UNDERSTANDING THE DISTRIBUTION OF SATURATION EXPONENT IN THE NUBIAN SANDSTONE FORMATION, SIRT BASIN LIBYA USING GLOBAL HYDRAULIC ELEMENT APPROACH

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Abstract: The estimation of hydrocarbon reserve is strongly dependent of electric logs data and the saturation exponent has either assumed or used on average value of the whole of reservoir. The reason of this that the petrophysist dos not usually has a more detailed description of reservoir. The main objective of this study is to use the Global Hydraulic Elements approach to estimating the distribution of saturation exponent in the Lower Cretaceous of Nubian Sandstone Formation Sirt Basin, Libya. Amaefule *et al* (1993) introduced the first rock typing approach which was strongly dependent on core plug data sets and was successful in determining different systems in a single dataset. But this method has a major limitation when applied many data sets. This limitation has been overcome by the new concept of 'Petrotyping' (using Global Hydraulic Elements) which was developed by Corbett *et al*, 2003; Kooistra, (2004). In this study two wells are selected from Sirt Basin to evaluate reservoir description of Nubian Sandstone Formation using Global Hydraulic Elements. Six samples plugs have been selected from different Global Hydraulic Elements to determine saturation exponent using porous plate method and to distinguish the saturation exponent between the Global Hydraulic Elements in the Lower Cretaceous of Nubian Sandstone Formation, Sirt Basin Libya.

Keywords: Petrotype (Global Hydraulic Elements) Approach, Global Hydraulic Elements Base map, Flow Zone Indicator, Boundaries of Global Hydraulic Elements, Reservoir description, Capillary Pressure, Saturation Exponent, Nubian Sandstone Formation (NSF).

INTRODUCTION

The most important and emerging challenge for geoscientist and engineering's is to improve the reservoir description programs, which though detailed, have not always included description at the pore throat scale (Amaefule *et al,* 1993). In this study the controls on porosity and permeability in the Lower Cretaceous, Nubian Sandstones Formation Sirt Basin, are considered with respect to their texture and cementation, their petrophysical classification and the effect of subdivision of the petrophysical rock types. The main controls on hydraulic properties and hence the fluid in the porous reservoir media is of major importance for reservoir description. The porosity and permeability of Nubian sandstone Formation which are determined from the laboratory are highly variable across the whole volume of the reservoir being moderate to good in some intervals and poor in other intervals. For this reason the Global Hydraulic Elements, an adaptation of traditional rock typing method, have been used in this study to improve the description of Nubian Sandstone Formation. Using this breakdown of petrophysical data-and we show that other rock typing approaches produce similar results-is a process of petrotyping (Corbett and Potter, 2004). This is different from more conventional petrophysical rock typing approach (Amaefule *et al*, 1993) because the boundaries of the petrophysical elements are predetermined prior to collecting any plug data. This allows for a rapid and more systematic approach for varying data sets in various wells. The estimation of hydrocarbon reserve is strongly dependent on electric log data and the saturation exponent has either been assumed or an average value for the whole of reservoir has been used. The reason for that is the petrophysist does not usually have a more detailed description of reservoir. Therefore, the main objective of this study is to use this approach to estimate the distribution of the saturation exponent in the Nubian Sandstone Formation, Lower Cretaceous in Sirt Basin, Libya.

