Figure 1. *Key data from fluvial reservoirs.*

Permeability generally increases with porosity although it sometimes varies significantly with similar porosity values (Figure 1b). With a porosity of 15%, permeability ranges from 315 to 670mD while permeability varies from 80 to 850mD for porosity of 17%. The average amount of hydrocarbon recoverable in these reservoirs is 40% and this generally increases with porosity and permeability. However, the top three recoverable values (75, 80, and 81%) occur with porosity of 20.5, 14.5 and 10.5% respectively. The three reservoirs with the highest recoverable of 81, 80 and 75% are producing gas which demonstrates that gas has tendency for higher recovery than oil.

A large proportion of the porosity range between 15 and 29% are well represented above depth of 2195m (Figure 1a). The amount of hydrocarbon also increases significantly well above this depth. Most of the fluvial reservoirs appear to have good quality above this depth and this may suggest a significant increase in the quality of fluvial reservoirs above 2100m. Apart from the reservoir with the lowest depth of 100m, recoverable generally increases with the average depth of reservoir (2068m) in this environment (Figure 1a).

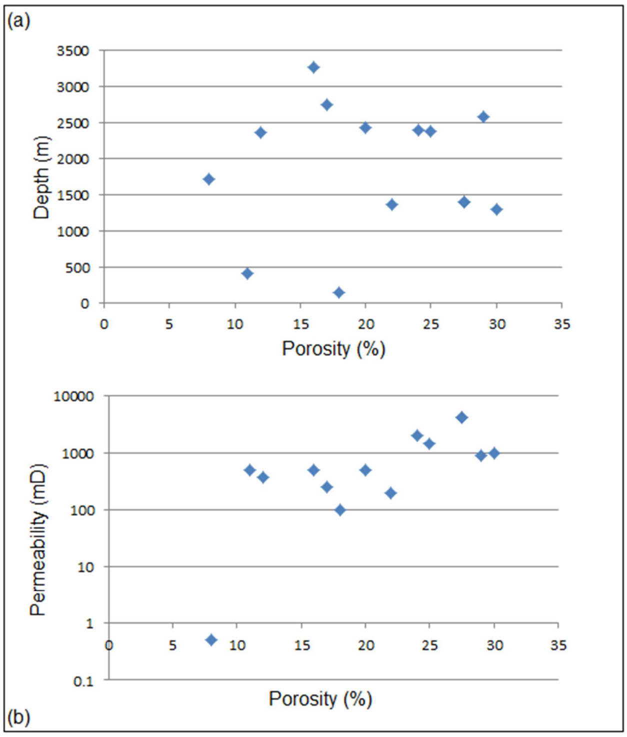

Figure 2. *Key data from deltaic reservoirs.*

3.2. Deltaic Reservoirs

From thirteen deltaic reservoirs (Table 2), the average porosity is 20.5%. Majority of the reservoirs have porosity between 15 and 30%. There is a correlation between porosity and the depth of reservoirs (Figure 2a). Apart from one reservoir, the top six porosity values are in the depth below (2500m). In the three reservoirs with the smallest porosity, one of them (11%) occurred in the shallowest depth of 410m. The maximum depth recorded in this environment is 3270m while 145m is the shallowest depth (Figure 2a). There is a correlation between increasing porosity and decreasing depth but this is not a clear pattern (Figure 2a). However, the reservoir at the highest depth (3270m) in this environment has a porosity of 16% which is lower than the average of 20.5%.

The average permeability for these reservoirs is 1143.2mD. Permeability generally increases with porosity (Figure 2b). The highest permeability in this environment does not occur with the highest porosity. The average of the amount of hydrocarbon recoverable in these reservoirs is 47.5%. The recoverable generally increases with porosity and permeability (Table 2) and the highest recoverable value of 61% occurs with the highest porosity of 29%. It is important to point out that a reservoir with a relatively low porosity (8%) and permeability (0.5mD) has as a significant amount of recoverable (60%). This is a gas and oil-producing reservoir. This once again confirms that gas reservoirs have the tendency to recover significantly higher hydrocarbon with relatively smaller porosity and permeability when compared to oil reservoir.

