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Analysis of the reservoir electrofacies in the framework of hydraulic flow units in the Whicher Range Field, Perth Basin, Western Australia

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Abstract

Reservoir characterization and recognition of the main factors controlling the reservoir quality has a significant share in presenting a real picture of the reservoir properties. In this study, by examining a set of reservoir well log data and their clustering based on mathematical and statistical principles, reservoir electrofacies are identified for the tight sands of Willespie Formation in five wells from the Whicher Range Field in Western Australia. These internally homogenous and externally heterogeneous clusters are truly a reflection of geological (sedimentary and diagenetic) and petrophysical properties of the reservoir. In this study, reservoir electrofacies (EF) were determined using clustering of well logs and along with porosity and permeability data in two individual sedimentary and petrophysical approaches.

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In the sedimentary approach, three EFs were identified that coincide with clean sands, dirty sands and shaly intervals. They are mostly related to the sedimentary texture and lithological properties indicating high reservoir heterogeneity.

In the second approach, four EFs were determined in relation to the petrophysical properties of sandy packages within the reservoir. In addition, in order to find a good connection between EFs and production zones within sandy packages, five hydraulic flow units (HFUs) were introduced. The results show that low quality HFUs (i.e. A, B and to some extent C) in all petrophysical electrofacies are mainly related to the fine grained facies deposited in low energy systems. In contrast, high quality HFUs (i.e. D and E) are related to the medium to coarse and very coarse grained facies, showing different petrophysical properties, although they have generally low permeability and they are considered as tight sands. Thus, three sand types, depending on the severity of diagenetic effects, known as type 1 or very tight sands, type 2 or tight sands and type 3 or sub-tight sands were differentiated. In comparison, sandstones in type 3 with higher porosity and permeability have the best reservoir quality, whereas low reservoir quality sandstones in type 1, have been strongly affected by diagenetic effects (quartz and clay cementation). The results indicate a good agreement between core derived rock types and log facies. Using the methodology described in this study, it is possible to track reservoir flow units from well log responses.

Keywords

Electrofacies, Hydraulic Flow Units, Reservoir Characterization, Tight Sands

1. Introduction

An accurate and proper understanding of the hydrocarbon reservoir requires a comprehensive study of the sedimentary and diagenetic characteristics of reservoir rocks. Integration of the results from these studies with petrophysical data has an important role in identification of production zones and main factors controlling the reservoir quality. On the other hand, the results obtained from different geological and petrophysical studies can partly be different depending on the methods used.

Nowadays, developments in various disciplines of geosciences to address industry requirements, presenting of new and applied statistical and mathematical methods in reservoir characterization, prevents from dispersion and import of personal tact in interpretation of the results and elevates the trust coefficient. Determination of electrofacies is used for identification of clusters of well logs responses with similar characteristics (Lee and Datta-Gupta, 1999). Behavior of individual well logs against reservoir rocks results in separation of distinct responses sets known as electrofacies. This response against reservoir rocks is in fact a reflection of variability related to geological and petrophysical properties of the reservoir recorded continuously along the well.

The application and importance of electrofacies in reservoir description and management has widely been distinguished (Bucheib and Evans, 1994; Dorfman et al. 1990; Doveton and Prensky, 1992; Kim and Lim, 1998; Moline and Bahr, 1995; Serra and Abbott, 1982). Thus, separation of reservoir facies based on available logs known as log facies or electrofacies, can be used as a useful, practical and economical procedure in this regard. In addition, study of the recognized electrofacies from petrophysical point of view and in relation to

hydraulic flow units, provides a suitable understanding of the reservoir properties and production zones.