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PETROTYPE METHODOLOGY

Historical Development of Global Hydraulic Element Approach

Reservoir description has many applications in the geology, petrophysics, reservoir engineering and production. Reservoir description is very important to understanding of the reservoir and it is generally hoped that more consideration of reservoir description may lead to less time spent history matching in reservoir modelling. Petrophysists have long tried to define a hydrocarbon-bearing reservoir as a limited set of elements number with unique characteristics of each one. To address this, Amaefule *et al* (1993) introduced the first approach of the Hydraulic Flow Units (HFU) concept. This concept was successful in determining different systems in a single dataset, such as a cored well, but this method has one major limitation, that different HFU's were found in each well. This limitation is of "overcome by the new concept petrotyping" using (Global Hydraulic Elements) which was developed in a series of studies Corbett *et al* (2003); Corbett and Potter, (2004); Svrisky *et al* (2004) Kooistra, (2004). The GHE approach also based on FZI values from the same underlying theory as Hydraulic Units (HU). However, the selecting of a systematic series of FZI values allows to determination of Hydraulic Units (HU) boundaries to define ten Global Hydraulic Elements (Table 1) that can be applied to any reservoir formation (Fig.1). The defineition of these boundaries is arbitrarily chosen in order to split a wide range of possible combinations of porosity and permeability in to a manageable number of Global Hydraulic Elements (Corbett *et al*, 2003; Corbett and Potter, 2004). Corbett and Potter (2004) have pointed out that the plotting of plug data on the Global Hydraulic Elements "base map" allows trends to be easily determined. This mapping approach allows for the ready comparison between reservoirs, wells, fields, core data and simulation data, and it can be recognized and exploited for permeability prediction. The consistent colour palette of Global Hydraulic Element (GHE) approach (Fig. 1) can also be applied to core data for identification of significant ordered trends in wide range of cross plots of different parameters (Corbett and Potter, 2004). Previous petrotyping studies in the Ordovician in Libya had produced encouraging results (Khalifa, 2006). In this paper, petrotyping has been applied in the Lower Cretaceous, Nubian Sandstone Formation Sirt Basin, Libya (Mousa and Corbett, 2009) and the usefulness of petrotyping as a screening approach to SCAL sample selection is emphasised in this technical note.

Table 1. Shows Boundaries of Global Hydraulic Elements defined by FZI values (Corbett and Potter, 2004).

FZI	GHE
0.0938	1
0.1875	2
0.375	3
0.75	4
1.5	5
3	6
6	7
12	8
24	9
48	10

Petrotyping (Global Hydraulic Elements) in the study area

The Global Hydraulic Element (GHE) approach has been applied for the study area Southeast Sirt Basin, Libya, to improve the reservoir description and identify petrophysical rock types for this reservoir formation (Two wells are selected A and B). The Global Hydraulic Elements base map was used to identify significant (or lack of) trends of Nubian Sandstone Formation (Figs. 2 and 3). Six (or possibly seven) Global Hydraulic Elements are identified for well A and four for well B (as shown in a Figs. 2 & 3). Photomicrographs (Figs. 4 & 5) show the textural differences between the extreme units.

Definition of Storage and Flow Dominated GHE

The transmissivity (flow) capacity and storability (storage) capacity can be estimated for the Global

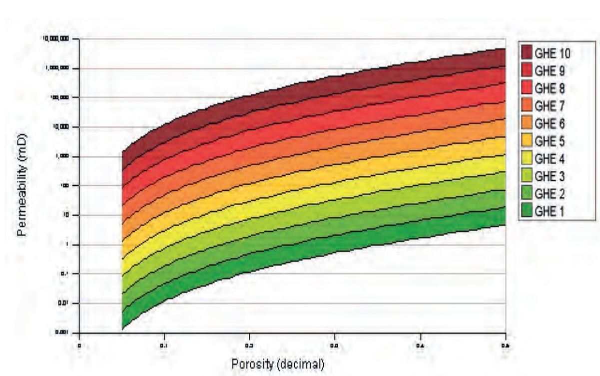

Fig.1. Global Hydraulic Elements Base map template showing GHE at the base GHE-1 at the base and GHE-10 at the top (Corbett and Potter, 2004)

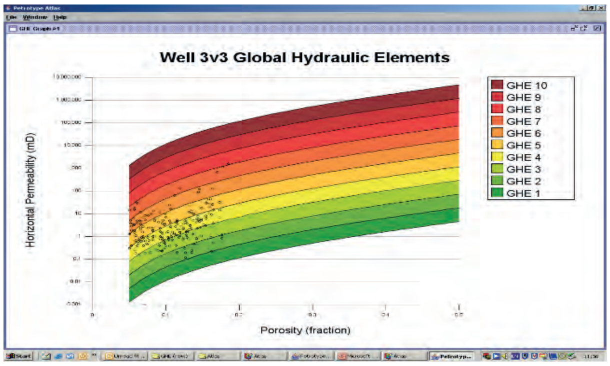

Fig. 2. Shows the GHE trends in well A GHE-1 is the lowest class and GHE-10 the uppermost