Table 3. *Details of shallow marine reservoirs.*

Field	Basin	Location	Strat Unit	Age	Depositional Environment
Troll		Norway	Viking	U. Ju	Stacked shallow shelf, prograding shoreface
Snohvit		Norway	Sto and Nordmela	U. Ju	Transgressive coastal plain, inner shelf, tidal channels
Draugen		Norway	Rogn	U. Ju	Shallow marine shelf sand bars
Piper		UK	Piper Ss	U. Ju	Marginal marine shelf
Northern Niger Delta	Niger Delta	Nigeria	Agbada	U. Eo- L. Mio	Paralic, shoreface, shelf, barrier bars and channel sands
Takula		Cabinda	Vermelha Ss	U. Cr	Stacked nearshore, coastal sands, foreshore, tidal channels
Cueta-Tomporo		Venezuela	Lagunillas	Eo-Mio	Shallow coastal bars and fluvio-deltaic channels
El Furrial		Venezuela	Naricual Ss	U. Oli	Shallow marine and barrier bars
Lagifu/Hedinia		Papua New Guinea	Toro Ss	L. Cr	Stacked regressive barrier bars
Fortescue	Southeast	Australia	Latrobe	Eo	Transgressive coastal plain, coastal plain, shoreface
Venture		Canada	Venture Ss	U. Cr	Shallow marine, deltaic
Tom O'Connor		USA	Frio	Oli	Inner-middle shelf to foreshore, beach
Middle Ob	West Siberian	Russia		L. Cr	Shallow marine and fluvio-deltaic
Cupiagua		Colombia	Llanos Foothills/ Mirador	Lt. Cr- Lt. Eo	Shallow marine-alluvial
Tom Walsh-Owen	Rio Grande Embayment	USA	Olmos	L. Cr	Marine shelf
Thomasville	Mississippi Interior Salt	USA	Smackover	L. Ju	Nearshore-mid ramp
Gudao	Zhanhua	China	Guantao	Mio	Lakeshore beaches, fan delta, fluvial channels

Table 3. *Continued.*

Depth (m)	Porosity (%)	Permeability (mD)	Thickness of Pay (m)	Net/Gross (%)	Area (Sq Km)	Type	In Place (MMBO/ BCFG)	Recoverable	References
1300-1500	25	500-10000				O,G		9000 MMBO	Morse [54]
2280-2418	5-15	200				G	4.5		Morse [54]
1600	28	700-10000				O	1100	410 (37.2%)	Provan [56]
2195	24	4000				O		600	Maher [43]
1700	15-25	1000-2000				O,G	4500		Morse [54]
971-1038	25	1000				O	2100		Dale et al. [20]
4510-5180	12-17	10-1200				O		1400	Ramirez and Marcano [58]
3962-4120	11-16					O	4500	890 (19.7%)	Prieto and Valdes [55]
2438	13	300	90			O		150	Matkze et al. [46]
2300-2400	20	100-10000	130			O	420	280 (66.6%)	Hendrich et al. [30]
4436-5800	16	10-40	130			G		250	Mills [53]
1371-1828	31	500-2000	1000			O,G	670		Morse [54]
2380-2820	3-25	0.01-300	30			O			James [36]
3953-4590	2-8.1	0.1-90	1800			O,G	1100/4.5	550/2.25 (51%)	Ramon and Fajardo [59]
2195	8-23 (15)	0.01-8 (0.4)	6.1	57	90	G	228	115 (51%)	Snedden and Jumper [64]
6075	5-10 (7)	0.001-6 (0.35)	90	43	50.3	G	600		Shew and Garner [63]
1190-1300	30-32	500-2000				O		60	Chen and Wang [15]

3.3. Shallow Marine Reservoirs

The average porosity from thirteen shallow marine reservoirs (Table 3) is 18.7%. There is a correlation between porosity and the depth of reservoirs. Porosity increases with decreasing depth of reservoirs (Figure 3a). However, there are two reservoirs with an exception. These reservoirs with 14.5% and 16% porosity below the average porosity (18.7%) are located at depths of 4845 and 5118m respectively.