In this section, we first address a brief history of rock typing. There are different definitions in the literature to describe rock type depending on the available data and the targets we follow. In addition, using various methods and techniques by different researchers reflects an evolutionary history of rock typing. Firstly, rock typing defined based on characteristics gained from core (lithofacies) and petrographic (microfacies or petrofacies) studies especially for sandy reservoirs (e.g. Davies et al. 1991; Porras et al. 1999). Then, petrophysical rock typing based on core measurement of porosity, permeability and water saturation introduced in conjunction with geological parameters (e.g., Aplin et al. 2002; Ali-Nandalal & Gunter, 2003; Acosta et al. 2005). In carbonate reservoirs, electrofacies entered new aspects of rock typing based on log responses (e.g., Al-Farisi et al. 2004; Lee et al. 2002; Mathisen et al. 2001; Perez et al. 2003, 2005). In fact reservoir rock typing is a synergetic process between geology and petrophysics (Gomes et al. 2008).

Archie (1950) defined a rock type as units of rock deposited under similar conditions which experienced similar diagenetic processes resulting in a unique porosity-permeability relationship, capillary pressure profile and water saturation for a given height above free water in a reservoir.

In Schlumberger oilfield glossary rock type defined as: A set of characteristics that several rocks have in common. The characteristics of interest are usually those pertaining to fluid movement and fluid storage capacity. In this respect, petrophysical rock types are rock types that have been classified according to their petrophysical properties, especially

properties that pertain to fluid behavior within the rock, such as porosity, capillary pressure, permeabilities, irreducible saturations or saturations. Petrophysical rock types are often calibrated from core and dynamic data, but are usually calculated from wireline logs, where possible, because the wireline logs are generally the only measurements that are available for all wells at all depths. Electrofacies approaches are often used to determine rock types from logs. In this regard, electrofacies is applied for a set of log responses which characterizes bed/strata and allows it to be distinguished from others (Serra, 1986).

Rock typing based on flow units is the one that has been used by many researchers (Ahr, 1991; Amaefule et al. 1993; Ebanks, 1987; Gunter et al. 1997; Slatt and Hopkins, 1990; Stoudt et al. 1992; Ti et al. 1995). Amaefule or FZI method for determination of hydraulic flow units is a common method and many researchers (e.g., Amabeoku et al. 2005, 2006; Kadkhodaie-Ilkhchi and Amini, 2009; Svirsky et al. 2004) proposed different methods mainly based on Amaefule model. He defined Hydraulic Flow Unit as the elements of the reservoir rock which have similar averages of petrophysical rock properties that affect fluid flow. In this study, we propose an approach to hydraulic flow unit identification in tight sands using common Amaefule method. We demonstrated that rock typing of tight sands (as a type of unconventional reservoirs) by using a suite of well logs or electrofacies techniques is a good approach specially when integrated with flow properties can provide a real picture of reservoir heterogeneity related to dominant depositional and post-depositional processes controlling pore properties and resulted reservoir behavior. In other words, the integration of two rock typing methods, electrofacies and hydraulic flow units can efficiently combine both geological and petrophysical aspects of tight sands. This

can help reservoir geoscientists and engineers for a comprehensive understanding and interpretation of production behavior in the field.

The results of this research can be useful in the development of the field, taking a decision and proper strategy in the connection of hydrocarbon production and recovery in the future.

2. Geological setting and stratigraphy of the Perth Basin

Perth Basin is an N-S trending, long and narrow and asymmetrical rifting basin (Fig. 1) located in the southwest of Australia (Cadman et al. 1994). Tectonic movements have had an important role in the formation and structural features of the basin. Both north and south parts of the basin structurally have been subdivided into different sub-basins (Song and Cawood, 2000).

A thick succession of Late Permian through Cretaceous sediments has been deposited in marine to non-marine environments in this basin. They are mostly composed of sandstone, siltstone and mudstone associated with minor amounts of conglomerate, carbonate and coal (Playford et al. 1976; Crostella, 1995). Figure 2 shows a general stratigraphic column of the south Perth Basin.

Study of the oil system in the Perth Basin indicates mature and extensive source rocks, enormous reservoirs and suitable structures for trap formation (Owad-Jones and Ellis, 2000). Whicher Range is one of the most important gas fields in the South Perth Basin. The field is located in a large anticline structure in Bunbury trough and five wells have been drilled in this structure so far (Fig. 3). The sandstones of Willespie Formation, with Late Permian in age, constitute the main reservoir rock of the field (Crostella and Backhouse,

2000; Sharif, 2007). These sandstones are mostly reported as tight, with low porosity and low permeability. As stated above, the purpose of this study is to evaluate the reservoir characteristics of these sandstones, using electrofacies.