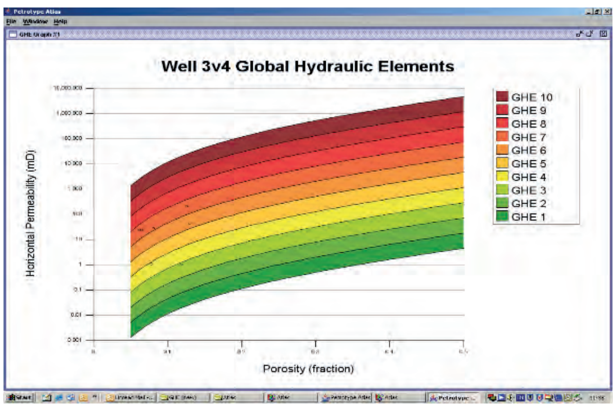

Fig. 3. Shows the GHE trends in well B GHE-1 is lowest class and GHE-10 the uppermost. This well has very few data points but these can be seen to be related to the GHE data in Well A (Fig. 2.).

Hydraulic Elements (GHE) by using a Lorenz Plot. It is useful to identify the storage capacity and flow capacity of the reservoir formation and to use this information in a petrography to see what the difference between the GHEs is dominating storage capacity and GHEs which are dominating flow capacity. The properties transmissivity and storativity are important in well test analysis and the identification of flow intervals, they will affect the thickness assigned in the determination of predominant flow interval indicated. (Zheng *et al*, 2000). The Lorenz Plot displays the petrophysical data in a useful way for reservoir engineering. The Lorenz Plot is the general static measurement of variability and to compute this, first arrange the permeability values in decreasing order of K/Φ and then calculate the partial sums (Jensen *et al*, 2000):

$$F_j = \sum_{j=1}^{j} K_j h_j \Big/ \sum_{i=1}^{i} K_i h$$

$$C_j = \sum_{j=1}^{j} \Phi_j h_j \Big/ \sum_{i=1}^{i} \Phi_i h_i$$

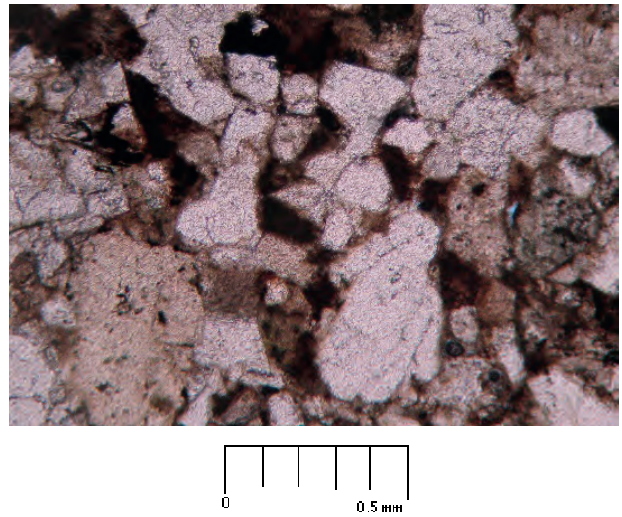

Fig. 4. Nubian Sandstone GHE 2–the worst reservoir quality found in this study–showing very little porosity