Permeability generally increases with porosity although this is not a straight-line relationship (Figure 3b). As in fluvial reservoirs, permeability varies with the same porosity values. In two different reservoirs with 20% porosity, permeability ranges from 1500 to 5050mD while permeability also ranges from 1000 to 5250mD when porosity is 25% in two other reservoirs (Figure 3b). As in fluvial and deltaic reservoirs, the highest permeability does not occur with the highest porosity. The permeability of 1250mD, which occurs with the highest porosity (31%), is less than the average permeability (1623.9mD) for the shallow marine reservoirs. The maximum depth in this environment is 6075m while 1245m is the minimum. There is a correlation between increasing porosity and decreasing depth (Figure 3a). The reservoir at the second highest depth (5118m) has a porosity of 16% which is lower than the average of 18.7%.

There are only four data available on the amount of hydrocarbon recoverable in this environment (Table 3). The average amount of hydrocarbon recoverable in these reservoirs is 53.16%. Although the datasets are small, the recoverable generally increases with porosity and permeability. It is however important to point out that a reservoir with the lowest recoverable amount (37.2%) has the second highest porosity (28%) and the maximum permeability (5350mD). A reservoir with a relatively low porosity (5.1%) and permeability (45.1mD) has as a significant amount of recoverable (51%) which is very close to the average for this environment. This reservoir produces oil and gas and the amount of total recoverable may have been significantly increased by the amount of gas recoverable.

3.4. Deep Marine Reservoirs

From ten deep marine reservoirs (Table 4), the average porosity is 27.4% which is the highest among all the environments. The maximum porosity of 35% is the joint highest in all the environments while minimum porosity of 17.5% is the highest of all the minimum porosity. There is a correlation between porosity and the depth of reservoirs as in other reservoirs. Porosity generally increases with decreasing depth of reservoirs (Figure 4a). The top three porous reservoirs have the shallowest depths. Apart from one reservoir, the amount recoverable in this environment increases with porosity and has a straight-line relationship with porosity (Table 4).

Table 4. *Details of deep marine reservoirs.*

Field	Basin	Location	Stratigraphic	Age	Depositional Environment
Yowlumne	San Joanquin	USA	Stevens Ss	L. Mio	Submarine fan
Forties	Central Garben	UK	Forties	U. Pal	Submarine fan
Midway-Sunset (Webster Zone)	San Joanquin	USA	Webster Zone	L. Mio	Turbidite
Arbuckle	Sacramento	USA	Forbes	L. Cr	Deep sea fan
Alba	North Sea	UK	Alba	Eo	Deep sea fan, channel and levee complex
Miller	North Sea	UK	Brae	U. Ju	Submarine fan
Marlim		Brazil	Carapebus Ss	U. Olig	Submarine fan
Albacora		Brazil		U.Cr-Mio	Submarine fan, lobe and channels
Namorado		Brazil		U. Cr	Submarine fan, stacked channels and lobes
Marimba		Brazil		U. Cr	Turbidite
Willimington	Los Angeles	USA	Puente, Repetto	U. Mio- U. Pli	Turbidite

