Understanding Low resistivity heterogeneous carbonate pays with variable ‘m’ (cementation Factor) approach – A case study

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Abstract:
Carbonate reservoirs of Mumbai offshore Basin, India are one of the major hydrocarbon producers. Significant lateral as well as vertical heterogeneity in the reservoirs has been observed during the study of one such field of Mumbai offshore Basin. Some of the layers in these diagenetically complex reservoirs have low resistivity and the water saturation computation is at variance with their production behavior and also few layers with good resistivity have contributed mainly water. The challenges in characterizing these type of reservoirs require understanding multi porosity systems prevalent in carbonates and accounting them in terms of petrophysical constants such as cementation exponent ‘m’ and saturation exponent ‘n’.

Many studies in literature supported by core studies enumerate variation in cementation exponent ‘m’. These studies also focused to get a realistic value of ‘m’ to minimize the uncertainty related to it. Most of the methods/studies involve primary & secondary porosity and their inter-relation is used to estimate the variable ‘m’. However, these studies are field specific and none of the mechanism works perfectly in case of a particular field, except the one for which study is carried out.

This paper deals with the methodologies for computing variable ‘m’ level by level with the help of conventional logs as well as Resistivity imaging logs for the reservoirs in a studied field of the Mumbai Offshore Basin. Two techniques have been adopted in this study. One, which essentially uses combination of conventional porosity logs such as Neutron-Density and Sonic log. The computation of variable ‘m’ with Resistivity imaging involves heterogeneity analysis and estimation of proportional resistive area azimuthally and converting the resistive proportion inclusion with a specified transform with a limitation in the very low porosity regimes. The results from both the methods are calibrated with core data for one well of the studied field and validated with core data of another well. The methodology adopted for conventional logs has more versatility for its deep depth of investigation compared method using Resistivity Imaging. These methodologies have been propagated in the entire field and the production of hydrocarbons from relatively low resistive carbonates could be explained.

1.0 Introduction

D1 Field within DCS (Deep Continental Shelf) Block of Mumbai Offshore Basin at an average water depth of 85-90 m is located about 80 km South West of Mumbai High. The area is bounded by shelf margin in the West, D-2, D-3 and D-17 structures in the East (Fig-1).
Main interest from hydrocarbon points of view in D1 field is in lower pay of Panvel formation of late Oligocene age & upper, middle pays of Ratnagiri formation of early to middle Miocene age. Dolomitization is observed to be more pronounced in the lower pay of Panvel formation as compared to middle & upper pay of Ratnagiri formation. Some of the MDT sampling and extracted MSCT samples showed presence of oil against the low resistive carbonate sections belonging to Upper, Middle & Lower Pay of this well (Fig:2).

2.0 Challenges in Petrophysical Evaluation

D1 reservoirs are heterogeneous in nature that poses problems in their characterization. Presence of secondary porosity is also adding the heterogeneity in reservoirs of this field. Core samples as well as hi-tech log data like CMR, FMI, sonic scanner etc. recorded in recently drilled wells also show presence of secondary porosity viz. vugs, molds & fractures.

These reservoirs are associated with a number of uncertainties in terms of depositional environment, diagenesis, structural etc. Carbonates are more prone to diagenesis as compared to clastics which is responsible for change in porosity system of the reservoirs. This makes the porosity system of carbonates very complex, which includes a range of porosity types such as vugs (touching as well as non-touching), molds, fractures etc. along with the inter-granular & intra-granular porosity. Bimodal or tri-modal porosity systems are common in the carbonate reservoirs.

The connectivity of these different types of pore system modifies the path of current flow inside the formation as seen by the logging tools and hence introduces uncertainty in inherent reservoir properties such as cementation exponent ‘m’. Hence in carbonate reservoir, using constant ‘m’ may not give the true petrophysical characterization and usage of variable ‘m’ representing different porosity systems and their inter connectivity has to be adopted to compute realistic reservoir parameters and their integration with core & production behavior of the field.

3.0 Methodology Adopted

3.1 Computation of ‘m’ from Sonic & Neutron - Density logs

PHIS-PHIT relations are widely used in oil industry to get variable ‘m’ level by level. Conventional porosity logs where Neutron, Density & Sonic travel time was available were used to get variable m. The theory behind the methodology is that Neutron & Density logs provide us total porosity which includes intergranular, vugs & fracture porosity, whereas Sonic travel time gives us only primary porosity. Sonic waves bypass vugs & fracture and compressional wave slowness measure primary porosity only. Various transforms
developed by many geoscientists for their fields are available for computing variable ‘m’ with depth. Some of them are given as below.

- **Formula for vuggy & low porosity carbonates by Neustadter, 1968**
  \[ m = 0.019/\phi + 1.87 \]

- **Formula for vuggy & intergranular / intercrystalline porosity by Nugent et. al., 1978**
  \[ m = (2\log \phi_s)/(\log \phi_t) \]
  (where \( \phi_s = \) sonic porosity and \( \phi_t = \) total porosity from nuclear porosity logs)

- **Formula for carbonates with intergranular/ intercrystalline porosity by Sethi, 1979**
  \[ m = 2.05 - \phi \]

- **Formula for low porosity and tight carbonates by Borai, 1987**
  \[ m = 2.2 - 0.035/(\phi + 0.042) \]

Computed ‘m’ from above equations is failed to match with core measured ‘m’ values so we attempted to develop separate transform for the reservoirs of D1 field.