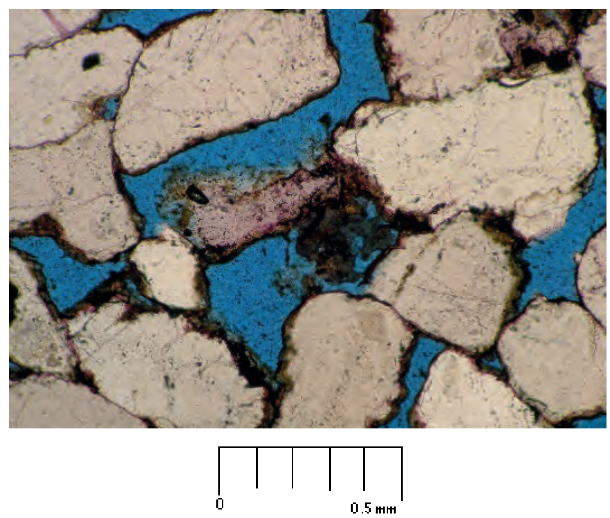

Fig. 5. Nubian Sandstone GHE 7–the best reservoir quality in this study showing well connected porosity.

Where:

F_j = Fraction of total flow capacity (permeability * thickness).

C_j = Fraction of total storage capacity (porosity * thickness).

K = Permeability (mD).

Φ = Porosity (fraction).

h = Thickness (ft).

In the well A, the Lorenz Plot shows that the approximately 83% of the total flow is coming from GHE's 8 and 7 which provide only 8% of the storage. Only 17 % of the total flow is coming from the GHE's 3, 4, 5 and 6, which provide 92% of the storage capacity of these Global Hydraulic Elements. The core data porosity and permeability in Well B is actually not sufficient to make analysis but from the

Lorenz Plot we can recognise that the 60% of the flow is coming from GHE-7. We recognize from the Lorenz Plot that the permeability distribution are very heterogeneous with the flow capacity (TGHE) and storage capacity (SGHE) elements for both wells (A and B) being very unevenly distributed (Figs. 6 and 7).

EXPERIMENTAL MEASUREMENTS

Seven core plugs samples from well A were selected following the petrotype screening process described above and have been examined in details (Table 2). These samples are representative of the GHE found in the two wells (Tables 3 and 4). These core plugs show a distinct trend in texture contrast where the finer grained and poorly sorted sands are associated with GHE-2 which has the worst reservoir rock quality (Figs. 4) while the coarse grained and well sorted sands are associated

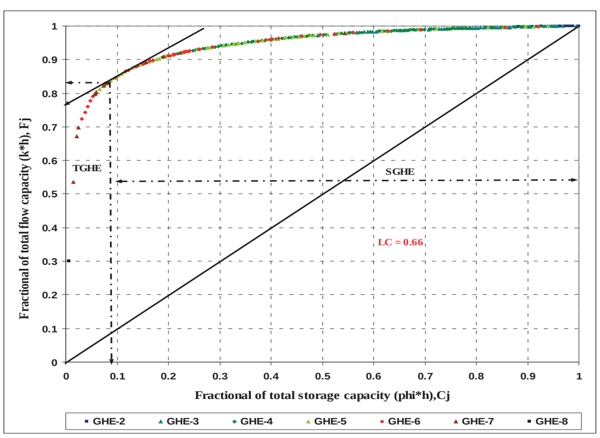

Fig. 6. Well A GHE-coded Lorenz Plot shows the transmissive – dominated GHE,s (TGHE) and storage dominated GHE's (SGHE) defined by tangent to the curve (Mousa, 2008).

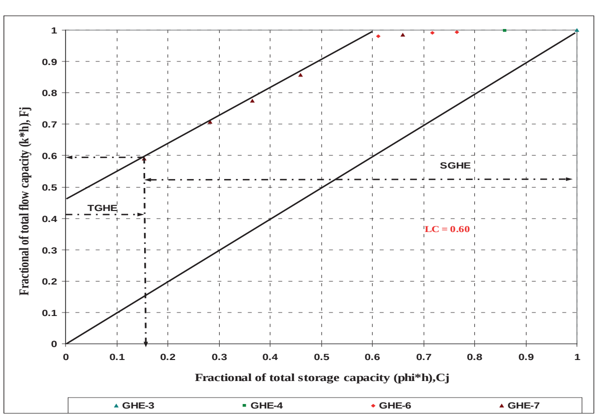

Fig.7. well B GHE-coded Lorenz plot shows the transmissive-dominated GHE's (TGHE) and storage-dominated GHE's (SGHE) defined by a tangent to the curve.

with GHE-7 and GHE-8 with the best reservoir rock quality (Fig.5). Primary depositional texture (grain size), quartz overgrowth and clay minerals appear to drive the variation in the permeability and porosity relationship in the Lower Cretaceous Nubian Sandstone Formation.