Table 4. *Continued.*

Depth (m)	Porosity (%)	Permeability (mD)	Thickness of Pay (m)	Net/Gross (%)	Area (Sq Km)	Type	In Place (MMBO/ BCFG)	Recoverable	References
3445-4085	5-23 (18)	1-700 (100)	46	75	13.4	O	280	78 (28%)	Berg and Royo [9]
2135	24-27 (26)	500-2000 (1000)	120	25-100	96	O	4300	2500 (59%)	Kulpecz and Van Geuns [40]
210-365	28-35 (33)	800-4000 (1000)	15-76	60-80	2.9	O			Hall and Link [27]
1525-1980	20-25 (23)		3-46	50-100	46.6	G		75	Imperato and Nilsen [35]
1860	35	2800	90			O	1100		Mattingly and Bretthauer [47]
3890-4090	12-23	50-1200	60			O,G	670	400 MMBO (59.7%)	McClure and Brown [49]
2500-2700	30	1200	200			O	8200		Morse [54]
2350-3260	25	1500	110			O	4000		Morse [54]
2980-3080	30	1000				O		250	Bacoccoli et al. [6]
2700	27	1700				O	470	170 (36.1%)	Horschutz et al. [32]
610-1830	30-35	700-1500	>600			O	9600	2500 (26%)	Mayuga [48]

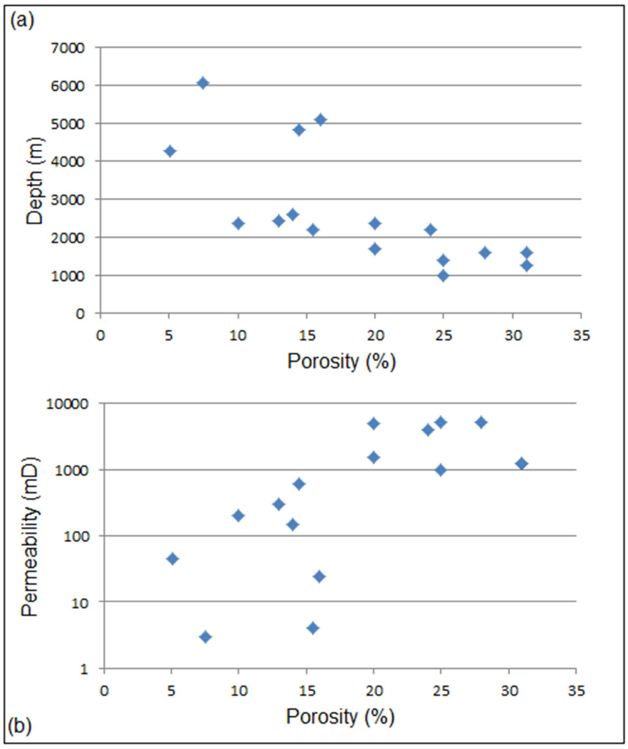

Figure 3. Key data from shallow marine reservoirs.

The average permeability (1202.5mD) for these reservoirs is the second highest permeability after shallow marine reservoirs among all the environments. Permeability increases with porosity (Figure 4b). Unlike other environments, the highest permeability occurs in the same reservoir with the highest porosity. This may suggest that the porosity in this reservoir is an effective porosity. Unlike other reservoirs, the variability of permeability with the same porosity is not well pronounced.

The maximum depth is 3990m while 287.5m is the shallowest depth. There is a correlation between increasing porosity and decreasing depth (Figure 4a). The reservoir at the highest depth has a significant amount of recoverable (59.7%), with 17.5% porosity and permeability of 625mD. The average amount of hydrocarbon recoverable in these reservoirs is 41.7%. The amount recoverable generally increases with porosity and permeability and decreases with depth (Table 4).