3. Data and Methodology

In order to determine and differentiate different types of electrofacies in the reservoir, well log data from the Willespie Formation from four wells (WR1, WR2, WR3, and WR4) of the Whicher Range Field are used. The Willespie Formation is part of the Sue Group with Late Permian in age (Fig. 2). Well log data used in this study are gamma ray, density, neutron, and sonic logs. Core porosity and permeability data are available for all wells with exception of WR5, but these data are spars and does not cover the entire reservoir interval. Thus, porosity data derived from sonic log for all wells (with the exception of WR5 without core porosity and permeability data), after removing the shale effect, are used. Also, permeability data from PDPK-300 (done by Core Laboratories Australia, 1998) covering whole parts of the reservoir interval are used. The PDPK-300 is a computer automated unsteady-state permeameter where in a known pressure is allowed to decay through the surface of the core. Klinkenberg permeability and permeability to air are determined from the pressure decay versus time (rate) data. Validity of data from both sources (porosity from sonic log and permeability from PDPK-300) checked by available core data for some wells (WR1 and WR4). The results with relatively good correlation have been shown as plots in Figure 4.

Tight sands in the Whicher Range gas field show some degree of heterogeneity related to depositional and diagenetic features in the reservoir, making problematic description and

interpretation of the reservoir characteristics in the field. On the other hand, using traditional methods for reservoir rock typing only based on sedimentology and stratigraphy evidences and simple core porosity and permeability relationships, although work best with relatively homogenous reservoirs, but is not accurate especially with respect to heterogeneous reservoirs such as tight sand reservoirs in this study. This study is to demonstrate a useful and practical method showing significantly this heterogeneity in the reservoir, and more efficiently differentiating rock types in tight sands of the Whicher Range field. In this respect available well logs provide valuable information, when combine with core data, reveal a real picture of reservoir rock properties in the field. Classification of facies based on well logs do not require any manual data categorization, but it is natural and is on the basis of individual well logs characteristics that reflect their mineralogical, lithological and petrophysical properties (Lee and Datta-Gupta, 1999). However, at the first step these raw data should be quality controlled and ranked based on their validity. Therefore, in this study, for performing some corrections such as cable tension effects for adaptation of core and well log data readings, the core porosity data with regard to neutron log was checked. Also, corrections such as removal of bad hole flags (BHF) data, null values and log tails were performed. In this research, cluster analysis technique based on cluster tree is used for grouping data and identifying reservoir electrofacies. Cluster analysis is the classification of objects into different groups, or more precisely, the partitioning of a data set into subsets (clusters), so that the data in each subset (ideally) share some common trait - often proximity according to some defined distance measure (Jain et al. 1999). The input data for clustering of well log data include gamma-ray (GR), sonic transit time (DT), bulk density (RHOB), and neutron porosity (NPHI) logs.

At the first step of the study, sedimentary rock types are identified based on integration of available core descriptions and petrographic studies, and clustering analysis of well log data for the gross reservoir interval comprising of sandy packages and shaly beds and interbeds. At the next step, petrophysical rock types are identified for the sandy packages based on integration of flow units and clustering analysis of porosity logs. Finally, the quality of sandy packages in the reservoir is interpreted in the framework of petrophysical rock types. Figure 5 shows a general description of workflow for rock typing of tight sands in the reservoir.

3.1. Sedimentary rock types

In this section, reservoir from non-reservoir units was distinguished using clustering of well log data and verification of results with petrographic data. The steps are as follows

3.1.1. Finding distance between data object

An important step in any clustering is to select a distance measure, which will determine how the similarity of two elements is calculated. This will influence the shape of the clusters, as some elements may be close to one another according to one distance and further away according to another. The processed log data (i.e., GR, DT, RHOB, and NPHI) were loaded as an input matrix (x) in MATLAB software workspace and Euclidean distance function (Eq. 1) was employed to calculate distance data because more accurate results are obtained with this procedure:

$$d^2_{rs} = (x_r - x_s) (x_r - x_s)' \quad (\text{Eq. 1})$$

where d for two clusters r and s is the various distances between the vector x_r and x_s for an m by n data matrix x , which is treated as m (1-by- n) row vectors $x_1, x_2, \dots, x_m$.