CAPILLARY PRESSURE

The Mercury Injection Capillary Pressure technique was used in this study to investigate the pore throat properties of the GHE's in the Lower Cretaceous of the study area to confirm the rock type selection and to predict the variation in the hydrocarbon saturation in the Nubian Sandstone reservoir. The reservoir capillary pressure/water saturation relationship in the Lower Cretaceous here is dependent on rock type (Fig. 8) and related to grain size and cementation. This would suggest that rock type distribution within oil-column height could have a large impact on oil in- place determination as oil-water contact (Khalifa, 2006).

POROUS PLATE METHOD

The porous plate method is used in this study to derive the saturation exponent in the laboratory. Six samples plugs have been selected from different Global Hydraulic Elements for the NSF to determine water saturation, cementation exponent and saturation exponent. The samples were cleaned in hot solvents, dried and then mounted in to the core holder. All the samples were saturated with the brine (110,000ppm) which represents the salinity of the NSF. Clay powder was used between the samples and the porous plate to maintain hydraulic contact during the test. A fi ne metal coated sponge was placed at the inlet end of the plug to ensure good electrical contact. The resistivity of saturated samples (*Ro)* and brine resistivity (*Row)* were measured on consecutive days until the results were stabilized. The resistivity index measurements were carried out using the porous plate method. In this method, the resistivity measurements and de-saturation process takes place separately. The samples were de-saturated simultaneously. By placing them on a porous place in a pressure cell, and gas pressure was applied. The gas (nitrogen) enters the samples from all direction except from the end face. The gas pressure was maintained until no more brine was produced. After capillary equilibrium was reached, the gas was then released and the samples removed from the pressure

Table 2. Showing the selection GHE core samples for detail study

Well A	Plug No.	Porosity %	Permeability mD	FZI	Grain Size	Sorting	GHE
A	240	11.6	0.2	0.316	fine	Poor	2
A	138	15.9	1.12	0.443	fine	Moderately-Poor	3
A	87	15.8	7.2	1.207	fine-medium	Moderatly-Poor	4
A	216	13.4	24.7	2.74	fine-medium	Moderately	5
A	76	16.6	96	3.82	fine-medium	Moderately	6
A	69	18.3	1104	10.9	medium-coarrse	Well Sorted	7
A	66	18.6	1535	12.6	medium-coarrse	Well Sorted	8

Table 3. Showing the Nubian Sandstone Well A Global hydraulic Elements Statistical Summary

GHE	Number of samples	Average FZI	Average permeability (mD)	Average Porosity %
2	11	0.298	0.53	14.6
3	45	0.601	1.07	12.1
4	85	1.093	2.8	11.1
5	58	2.031	7.7	9.3
6	41	4.174	15.5	15.5
7	13	8.911	155	7.1
8	1	12.58	1536	18.5

Table 4. Showing the Nubian Sandstone Well B Global Hydraulic Elements Statistical Summary

GHE	Number of samples	Average FZI	Average permeability (mD)	Average Porosity %
3	1	0.681	1.014	12
4	1	1.379	1.068	7.8
6	3	4.03	15.5	7.3
7	5	7.773	56.4	7.4

cell and weight measurements were taken as well as resistivity reading. The procedure was repeated for several pressures in the range of 1-120psi. The de-saturated process for each sample typically took 2-3 days to complete. Finally, the saturation exponent (n) was calculated (Table 5 & Al-Mahtot *et al*, 1998).