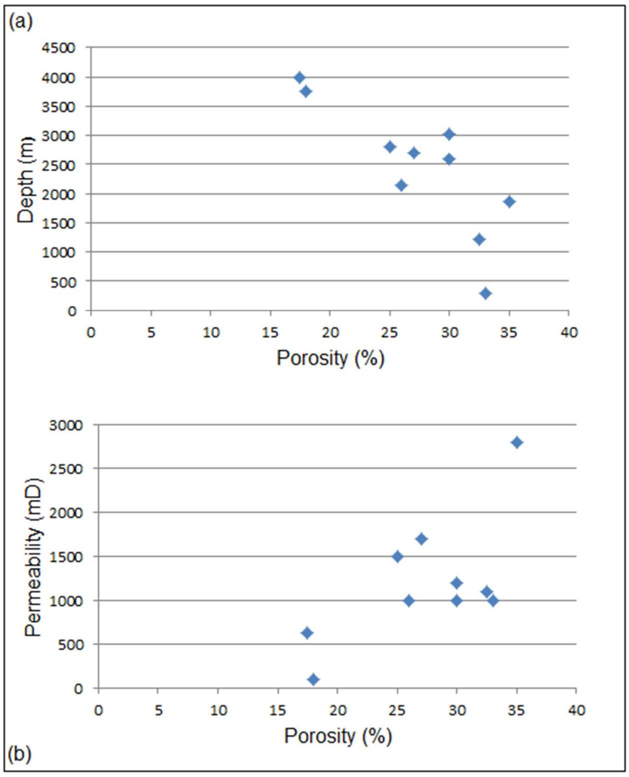

Figure 4. Key data from deep marine reservoirs.

Table 5. Details of Aeolian reservoirs.

Field	Basin	Location	Stratigraphic Unit	Age	Depositional Environment
Caprock	Permian	USA	Shattuck/ Queen	Per	Aeolian, desert fluvial, and sabkha
Pisgah Anticline	Mississippi Interior Salt	USA	Norphlet	L. Ju	Aeolian
South State Line	Mississippi Interior Salt	USA	Norphlet	L. Ju	Aeolian
Viking		UK	Leman Ss	L. Per	Aeolian with Sabkha and alluvial beds
Urucu		Brazil	C. Itaituba		Aeolian
Painter		USA	Nuggest Ss	L. Ju	Aeolian

Table 5. Continued.

Depth (m)	Porosity (%)	Permeability (mD)	Thickness of Pay (m)	Net/Gross (%)	Area (Sq Km)	Type	In Place (MMBO/ BCFG)	Recoverable	References
945	15-30	30-650	3	50	100	O	290	75.5 (26%)	Malicse and Mazzullo [44]
4880-5180	1-24 (12)	0.05-1200 (1)	151-362	100	57.6	G	2000	1300 (65%)	Studlick et al. [66]
5460	1-21 (9.5-16.5)	0.1-84 (0.6-15.5)	181	100	6.5	G			Thomson and Stancliffe [69]
2850-2877	14	30-80	244			G		0.6	Gage [23]
	10-30	10-1200				O	70		Mello et al. [50]
2918	14	23	260			O,G		910 MMBO	Lamb [41]

3.5. Aeolian Reservoirs

From only six aeolian reservoirs (Table 5), the average porosity is 15.9% and this is the lowest average among the entire depositional environments. The maximum and minimum porosity are 22.5% and 11% respectively. The minimum porosity of 11% is higher than the minimum porosity in fluvial and deltaic reservoirs. The porosity increases with depth (Figure 5a). Permeability generally increases with porosity (Figure 5b). The average depth of reservoir is 3443.4m and it is the highest among all the environments. The maximum depth recorded in this environment is as high as 5460m while 945m is the shallowest depth. Since permeability depends on the effective porosity, the depth of burial of the reservoirs may have affected permeability. The reservoir at the maximum depth has porosity of 11% and permeability of 42mD that are lower than the average for this environment. The relatively deeper burial depth of these reservoirs may partly explain the lower porosity and permeability. There is a good correlation between increasing porosity and decreasing depth (Figure 5a). Recoverable data are available from only two reservoirs in this environment and these are 65% and 26%. A significant amount of recoverable (65%) is obtainable at relatively high depth of 5030m.

