Detection and quantitative evaluation of hydrocarbon present in Younger Camay shale is invariably a key desire of the petrophysicist as Cambay shales are the only chief source rocks of hydrocarbon in Camay basin. Shales are generally non-reservoir rock. Presence of hydrocarbon in shale may be due to accumulation of hydrocarbon in thin laminae of silt/sand layers embedded in shale which can’t be detected by conventional logs for resolution constraints of logging tools or due to presence of fractures connecting to a reservoir. Younger Cambay shale being unconsolidated, the possibility of sustaining fractures is ruled out. However, the presence of a good number of thin silt/sand layers has some average effect on resistivity as well as porosity logs. This effect may not be appreciable enough as seen in a potential reservoir rock. A statistical approach has been adopted to find a meaningful parameter which is a function of resistivity and density to find out the zones of interest and parameters. FMI confirms the presence of thin laminae against the zones of interest in Cambay shale. An attempt has been made to identify hydrocarbon in shale using conventional logs and validation by art of technology in this paper.

Introduction:
Explorationists are in search of hydrocarbon broadly from clastic & carbonate rocks. Shales are generally non-reservoir rock and act as a cap rock that helps in accumulation of hydrocarbon in the underlying reservoir rocks. On the other hand, shales are the source of hydrocarbon generation. The area of study in this paper is Camay Basin within which older Camay shales are the chief source rock of hydrocarbon. Main reservoir rocks of this basin are silt and sands of middle Eocene age. Hydrocarbon potential reservoirs are also present in upper & lower Eocene, Miocene and Oligocene age. Hydrocarbon accumulation have been observed in Younger Camay shale of this basin although log characteristic as well as analysis of log data are unable to determine the presence of hydrocarbon. The problem associated with the evaluation of formation are of direct concern to the log analyst. Various efforts were made to identify the potential intervals and it’s nature on the
basis of geological data and log data. Production of hydrocarbon from shale may be due to accumulation in thin silt layers embedded in shale or it may be due to the presence of fractures connecting to a reservoir. When the thickness of silt is less than the resolution of conventional logs, it becomes a hard task for explorationist to identify thin silt reservoir. However, hydrocarbon bearing thin silt layers or presence of fractures in shales have some influence on resistivity and porosity logs. This effect is not visible from well logs as compared to a good reservoir rock. This paper presents techniques developed for identification of hydrocarbon bearing shale zones using well log data specifically resistivity and density data (Mathur A.D. (2005)). A parameter ‘P’ related to resistivity and bulk density has a normal frequency distribution for a uniform shale section and a skewed frequency distribution of the shale layer having carbonaceous layer as well as hydrocarbon bearing layers. FMI logs recorded in Cambay shale confirms presence of thin laminae of silt/sand in the zone of interest.

**Theory:**

Quantitative and qualitative concepts are necessary for simple log interpretation. Well log interpretation is an art to find out the anomaly in the log characteristic. Resistivity log shows anomaly against hydrocarbon bearing layer. Similarly anomaly in neutron response against gas bearing layer helps in detecting gas bearing zones (low neutron porosity response). Empirical equations are used in formation evaluation. Archie’s empirical equation given below is extensively used to estimate hydrocarbons in place.

\[ F = a / \Phi^m \] and \[ S_w = (F R_w / R_t)^{1/n} \] (1)

Where \( F \) = Formation Resistivity Factor,
\( a \) = Empirically derived constant (depends on consolidation of formation)
\( \Phi \) = porosity of the formation
\( m \) = Cementation factor
\( S_w \) = Water saturation
\( R_w \) = Formation water resistivity
\( R_t \) = True resistivity of the formation
\( n \) = Saturation exponent

\[ \Phi = (\rho_{ma} - \rho_b) / (\rho_{ma} - \rho_f) \] (2)

\( \rho_{ma} \) = Matrix Density,
\( \rho_f \) = Formation water Density = 1.0,
\( \rho_b \) = Bulk Density of the formation

Substituting \( \Phi \) in equation (1)

\[ S_w = ((a R_w / R_t) (((\rho_{ma} - 1.0)/(\rho_{ma} - \rho_b))^m))^{1/2} \] for \( n = 2 \)

In a water bearing formation ‘Sw is expected to be equal to 1 (100%). Then the above expression can be written as

\[ 1 = ((a R_w / R_t) (((\rho_{ma} - 1.0)/(\rho_{ma} - \rho_b))^m))^{1/2} \]

or

\[ S_w = (((\rho_{ma} - 1.0)/(\rho_{ma} - \rho_b))^m))^{1/2} \]
\[(R_t (\rho_{ma} - \rho_b))^m \cdot \frac{1}{2} = (a R_w (\rho_{ma} - 1.0)^m)^{\frac{1}{2}} \quad (4)\]

Now a parameter is defined as ‘P’

\[P = R_t \ (\rho_{ma} - \rho_b)^m\]

Then the equation (4) reduces to

\[P^{\frac{1}{2}} = (a R_w (\rho_{ma} - 1.0)^m)^{\frac{1}{2}} \quad (5)\]

For \(S_w = 1\) (100%), \(P^{\frac{1}{2}}\) becomes a constant as \(a, R_w, \rho_{ma}\) and \(m\) values on the R.H.S. of the equation (5) have fixed value against a particular formation. In water bearing formation, estimated \(S_w\) is not always equal to 1 but has distribution around 1. Subsequently \(P^{\frac{1}{2}}\) also has a distribution in water bearing formation. ‘Porter & Pickett’ have also studied number of water bearing samples where they have found a Normal frequency distribution for \(P^{\frac{1}{2}}\). In the presence of hydrocarbon, frequency distribution of \(P^{\frac{1}{2}}\) shows deviation from the normal distribution of \(P^{\frac{1}{2}}\).