3.1.2. Linking between distance data

In the next step the matrix of input distance data was linked through a linkage function known as weighted average distance. The linkage function takes the distance information generated by `pdist` and links pairs of objects that are close together into binary clusters (clusters made up of two objects). The linkage function then links these newly formed clusters to each other and to other objects to create bigger clusters until all the objects in the original data set are linked together in a hierarchical tree.

This is an important step in data clustering which determines primary grouping in data and prepares input data for cluster tree or dendrogram generation for the next stage.

The cophenetic correlation coefficient (Eq. 2) is used to examine the reliability of applied method (Scott et al. 2004). In other words, one way to measure how well the cluster tree generated by the linkage function reflects data is to compare the cophenetic distances with the original distance data generated by the Euclidian function. If the clustering is valid, the linking of objects in the cluster tree should have a strong correlation with the distances between objects in the distance vector. The `cophenet` function compares these two sets of values and computes their correlation, returning a value called the cophenetic correlation coefficient. The closer the value of the cophenetic correlation coefficient is to 1, the more accurately the clustering solution reflects data.

The cophenetic correlation coefficient for the present study (Whicher Range Field) is determined as high as 0.74, which reflects a high quality respond of the applied method.

$$c = \text{cophenet}(Z, Y) \quad (\text{Eq. 2})$$

Where Z is the matrix output by the linkage function and Y is the distance vector output by the `pdist` function.

3.1.3. Dendrogram or Cluster Tree generation

The next step is to extract a dendrogram of data based on the linkage data. A dendrogram consists of many U-shaped lines connecting objects in a hierarchical tree. The Lines connect two clusters with minimum distance and the procedure continues until all the groups come together as a single cluster (Fig. 6). The tree is not a single set of clusters, but rather a multilevel hierarchy, where clusters at one level are joined as clusters at the next level. This allows you to decide the level or scale of clustering that is most appropriate for your application. The height of each U represents the distance between the two objects being connected. If there were fewer data points in the original dataset, each leaf in the dendrogram corresponds to one data point. If there were more data points, the complete tree can look crowded and dendrogram collapses lower branches as necessary, so that some leaves in the plot correspond to more than one data point. The extracted dendrogram for the Willespie reservoir is shown in Figure 6. The horizontal axis of the diagram shows the variety of identified clusters and vertical axis displays their distances or similarities rank. Different clusters in the diagram are hierarchically linked together from small clusters with higher similarity degree to large clusters having lower similarity degree, and finally total data are placed in a large cluster surrounded all clusters.

In the final step, using a set of cutoff values applied on the dendrogram, shown as horizontal dashed line on Figure 6, data clusters were extracted. Cutoff for inconsistent or distance measure is a threshold for cutting the hierarchical tree generated by linkage into clusters. So, cluster generation function was run and three clusters representing three electrofacies were extracted over the studied reservoir. Each of these electrofacies has certain values of readings or responses of any used well logs that in fact reflects geological (textural and diagenetic) and petrophysical (porosity and permeability) characteristics of the reservoir rocks.

The cutoff level can be determined at any distances of the dendrogram. An examination, based on trial and error revealed that the case of extracting three clusters by selecting a cutoff level at distance of 50 on the dendrogram is more compatible with the tight sands characteristics and heterogeneity of the reservoir. In the mean time, identifying more clusters will complicate facies analysis and their modeling and fewer clusters cannot reflect the reservoir heterogeneity. It was also found that GR log responses are more dominant in three separate clusters (electrofacies). Thus, in an effort to attain a reasonable and clear understanding of the reservoir quality of tight sands in the field, it is better to consider and classify different reservoir rocks, and in this case GR log is a good indicator. Three recognized electrofacies, based on mostly GR log responses, are as follows:

EF1: Fine to coarse and very coarse grained clean sandstone with low shale volume and low GR value (<80). These sandy units are mainly deposited in river channels.