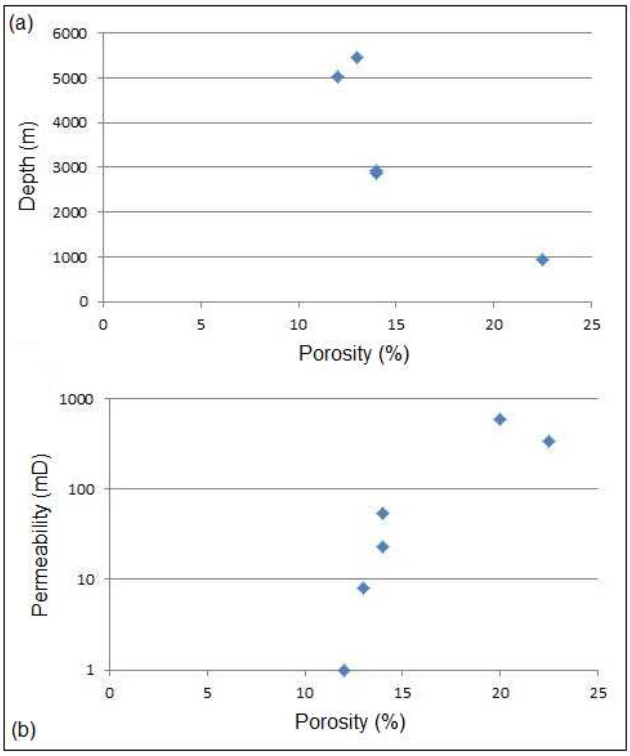

Figure 5. *Key data from aeolian reservoirs.*

4. Discussion

From the available data (Table 6), the average porosity of all the reservoirs is 20.1%. When compared with the averages in the different environments, only the deep marine and deltaic reservoirs have higher porosities (Table 7). About 47% of the reservoirs have porosity above 20% (Figure 6a). As expected, permeability generally increases with porosity (Figure 6a). The average permeability is 1100.6mD. Only the shallow marine, deep marine and deltaic reservoirs have higher permeability than this. About 72% of the reservoirs have permeability of 1100mD or less while about 15% have permeability equal to or greater than 2000mD. It appears that in many reservoirs, once the porosity gets to 20% and above, the permeability jumps significantly to 4000mD and above. In some reservoirs once the porosity reaches 35% and above, the permeability hovers around 1000mD and beyond. The average depth of reservoirs is 2350.2m. Aeolian, shallow, and deep marine reservoirs in increasing order have higher depths than this average.

When all these averages (Table 6) are taken into consideration, it is likely that a reservoir with porosity of about 20% and a permeability of around 1100mD may recover about 41% of hydrocarbon in place provided all other necessary factors are favourable. In addition to this, gas reservoirs are likely to recover more than 41% with porosity of 20% or less because gas reservoirs generally recover relatively higher hydrocarbon with similar or lower porosity and permeability than oil reservoirs. Permeability varies with same porosity in many reservoirs across all the depositional environments. The implications of this for hydrocarbon exploration may include but not limited to: (1) the variation in the effective porosity of reservoir sandstones with similar total porosity. Significant difference in the connectivity of pores may also account for variation in the permeability of sandstones with similar or same porosity, (2) spatial and temporal variations and heterogeneity at different scales may also cause variation in the permeability when the reservoir sandstones have similar porosity [45, 54, 62].

