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 second 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 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 fluvial, braided channels             |
| McArthur River| USA         | Hemlock Ss-S- | Olig       | Alluvial-fluvial |
| October       | Egypt       | Nubia Ss | Carb-Cr    | Stacked fluvial, blanketed sandstone          |
| Hassi Messaoad| Algeria     | Ra Ss    | Cam        | Blanket sandstone                                   |
| Brent         | UK          | Stafford | U. Tr- L. Ju | Braided/meandering |
| Buchan        | UK          | Old Red  | 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      | Stafford | L. Tr      | Braided/low sinuosity                                  |
| Statford      | UK/Norway   | Statford | U. Tr-L. Ju| Braided/meandering?                                |
| Azal          | Yemen       | Alif     | Cr         | Braided/sandstone/blanket channel                   |
| Bu Attifel    | Libya       | Sarir Ss | L. Cr      | Braided                                                   |
| North Rankin  | Australia   |           | Lr- L. Ju | Braided                                                   |
| Poco          | Western Interior | Canada | Belly River | Lr- Cr | Braided/single channel |
| Prudhoe Bay   | Colville Trough | Alaska | Ivishak Ss  | Per-Tr | Braided, fluvo-deltaic |
| South Belridge| San Joaquin Valley | USA  | Tulare | Ple | Braided, fluvo-deltaic |
| Ninian        | UK          | Brent    | Ju         | Fluvio-deltaic                                        |
| Tiffany       | Venezuela   | Misoa Ss | Eo         | Fluvio-deltaic                                        |
| Weixing       | Songliao    | NE China | Putahua    | 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  | Tyler | L. Cr | Meander belt |
|               |             |          | Tuscaloosa | Fluvio-deltaic |
| Greater Burgan| Kuwait      | Burgan   | L. Cr      | Fluvio and tidal dominated                             |
| Crawford      | UK          |          | Tr-Cr      | Fluvio channel fills                                   |
| Wytch Farm    | UK          | Sherwood Ss | Tr       | Braided                                                   |
| Barryroe      | Celtic Sea  | Ireland  | Wealden    | L. Cr | Fluval? |
| 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]    | Morse [54]  |
| 2560      | 17           | 80               |                     | 570           | O            | 3000 |                     |                         |            |
### 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/ fluvo-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-Pl | Stacked delta plain, channel, mouth bar and delta front |
| Bekapai | Indonesia | Balikpapan | Mio-Pl | Stacked delta plain, channel, mouth bar and delta front |
| Oseberg | Norway | Oseberg Ness | | Delta lobes stacked with delta plain |
| Smorbbuk | Norway | Tille, Iie, Garn | | Tidal influence shoreline and braided delta complex |
| Statford | UK/Norway | Brent and Statford | Ju | Delta front, mouth bar and channels |
| Cambay-Hazard (1) | India | Hazad | M. Mio | Prograding deltaic Sandstone |
| Prudhoe Bay | USA | Sadlerochit | L. Tr | Deltaic, fluvial |
| Island Block 300 | Gulf of Mexico | | | 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                  |               |             | G,O  | 200.1               | 3160 BCFG                | Morse [54]               |
| 1372      | 22           | 200               |                     |               |             | O    | 1420                | 770 MMBO (51%)           | Morse [54]               |
| 1300      | 25-35        | 1000              |                     |               |             | O,G  | 1180                |                          | Hagen and Kvalheim [26]  |
| 2120-2700 | 24           | 2000              |                     |               |             | O,G  | 1420                | 770 MMBO (51%)           | Morse [54]               |
| 3800-4400 | 11           | 10-1000           | 300                 |               |             | O    | 1180                |                          | Ehrenberg et al. [22]   |
| 2585      | 29           | 250-1500          |                     |               |             | O,G  | 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                 |               |             | O    | 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       | Norwegian   | Viking        | U. Ju      | Stacked shelf, prograding shoreface |
| Snohvit     | Norwegian   | Sto and Nordmela | U. Ju   | Transgressive coastal plain, inner shelf, tidal channels |
| Draugen     | Norwegian   | Rogn          | U. Ju      | Shallow marine shelf sand bars    |
| Piper       | UK          | Piper Ss      | U. Ju      | Marginal marine shelf              |
| Northern    | Niger Delta  | Nigeria       | U. Eo- L. Mio | Paralic, shoreface, shell, barrier bars and channel sands |
| Niger Delta  | Niger Delta  |              |            |                                      |
| Takula      | Cabinda     | Vermelha Ss   | U. Cr      | Stacked nearshore, coastal sands, foreshore, tidal channels |
| Cueta-Tomporo | Venezuela | Lagerinillas  | U. Oli     | Shallow coastal bars and fluvo-deltaic channels |
| El Furrial  | Papua New Guinea | Toro Ss  | L. Cr      | Shallow marine and barrier bars    |
| Lagif/ Hedinia |             |              |            |                                      |
| Fortescue   | Southeast   | Australia     | Eo         | Transgressive coastal plain, coastal plain, shoreface |
|             |             | Latrobe       |            |                                      |
| Venture     | Canada      | Venture Ss    | U. Cr      | Shallow marine, deltaic             |
| Tom O’Connor | USA         | Frio          | OI         | Inner-middle shelf to foreshore, beach |
| Middle Ob   | Russia      |              | L. Cr      | Shallow marine and fluvo-deltaic    |
| Cupiaguia   | Colombia    | Llanos Foothills/ Mirador | Lt. Cr- Lt. Eo | Shallow marine- alluvial         |
| Tom Walsh-Owen | USA        | Olmos         | L. Cr      | Marine shelf                        |
| Thomasville | Mississippi Interior Salt | Smackover | L. Ju      | Nearshore-mid ramp                 |
| Gudao       | 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 (MMBO/ BCFG) | References |