DISCUSSION OF SATURATION EXPONENT RESULTS

The laboratory measured saturation exponent (n) showed some variation. An exact value of saturation exponent is necessary for a good log interpretation analysis aiming to a precise water saturation determination. There are concerns with any laboratory method but here we wish to illustrate that the samples produce a trend. There are many factors affecting saturation exponent such as rock wettability, grain pattern, presence of certain authigenic clays, particularly chamosite, which may promote oil wet characteristics and history of fluid displacement. However, it is found that the rock wettability is the main factor affecting the saturation exponent (Hamada et al, 2002). The saturation exponent value is a function of both pore system geometry and formation wettability. The saturation exponent value is therefore, of essential importance for the calculation of true initial water saturation from logs. Saturation exponent is normally determined experimentally in the laboratory on core samples of the actual formation under consideration. To obtain a more realistic evaluation of the (n) value because the saturation exponent value varies with both lithology and wettability a suite of saturation exponent value measurement is often conducted on samples from range of porosity and permeability and lithology which may be present in the formation (Bennion et al, 1996). The saturation exponent is related to the texture and affected by wettability and clay minerals, the wettability of those Global Hydraulic Elements are water-wet because the range of saturation exponent is from 1-2. Figure 9 shows that there is a good relation between the Global Hydraulic Elements and saturation exponent. For this study the saturation exponent decreases from GHE-2 which is the poorest reservoir quality and

Table 5. Showing the saturation exponent (n) of Global Hydraulic Elements

Sample No.	Porosity %	Porosity (fraction)	Permeability (mD)	Swi	Saturation Exponent (n)
GHE-2	11.77	0.1177	0.1	0.71	-2.7
GHE-3	15.85	0.1585	1.12	0.7	-1.99
GHE-4	14.35	0.1435	7.19	0.6	-1.91
GHE-5	13.23	0.1323	24.7	0.17	-1.98
GHE-6	16.55	0.1655	96.4	0.27	-1.75
GHE-7	18.27	0.1827	1104	0.11	-1.54

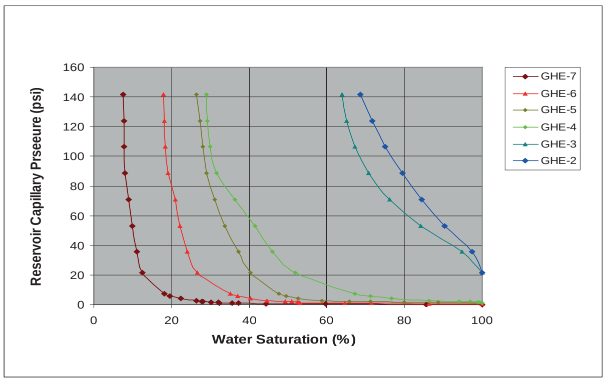

Fig. 8. Shows the relationship between reservoir capillary pressure, water saturation and systematic trend according to the GHEs in the study area

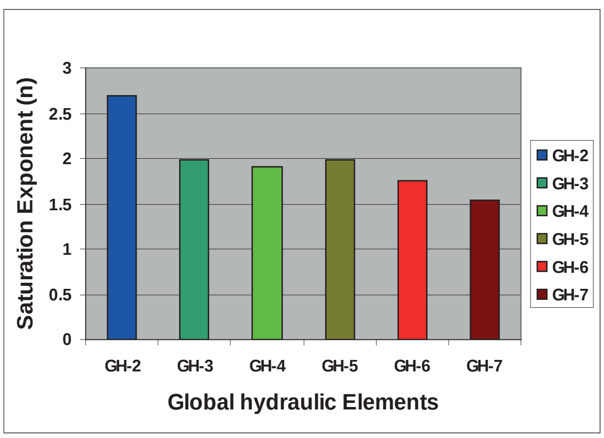

Fig. 9. Showing the distribution of saturation exponent for Global Hydraulic Elements which derived from laboratory study.

tends to be oil-wet to GHE-7 which is the best reservoir quality and is water-wet.