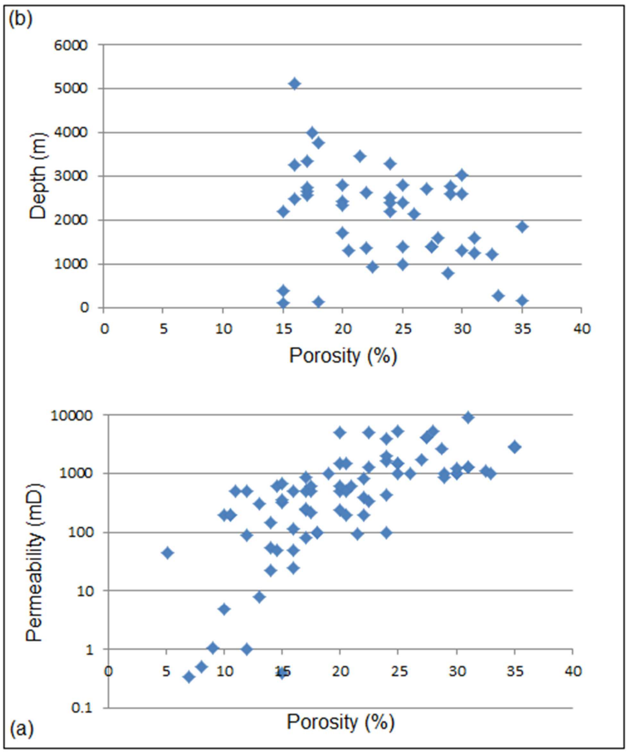

Figure 6. *Key data from clastic reservoirs.*

Except for secondary porosity, it is generally expected that porosity will decrease with depth in sandstones due to diagenesis and other related processes. In the current review, the impact of depth on porosity is clearly evident especially in the aeolian reservoirs (Figure 5a). On the average they have the deepest burial depth and as a result have the lowest porosity and permeability among the reservoirs in all the environments. The deep burial may have resulted in significant reduction in the original porosity of these reservoir sandstones. From the smallest porosity of 5.1% to below 20%, the depth of reservoirs reaches maximum depth of 6075m (Figure 6b). However, once the porosity reaches 20% and above, the depth of reservoirs dropped to 3450m. This may suggest that the quality of reservoir porosity may be significantly affected and reduced beyond this depth. However, based on other factors of individual reservoirs, there may be some exceptions to the relationship between depth and porosity described above. However, other factors such as facies, heterogeneity, subsidence, faulting, fracturing, etc will have to be taken into consideration when considering the effect of depth on the porosity and permeability of clastic reservoirs [45, 51, 54, 62].

The average value of the amount recoverable from all the reservoirs is 41.8%. Apart from the fluvial and deep marine reservoirs, the reservoirs in the other environments have higher recoverable than this average (Table 7). There is a correlation between the amount and type of hydrocarbon recoverable. The present data shows that a gas reservoir recovers significantly higher hydrocarbon than an oil reservoir even when the former has lower porosity and permeability. The viscosity of gas may be an important factor responsible for this. The two gas reservoirs with the highest recoverable (81 and 80%) have porosity and permeability that are significantly lower than the average of 20% and 1100mD respectively. In addition, the minimum recoverable amount for a gas reservoir is 51% and this was achieved with lower than average porosity and permeability. There is no clear trend with depth of reservoirs and the amount of hydrocarbon recoverable although more than 85% of the data on recoverable are recorded at depth of 2700m or below (Table 6).

Table 6. *Key data from clastic reservoirs based on Tables 1-5.*

Type	Porosity (%)	Permeability (mD)	Depth (m)	Recoverable (%)
Oil & Gas	5.1	45.1	4271.5	51
-	7	0.35	6075	-
Gas & Oil	8	0.5	1710	60
Oil	9	1.05	-	18
Oil & Gas	10	5	2195	10
-	10	200	2349	-
Gas	10.5	200	-	81
Oil	10.5	200	1750	34
-	11	505	410	-
Oil	12	500.5	-	15
Oil	12	90	2367	29
Gas	12	1	5030	65
-	13	8.1	5460	-
-	13	300	2438	-
-	14	55	2864	-
-	14	23	2918	-
-	14	150	2600	-
Gas	14.5	50.5	-	80
-	14.5	605	4845	-
Oil	15	315	-	25
Oil & Gas	15	350	100	23
Oil & Gas	15	670	380	33
Gas	15	0.4	2195	51
-	16	50	-	-
Oil	16	115	2470	30
-	16	500	3270	-
-	16	25	5118	-
-	17	80	2560	-
-	17	236	3350	-
-	17	500	2644	41.5
Oil & Gas	17	850		-
-	17	250	2750	-
-	17.5	500		-
Oil	17.5	217		9.6
Oil & Gas	17.5	625	3990	59.7
Oil & Gas	18	99	145	30
Oil	18	100	3765	28
-	19	1000		-
-	20	240	2800	-