|------------|--------------|-------------------|----------------------|---------------|--------------|------|----------------------|--------------------------|------------|
| 1300-1500  | 25           | 500-1000          | G                     | O,G           | 9000 MMBO    | Morse | [54]                 |                          |            |
| 2280-2418  | 5-15         | 200               | G                     | O,G           | 4.5          | Morse | [54]                 |                          |            |
| 1600       | 28           | 700-1000          | O                     | O             | 1100         |        | 410 (37.2%)          | Provan [56]             |            |
| 2195       | 24           | 4000              | O                     | O             | 600          |        | 600                  | Mahers [43]              |            |
| 1700       | 15-25        | 1000-2000         | O,G                   | O,G           | 4500         | Morse | [54]                 |                          |            |
| 971-1038   | 25           | 1000              | O                     | O             | 2100         | Dale  | [20]                 | Ramirez and Marciano [58]|            |
| 4510-5180  | 12-17        | 10-1200           | O                     | O             | 1400         |        | 890 (19.7%)          | Prieto and Valdes [55]  |            |
| 3962-4120  | 11-16        | 10-1200           | O                     | O             | 4500         |        | 280 (66.6%)          | Hendrich et al. [30]    |            |
| 2438       | 13           | 300               | O                     | O             | 150          |        | 500                  | Matzek et al. [46]      |            |
| 2300-2400  | 20           | 100-10000         | O                     | O             | 420          |        | 250 (66.6%)          | Hendrich et al. [30]    |            |
| 4436-5800  | 16           | 10-40             | G                     | G             | 130          |        | 250                  | Mills [53]               |            |
| 1371-1928  | 31           | 500-2000          | O,G                   | O,G           | 670          | Morse | [54]                 |                          |            |
| 2380-2820  | 3-25         | 0.01-300          | O                     | O             | 30           | James  | [36]                 |                          |            |
| 3935-4590  | 2-8.1        | 0.1-90            | O,G                   | 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                  | Snowden and Jump [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          | G                     | O             | 60           |        | 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 (1623.9mD) for the shallow marine reservoirs. The maximum permeability does not occur with the highest porosity (1245mD). 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        |
|--------------|-------------|------------|----------------|------|-------------------------------|
| Yowlamme     | San Joaquin | USA        | Stevens Ss     | L. Mio | Submarine fan                |
| Forties      | Central Garben | UK    | Forties        | U. Pal | Submarine fan                |
| Midway-Sunset (Webster Zone) | San Joaquin | 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                |
| Marlin       | Brazil     | Carapebus Ss | U. Olig     | Submarine fan |
| Albacora     | Brazil     | Carapebus Ss | U.Cr-Mio    | Submarine fan, lobe and channels |
| Namorado     | Brazil     | Brazil     | U. Cr          | Submarine fan, stacked channels and lobes |
| Marlima      | Brazil     | 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 (MMBO/BCFG) | 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%)               | Kulpeetz and Van Guem [40] |
| 210-365   | 28-35 (33)   | 800-4000 (1000)   | 15-76               | 60-80         | 2.9          | O    | 75                  |                         | Hulst and Link [27]        |
| 1525-1980 | 20-25 (23)   | 3-46              | 50-100              | 46.6          | G            | 1100 |                     |                         | Imperato and Nilsen [35]   |
| 1860      | 35           | 2800              | 90                  |              | O            | 1100 |                     |                         |                          |
| 3890-4090 | 12-23        | 50-1200           | 60                  | 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              |                     | 250           | O            | 470  | 170 (36.1%)         |                         | Bacoccoli et al. [6]       |
| 2700      | 27           | 1000              |                     | 250           | O            | 9600 | 2500 (26%)          |                         | Horschutz et al. [32]      |
| 610-1830  | 30-35        | 700-1500          | >600                |              | O            | 9600 |                     |                         | 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.

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            |
| Piggah 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|                    |     | Aeolian                                        |

Table 5. Continued.

| Depth (m) | Porosity (%) | Permeability (mD) | Thickness of Pay (m) | Net/Gross (%) | Area (Sq Km) | Type | In Place | Recoverable (MMBO/ BCFG) | 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    | 0.6      |                          | Thomson and Stancliffe [69] |
| 2850-2877 | 14           | 30-80             | 244                 |               |              | O    | 70       |                          | Gage [23] |
| 10-30     | 10-1200      | 23                | 260                 |               |              | O,G  | 910 MMBO |                          | Mello et al. [50] |
| 2918      | 14           |                   |                     |               |              |       |          |                          | 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.

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].

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              | 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           | 9075             | 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.

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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