EF2: Dirty sands, siltstones and very fine grained sandstones associated with some shale partings and clays. In comparison, this facies has an intermediate GR response (<130) and shale volume.

EF3: Shaly units include laminated carbonaceous-silty shale and argillaceous sandstones, very fine in size, with high shale volume and high GR response (>130). This facies is probably deposited in low energy systems such as lacustrine environment.

At the first step, we differentiated the reservoir facies based upon lithological properties and GR responses in the five wells (i.e. WR1, WR2, WR3, WR4 and WR5) from the Whicher Range gas field. Three electrofacies based on GR log responses (High, medium and low value) versus lithology column for these wells are shown in Figure 7.

3.2. Petrophysical rock typing of sandy packages

In the second step, petrophysical facies were identified for the tight sands and HFUs were classified. Sandy packages are the main potential production zones and correspond to EF1 which is more probable in the field. Sandy packages in fact are those identified based on DST and production flow test information provided by Pennezoil Far East Company (1998), and considered as reservoir units throughout the well interval. These reservoir units are correlatable in all wells of Whicher Range gas field.

In this respect, detailed studies for identification of petrophysical facies were focused on sandy packages.

3.2.1. Identification of hydraulic flow units

Porosity and permeability are considered as two important factors in reservoir characterization. Pore spaces properties and their relation to each other are basically affected by geological processes (sedimentary texture and diagenesis) that have notable role in fluid movement within reservoir units. Hydraulic flow units are considered as a criterion of reservoir units in which fluid flow properties is uniform due to the same pore throat properties. In other words, flow unit zonation subdivides reservoir into zones (layers) based on hydraulic flow properties and are best suited to determine reservoir layering for flow simulation studies (Bhattacharya et al. 2008). Figure 8 shows distribution of core porosity and Permeability as well as a cross plot of them for four wells in the Whicher Range gas field.

The porosity and permeability data were used to identify flow units of the reservoir. The steps are as follows: First, reservoir quality index was calculated by using the method proposed by Amaefule et al. (1993):

$$RQI = 0.0314 \sqrt{\frac{k}{\phi}} \quad (\text{Eq. 3})$$

where RQI is reservoir quality index, μm ; k is permeability, mD; and ϕ is porosity in fraction. Figure 9 shows the relationship between porosity and permeability with RQI for different hydraulic flow units in the studied reservoir. As it is clear from the plot

permeability has a stronger relationship with RQI that is a main factor controlling reservoir quality representing pore throat properties through porous media.

In the next step, pore to matrix ratio (PMR) was calculated as follows:

$$PMR = \frac{(Eq. \phi)}{1 - \phi}$$

Finally, flow zone indicator was obtained by the following correlation:

$$FZI = \frac{RQI}{PMR} \quad (Eq. 5)$$

A cumulative density plot was used to analyze the optimal number of flow units (Fig. 10). According to the plot of log FZI data shown in Figure 11, five hydraulic flow units (A, B, C, D and E) could be identified within the studied reservoir.

The following cutoff values were used for identification of HFUs.

HFU A: $\text{Log FZI} < -0.9$

HFU B: $-0.9 < \text{Log FZI} < -0.6$

HFU C: $-0.6 < \text{Log FZI} < -0.1$

HFU D: $-0.1 < \text{Log FZI} < 0.5$

HFU E: $\text{Log FZI} > 0.5$

Core description shows that HFU A and HFU B are related to the fine and very fine grained argillaceous sandstones and siltstones. Sandstones in HFU C vary from the fine grained to

medium and coarse grained facies. HFU D and E are mostly related to the medium to coarse and very coarse grained sandstones.

The porosity and permeability relationships demonstrate each hydraulic flow unit that has a certain porosity-permeability zone (Fig. 12). This is basically related to the pore throat system properties dominated by sedimentary and diagenetic processes within each unit. Representative photomicrographs for any hydraulic flow units in the Willespie Formation have been shown in Figure 13.