Type	Porosity (%)	Permeability (mD)	Depth (m)	Recoverable (%)
-	20	500	2438	-
-	20	605		-
-	20	1500	1700	-
Oil	20	5050	2350	66.6
	20.5	200	1320	
Gas	20.5	500.5	-	75
Oil	20.5	1500	-	42
-	21	625	-	-
-	21.5	92.5	3450	-
Oil & Gas	22	400	2620	56
-	22	805	-	-
-	22	200	1372	-
-	22.5	1255	-	-
Oil & Gas	22.5	5010	-	45.8
Oil	22.5	340	945	26
Oil	24	100	3283	67
Oil	24	427.5	2526	31
Oil	24	1650	-	37
Oil & Gas	24	2000	2410	51
-	24	4000	2195	-
Oil	25	1450	2393	54
-	25	5250	1400	-
-	25	1000	1004.5	-
-	25	1500	2805	-
Oil	26	1000	2135	59
Oil	27	1700	2700	36.1
-	27.5	4125	1400	-
Oil	27.5	4125	1400	37
Oil	28	5350	1600	37.2
Oil	28.8	2750	790	7.5
-	29	1000	2779	-
Oil	29	875	2585	61
-	30	1000	1300	-
-	30	1000	3030	-
-	30	1200	2600	-
-	31	9000		-
-	31	1250	1245	-
-	31	1250	1599.5	-
Oil	32.5	1100	1220	26
-	33	1000	287.5	-
-	35	3000	152	-
-	35	2800	1860	-
Average	20.1	1100.6	2350.2	41.8
Maximum	35	9000	6075	81
Minimum	5.1	0.35	100	7.5
N	81	81	62	38

Table 7. *The summary of key data from clastic reservoirs based on Tables 1-5.*

Environment	Porosity (%)				Permeability (mD)				Depth (m)				Recoverable (%)			
	Ave	Max	Min	N	Ave	Max	Min	N	Ave	Max	Min	N	Ave	Max	Min	N
Aeolian	15.9	22.5	12	6	172	605	1	6	3443.4	5460	945	5	45.5	65	26	2
Shallow Marine	18.7	31	5.1	16	1623.9	5350	25	16	2686.6	6075	1245	16	53.2	66.6	37.2	6
Fluvial	19.4	35	9	35	1027	9000	1.05	35	2068.8	3450	100	17	38.1	81	10	20
Delta	20.5	30	8	14	1143.2	4125	0.5	14	1853.6	3270	145	14	47.5	61	30	7
Deep Marine	27.4	35	17.5	10	1202.5	2800	100	10	2439.3	3990	287.5	9	41.7	59.7	28	5
Clastic Reservoirs (Average)	20.1	35	5.1	81	1100.6	9000	0.35	81	2350.2	6075	100	62	41.8	81	7.5	38

5. Conclusions

Based on a comprehensive review of reservoir data from eighty-one clastic reservoirs across the world, the following conclusions can be made. Porosity and permeability have significant controls on the amount of hydrocarbon recoverable in clastic reservoirs although they may not necessarily guarantee the highest possible recoverable. Within a reservoir, the permeability can vary considerably with the same porosity and the highest permeability may not occur with the highest porosity in other reservoirs. A drastic reduction in porosity at depth greater than 3450m was observed in all the reservoirs regardless of the depositional environments. Gas reservoirs consistently demonstrate tendency to recover higher amount of hydrocarbon than oil reservoirs even with lower porosity and permeability. It is likely that an oil reservoir with porosity of about 20% and a permeability of around 1100mD may recover about 41% of oil in place provided all other necessary geologic factors are in place. Gas reservoirs are likely to recover more than 41% even when they have similar or lower porosity and permeability compared to oil reservoirs. The result of this review, though not exhaustive will serve as a useful guide to petroleum geologists and sedimentologists in predicting and understanding the quality of reservoirs in different continental environments.

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