A key well D1-A is selected to evolve the methodology because it has long cored interval as well as hi-tech logs like FMI, CMR were recorded in this well. Petrophysical study (a, m & n) was carried out on good amount of core plugs taken from conventional cores. Sonic porosity was computed from sonic travel time. Secondary porosity was measured by subtracting primary porosity (PHIS) from total porosity computed from Neutron-Density logs. Crossplots between lab-measured m on core plugs of well D1-A & various combinations like ((Log(PHIS)/Log(PHIT), Log(PHIS)/Log(PHID) were made. Two trends are clearly visible on crossplot between core measured ‘m’ & LogPHIS/LogPHIT (Fig: 3A & 3B). These trends may be attributed as

A) Contribution of fractures & primary porosity as ‘m’ value is in the range of 1.8 to 2.1 (Fig: 3A)

B) Contribution of isolated porosity (vugs) & primary porosity as ‘m’ value is in the range of 2 to 2.6 (Fig: 3B)
A best fit line regression was made by combining two trends to accommodate fracture as well as vuggy porosity to get an equation (Fig-3C) & used for other wells to compute variable ‘m’ level by level.

This equation was used to get variable m in well D-1-B for validation, where Neutron Density, Sonic log & core derived m values are available. A reasonable match is found with core measured m value & the said method (Fig-4).

### 3.2 Computation of ‘m’ from FMI:

Another method used to compute m from FMI using Textural Analysis. A theoretical resistivity curve is generated using all the resistivity values of micro resistivity responses and it is scaled to LLS or RLA3 curve to get synthetic resistivity curve. Scaled data is used in to compute conductive and resistive patches & spots. Resistive & conductive inclusion proportion, along with connectedness of the secondary porosity (includes vugs, molds etc.) are computed after putting proper cutoffs for resistive, conductive spots & patches etc..

The equation ‘m’=0.554*PRH +1.781 (Ref 3) is used to compute cementation exponent (m) from Resistive inclusion proportion (PRH). Computed ‘m’ from this methodology is presented in Fig: 5 for the same well. The limitation of this method is that it can be used only in the wells where image log is available and also shows unrealistic value of ‘m’ in low porous zones.

### 3.3 Petrophysical Model Selection:

The model selection is based on the log responses and the laboratory studies of sidewall & conventional cores. The lithology in general is Limestone & Dolomite with minor clays. The prepared cross plots support similar lithology and clay mineralogy as...
mentioned in lab reports. Based on the cross plots & lab study, working model has been framed up with Calcite, Dolomite as rock forming minerals. Illite, Smectite & Kaolinite have been incorporated as clay minerals while oil and water is introduced as fluids in the model. In wells having spectral gamma ray log, CGR is taken for the log data processing while in other wells GR is used where CGR is not available.

Variable ‘m’ computed from PHIS method is adopted in most of the wells, while ‘m’ computed from FMI images is also used wherever the resistivity image data is available. As core studies on wettability are not available, variable n has not been adopted in the present study.

4.0 Discussions

1. Extensive Lab core studies carried out in the well D1-A indicate the variation of m values ranging from 1.6 to 2.3 (Fig 6) in relatively better porosity layers. The image log and Nuclear Magnetic resonance logs indicate presence of more than single porosity system(fig 5) thus necessitating the understanding of multi porosity system and its effect on cementation exponent ‘m’. Continuous estimation of ‘m’ value is essential for realistic reservoir parameter computation in these types of reservoirs.

2. Low resistivity observed in some of the reservoirs may not be due to presence of conductive minerals & shale presence. Presence of micrite, in carbonate system is the main cause for Low resistivity in reservoirs of D1 field.

3. Resistivity Image and conventional logs, are used to compute variable ‘m’ with the methods described above and correlated with core measured ‘m’ values and it has been found that the ‘m’ values from both the methodologies are in tandem with the core data.

4. Using the continuous ‘m’ log curve from the above methodologies, all the pays of the Field are reinterpreted for effective porosity and water saturation with Dual-water model. Usage of variable ‘m’ from Resistivity image as well as secondary porosity based methodologies has given better hydrocarbon saturation in low resistivity reservoir layers, where the usage of constant ‘m’ does not represent the true picture of fluid distribution.

5. Amongst the above two methods for computing variable ‘m’ the Resistivity image based is providing optimistic results probably due to lesser depth of investigation.

6. The petro physical parameters computed using ‘m’ value from secondary porosity method are more rugged and appear to represent the actual reservoir characters as this model represent the formation to a larger extent volumetrically.

7. Hydrocarbon carbon indication from MDT sampling and oil extraction from MSCT cores in low resistivity heterogeneous carbonate layers could be explained form the estimation of water saturation with the usage of variable ‘m’ (Fig 7). However at few places more understanding is required in terms of mineralogy (presence of conducting minerals) and conventional testing to explain the oil shows observed.

8. The reservoir parameters viz. porosity and grain density are well correlatable with core measurements thus validating the interpretation model with variable ‘m’
approach. Production Logging results also confirm the interpretation results.

5.0 Conclusions

1. Innovative techniques, based on Resistivity Image and conventional logs, are adopted to compute variable ‘m’ and correlated with core measured ‘m’ values. Variable ‘m’ computed with PRH (Resistive Inclusion Proportion) from image logs is used only in wells having FMI data.

2. The variable m approach has given better understanding of the heterogeneous reservoirs and petrophysical parameters estimated with this approach are in general in tandem with production results.

3. The secondary porosity method for computation of variable ‘m’ is more versatile and outputs the better picture for heterogeneity accounted reservoir parameter estimation due to higher depth of investigation of the conventional logs compared to resistivity images.

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