3.2.2. Identification of electrofacies in sandy packages

In order to set a real and reasonable relation between HFUs and tight sands, well log responses of sandy packages were classified using a cluster analysis approach. The input well log data for clustering process were those of reservoir porosity and lithology (i.e. DT, RHOB and NPHI) from four wells (WR1, WR2, WR3, and WR4). As with the sedimentary rock typing, using the Euclidean function (Eq. 1) distance data were generated. The Ward function was employed to link between distance data as follows.

$$d^2(r,s) = n_r n_s \frac{\|\bar{x}_r - \bar{x}_s\|_2^2}{(n_r + n_s)} \quad (\text{Eq. 6})$$

where n_r is the number of objects in cluster r ; x_{ri} is the i th object in cluster r ; d_{rs} is Euclidean distance, $\bar{x}_r^G$ and $\bar{x}_s^G$ are the centroids of clusters r and s .

The extracted cluster tree for this case is illustrated in Figure 14. Cutoff value, as shown as horizontal dashed line in Figure 14, is implemented on cluster tree such that four electrofacies were generated from petrophysical logs. Further explanation of these electrofacies and their relationship with reservoir quality is provided in the next section.

4. Interpretation of the reservoir quality of the sandy packages in relation to petrophysical EFs and HFUs

In this section, we describe the general characteristics of petrophysical electrofacies and their connection with flow units and reservoir quality.

EF1 is mainly composed of medium to coarse and very coarse grained sandstones which is related to hydraulic flow units E and D. Fine to very fine and silty-argillaceous sandstones have a little share in this electrofacies and are related to HFU C and to some extent to HFU D.

EF2 shows a wide range of facies with respect to size varying from fine to coarse and very coarse grained sandstones. All flow units can cover EF2. Fine and very fine grained sandstones and siltstones are correlated with HFU A and B. HFU C is mostly related to fine to medium and occasionally coarse grained sandstones. Medium to coarse and very coarse grained-sandstones in this electrofacies coincide with HFU D and E.

EF3 includes low percent of facies in the reservoir. Fine grained sandstones in this electrofacies are related to HFUs A and B. In contrast, HFU C includes medium to coarse

grained sandstones. Petrophysically, coarse grained facies in this electrofacies are close to those in EF4, and therefore they are discussed in one group (i.e. sand type 3).

HFUs in EF4 ranges from A to D. Fine grained and argillaceous sandstones and siltstones are correlated with HFU A and B. Medium to coarse grained sandstones are correlated with HFU D and a significant portion of HFU C.

Figure15 shows a brief description of four electrofacies related to depositional facies and recognized hydraulic flow units in the reservoir.

Study of poro-perm characteristics of reservoir rocks show that in all recognized electrofacies, there is an ascending trend in permeability from low reservoir quality HFUs towards high quality ones. Porosity values, however, show a uniform distribution within each electrofacies.

In all EFs, low reservoir quality HFUs (HFUs A, B and some fraction of HFU C) can be correlated with the fine grained facies deposited in a low energy system. But, in the case of medium to coarse and very coarse grained sandstones, depending on the severity of the diagenetic processes, three sand types were recognized as follows:

a) Type 1 (very tight sandstones): This type coincides with EF1 and E and D flow unit are dominant. Medium to coarse and very coarse grained sandstones of this EF are severely affected by diagenetic processes (i.e. quartz, kaolinite and calcite cementation). As a result, reservoir quality in these sandstones has strongly been destroyed. Based on the core description, porosity is described very low. The average porosity and permeability in these facies are 3% and 0.5md, respectively.

b) Type 2 (tight sandstones): It is composed of medium to coarse and occasionally very coarse and granular sandstones that are related to HFU E and D and partially to HFU C. EF2 show a good agreement with type 2 tight sands. Diagenetic effects have also acted on these sandstones in the form of quartz overgrowths and kaolinite cementation. But in comparison to sandstones of type 1, pore spaces in this type, especially as intergranular, are relatively well preserved. Based on core description, porosity in this electrofacies is described as poor to fair. The average porosity and permeability are 6-7% and 0.87md, respectively. This type shows an intermediate reservoir quality between type 1 and 3.

c) Type 3 (sub-tight sandstones): It consists of medium to coarse and granular sandstones that are correlated with hydraulic flow unit C (dominant in EF3) along with HFU D and a significant portion of HFU C (dominant in EF4). In comparison with two others, type 3 sandy facies have the best reservoir quality. Similar to the type 2, porosity is intergranular and ranges from poor to fair based on core descriptions. Porosity and permeability are 12-13% and 1.65md in average, respectively.