DISCUSSION OF PETROTYPE SAMPLING APPROACH

A single core plug is selected from each petrotype class. Clearly using this very limited dataset to draw conclusions about this field is perhaps stretching the data. In that context this study might be considered a screening study. Additionally, the Generalized Hydraulic Unit (Shenawi *et al*, 2009) approach might also supply an alternative set of equations that could be used for petrotyping. The rationale for having a limited number of possible rock type elements in a reservoir takes in to account the following: sedimentologists use a limited number of grain size classes to describe texture and rock types in clastics are predominantly texturally controlled (Brayshaw *et al*, 1996). The variation-for a given porosity within a GHE-is within one order of magnitude and therefore is essentially homogeneous (Corbett and Jensen, 1992). Simulation studies suggest that capturing the variability between rock types is more important that the variability within rock type classes/elements when sampling issues are concerned (Mohammed and Corbett, 2003). Modelling the correlation lengths of many rock type elements (lithofacies) within a pixel (sequential indicator simulation) or object modelling workflow is most effective with a limited number of rock types. Using an industry-wide, standard, set of petrophysical elements for all reservoirs can also provide benefits. Identifying porosity and permeability properties within a limited and standard element framework allows for the consistent mapping of these properties within and across wells provides a basis for database construction at the rock typing level (rather than lithology, age, environment or any other criteria) and this has been found useful in petrophysical database studies (Kooistra, 2004). The petrotyping approach, therefore, provides a consistent approach for the petrophysical requirements for reservoir modelling where lithofacies-guided rock typing approaches are the vehicle to enable the 3D distribution of reservoir properties.

CONCLUSIONS

- Seven Global Hydraulic Elements (GHE's 2, 3, 4, 5, 6, 7 and 8) have been identified in Well A and four Global Hydraulic Elements (based on a more limited data set) have been identified in well B (GHE 3, 4, 6, and 7). Because the approach taken, the GHE's are consistent between the wells.

- The core data porosity and permeability for both wells A and B have been plotted on Global Hydraulic Elements Base map to identify the GHE trends.
- Seven representative core plug samples have been selected for the Global Hydraulic Elements in study wells for more detailed study.
- The Lorenz Plot shows that the flow capacity (TGHE) and the storage capacity (SGHE) of the study wells are unevenly distributed. Most of the flow in the wells comes from a few thin zones.
- The textural characteristics of Global Hydraulic Elements are variable. The grain size of GHE-2 is fi ne grained with poor sorting which is the poorest reservoir quality while in GHE-8 is coarse grained and well sorted which is the best reservoir quality. The primary depositional texture has a major role on controlling reservoir properties in the Lower Cretaceous sandstones.
- The petrotyping approach gives a clear trend idented able in the capillary pressure, despite the small sample size.
- The relationship between water saturation and height shows that the water saturation is 18.18% at 51.04ft for GHE-7 which is the best reservoir quality whereas, is 90.23% at 400ft for GHE-2 which is the poorest reservoir quality.
- There is a good relationship between water saturation and reservoir capillary pressure for Global Hydraulic Elements of study wells.
- The relationship between reservoir capillary pressure and water saturation is dependent on grain size, sorting and cementation which control the porosity and permeability.
- The saturation exponent in the reservoir volume is not uniform and the Global Hydraulic Elements approach provides a method for mapping saturation exponent which is a variable in the NSF.
- The petrotype (Global Hydraulic Elements) approach is useful for understanding variation in petrophysical properties which are extreme in the Nubian Sandstone Formation. The range of Global Hydraulic Elements in the reservoir volume can have a significant control on saturation exponent, the distribution of saturation (OIP) on GHE's.
- Following such a screening study, a more comprehensive programme across the range of rock types and porosities is recommended.

NOMENCLATURE

FZI Flow Zone Indicator
GHE Global Hydraulic Element
HFU Hydraulic Flow Units
NSF Nubian Sandstone Formation
SCAL Special Core Analysis

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