Relationships between three types of sandstones and petrophysical logs along with porosity and permeability data in the framework of flow units for the Whicher Range wells is shown in Figures 16 through 19. In addition, statistical parameters of log and core data for the three sand types and also fine grained argillaceous sandstones are listed in Table 1.

Comparison between the Whicher Range wells, as shown in Figures 17 through 20 and also as a histogram in Figure 20, show that WR1 and WR4 contain high portions of type 3 sands with high reservoir quality.

5. Conclusion

This study shows that investigation of reservoir facies from a suitable cluster of well logs (i.e. gamma ray, neutron, sonic and density) along with core porosity -permeability data is a practical way for identification and classification of reservoir rocks based on geological and petrophysical characteristics. On the other hand, studying the reservoir electrofacies in the framework of hydraulic flow units plays an important role in delineating of production zones.

EFs, were derived using five wells data from the Whicher Range Field, indicating the high heterogeneity of reservoir rocks varying from clean sands to shaly units. Detailed study of sandy packages in relation to petrophysical logs and their connection with HFUs resulted in distinction of three sand types (i.e. sand type 1, 2 and 3). These sandy units are basically tight, but based on severity of diagenetic effects, their porosity and permeability properties are different. The results of this study show that sand type 3 possesses the best reservoir quality distributed mostly in WR1 and WR4 wells in this field.

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Figure Captions

Fig. 1. Map showing the location of the Perth Basin with N-S trending in the southwest of Australia (Modified from Crostella and Backhouse, 2000)

Fig. 2. Pre-Cambrian to Late Cretaceous stratigraphic column of the south Perth Basin (modified from Playford et al. 1976). Willespie Formation with Late Permian in age, as the main reservoir rock of Whicher Range Field, has been highlighted

Fig. 3. Location map of the Whicher Range gas field with five drilled wells (1, 2, 3, 4, and 5) in the south Perth Basin (Sharif, 2007)

Fig. 4. Cross plots showing a good correlation between core porosity and log derived porosity (a) and core permeability and Klinkenberg permeability gained from PDPK-300 for two wells WR1 and WR4

Fig. 5. Workflow showing different stages for rock typing of tight sands in the Whicher Range Field

Fig. 6. Dendrogram or cluster tree extracted for the Willespie Formation based on well log data (GR, DT HOB, and NPHI). Horizontal dashed line indicates selected cut off value on the dendrogram (i.e. point 50). Three extracted clusters based on cut off are shown with different colors on the dendrogram.

Fig. 7. Lithological column with gamma ray log responses for five wells in the Whicher Range Field. The lithology column was determined from log analysis calibrated to core. Red and yellow vertical lines on the gamma ray log column show the boundary between three recognized

electrofacies from sedimentary rock typing using clustering analysis.(EF1, GR<80; EF2, GR<130; EF3, GR>130).

Fig. 8. Distribution of core porosity and permeability data for Whicher Range gas field a) Cross plot of porosity versus permeability for samples from 4 wells (WR1 to WR4b). Porosity frequency for the Whicher Range samples showing that 5-10% is the most common porosity; c) Permeability frequency for the Whicher Range samples

Fig. 9. Relationship between porosity (A) and permeability (B) with RQI for different hydraulic flow units in the reservoir

Fig. 10. Cumulative density plot to obtain the optimal numbers of flow units. Each flow unit on this plot is shown with a specific color indicating a certain district of FZI value

Fig. 11. Log FZI versus sample numbers. All samples are classified in five groups or HFUs based on FZI values

Fig. 12. Hydraulic flow units in relation to porosity and permeability data. Each HFU occupies a certain district on this plot

Fig. 13. Photomicrographs of the depositional facies representative of recognized HFUs in Willespie Formation. The red dot is used as a scale and is equal to 0.12mm. Blue areas are either pores, or edges of the thin section. All photographs are taken in plane polarized light. Each thin section has been stained with Alizarin Red "S" to facilitate distinction between calcite and dolomite. a) HFU A: This sample is very micaceous sand. Large biotite flakes (brown) have been deformed during burial compaction thereby reducing the porosity and permeability of this sample. b) HFU B: This sample consists of fine grained, poorly sorted, angular grains including quartz (colorless), metamorphic rock fragments (browns), and

chert (tan). The sample is heavily cemented mostly with clay minerals (kaolinite) c) HFU C: This sample with dominant quartz grains (colorless) shows some primary pores (blue) coated with a film of diagenetic clay (dark rim). d) HFU D: This sample is poorly sorted. Quartz (colorless) is the most grain type. Feldspar (colorless, partially altered to calcite (pink)), Chert (tan), and metamorphic rock fragments (tan) are also present. Several secondary pores (pale blue) are present and are filled with kaolinite. Diagenetic clay rims (gold) are common. e) HFU D: in this sample quartz (colorless) is dominant grain with abundant calcite cement (red). Light blue areas are secondary pores. The pores are coated with clay (gold) and are partially filled with kaolinite. f) HFU E: Several pores (blue) are visible in this micrograph. The pores are coated with clay (gold) and are partially filled with kaolinite. The pink grain has altered to calcite.

Fig. 14. Dendrogram resulted from the second stage cluster analysis of petrophysical logs (DT, RHOB, NPHI, and GR) from four wells (WR1, WR2, WR3, and WR4). Based on the selected cut off value (i.e. point 50), indicated by horizontal dashed line on the dendrogram, four clusters or electrofacies, differentiated by different colors, are recognized

Fig. 15. Petrophysical electrofacies related to depositional and hydraulic flow units in the reservoir. HFU A and B are in relation to fine grained facies are dominant in EF3 and EF4, and HFU D and E are in relation to coarse and very coarse grained facies are dominant in EF1 and EF2. HFU C is related to fine to coarse grained facies with varying distribution exists in all EFs

Fig. 16. Plots showing graphic well logs and corresponding flow units for three sand types in WR1. Sand types and HFUs are shown with colored coding columns (left), and well logs

(DT, RHOB) and porosity (derived from log) and Permeability (Klinkenberg permeability) with uncolored column (right) are shown. HFU 4(D) and sand types 2 and 3 are dominant in this well.

Fig. 17. Plots showing well log data and corresponding flow units for three sand types in WR2. Sand types and HFUs are shown with colored code columns (left) and well log (DT, RHOB) and porosity (derived from log) and Permeability (Klinkenberg permeability) with uncolored column (right) are shown. HFU 4(D) and sand types 1 and 2 are dominant in this well.

Fig. 18. Plots showing well log data and corresponding flow units for three sand types in WR3. Sand types and HFUs are shown with colored code columns (left) and well log (DT, RHOB) and porosity (derived from log) and Permeability (Klinkenberg permeability) with uncolored column (right) are shown. Distribution of HFUs and sand types in this well is similar to one observed in WR2.

Fig. 19. Plots showing well log data and corresponding flow units for three sand types in WR4. Sand types and HFUs are shown with colored code columns (left) and well log (DT, RHOB) and porosity (derived from log) and Permeability (Klinkenberg permeability) with uncolored column (right) are shown. HFU 3(C) and sand types 3 are dominant in this well.

Fig. 20. Histogram showing thickness (in percent) of three sand types in four wells from the Whicher Range Field. Sub-tight sandstones (type1) with better reservoir quality share high percent in wells WR1 and WR4.

Highlights

- Study and classification of tight sands using the electrofacies concept
- Investigation of reservoir quality in any electrofacies based on hydraulic flow units
- Interpretation of the results based on depositional and diagenetic properties of reservoir rocks

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

a

b

c

Figure 8

A

B

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20