Similarly ‘P’ can be defined as

\[P = R_t \ (\Delta t_{ma} - \Delta t)^m\]

and

\[P^{\frac{1}{2}} = (a R_w (\Delta t_{ma} - 189)^m)^{\frac{1}{2}}\] by sonic log.

Frequency distribution of parameter ‘P’ has been studied for fields of Wadu shale pay equivalent. Parameters related to calculation of ‘P’ have been chosen as follows.

Bulk-density and Resistivity cross plot (Fig. 1) reveals a wide variation of Bulk-density within the Cambay shale, a unit of interest in WELL # A. Similarly a wide variation in Gamma Ray deflection is seen in (Fig. 2) in the same section. Variation in Bulk-density as well as Gamma Ray indicates variation in lithology within the shale section which confirms the presence of sand / silt laminations. Younger Cambay Shale being unconsolidated, its possibility of sustaining fractures is ruled out. So bulk-density can be an important parameter for the calculation of ‘P’ and matrix density is taken as 2.65 gm/cc.

Cementation factor ‘m’ has an important role for the calculation of ‘P’. The cementation factor ‘m’ in shales is expected to be low. Cross plots of \(\rho_m - \rho_b\) vs. Resistivity (Fig. 3) show that a trend for m around 1.2.

Saturation exponent ‘n’ in shale environment is expected to be low. The value of ‘n’ is taken as 1. So frequency distribution of parameter ‘P’ is preferable over \(P^{\frac{1}{2}}\) frequency distribution.

Frequency Distribution:

The relative frequency distribution of ‘P’ and Normal distribution curve from data of well WELL # A and B have been plotted and shown in Fig. 4 and Fig. 5. Interestingly in both the cases frequency distribution is deviating from Normal Distribution curve. The alternative method is also adopted to see any deviation of frequency distribution from Normal Distribution. Plot of ‘P’ vs. it’s cumulative frequency on a normal probability graph. A normal distribution is represented by a straight line on the graph.
Fig. 6 shows the plot of ‘P’ against its cumulative frequency on Normal Probability graph w.r.to well data of WELL # A. In this case also deviation from Normal Distribution is clearly visible.

Estimation of Effective Porosity and Water Saturation Sw:

Effective porosity expression can be written as

$$\Phi_e = \Phi_d - (\Phi_d)_{\text{Shale}} \cdot V_{\text{shale}}$$

for $V_{\text{shale}} \sim 1$, $\Phi_e = \Phi_d - (\Phi_d)_{\text{Shale}}$ (6)

Estimation of Sw can be done using ratio of ‘P’ values as it involves both resistivity and porosity logs.

$$S_w = \frac{P_{50}}{P} \quad (7)$$

Where ‘$P_{50}$’ is the mean (most probable) value of the parameter ‘P’. This corresponds to cumulative frequency = 50 on Normal probability graph.

Rough estimation of water saturation and porosity can be done using expression (6) and (7) respectively.

Discussion:

Analysis of the computed parameter ‘P’ is the only source for identification of hydrocarbon rich layers within the shale section. A very low value of ‘P’ indicates presence of a conductive mineral like Pyrite. Whereas intervals having high value of ‘P’ i.e. ‘P’ higher than the most probable value, are expected to be hydrocarbon bearing. Very high ‘P’ value is obtained for Coaly layers.

WELL#A:

Frequency distribution of ‘P’ (Figure-6) deviates from Normal distribution for $P > 0.40$ (for $m=1.2$). This well was tested with slotted casing in 64 m thick shale interval and initially flowed Oil @ 25 M$^3$/day and Gas @ 19,529 M$^3$/day. Figure-7 depicts 40 m of this section.

WELL#C

Plot of ‘P’ Vs cumulative frequency (figure-8) on Normal probability graph shows a deviation from Normal distribution for values $P$ above 0.35. The intervals pertaining to $P > 0.35$ are of interest for exploiting hydrocarbons. Fig. 9 is showing display of well logs, ‘P’, estimated water saturation, effective porosity and FMI log. The effective pay thickness (with Sw cut off: 85%) is estimated to be 23.4 m. Average effective porosity is 6.9 PU and average water saturation is 72%. As per the
distribution, the most promising layer is identified and displayed in Fig. 9 (composite logs & FMI static data). FMI data reveals the presence of sand / silt lamination within shale having comparatively high resistivity. This well is producing 3 m³/day liquid with 45% water cut from Wadu pay.

Conclusions:

Hydrocarbon bearing zones in a predominantly shale section having dense laminations subsequently have an average effect on conventional resistivity and density data. High resistivity and low bulk density are favourable signature for the presence of hydrocarbon in such type of shale intervals. Hydrocarbon in this type of shale section can be identified from the anomaly of frequency distribution considering a parameter ‘P’ computed from resistivity and bulk density. ‘P’ may also be defined as function of resistivity and sonic travel time.

‘P’ is very high for carbonaceous layer. Such layers should be discarded during identification of zones of interest. Plot of ‘P’ Vs its’ cumulative frequency on a Normal probability graph is another way to study the frequency distribution. Consequently identification of anomaly. Water saturation in hydrocarbon bearing shale zones can be obtained from the ratio of mean value of ‘P’ to the ‘P’ for the zone.

Logs & other parameters presented in this paper are from Cambay Basin, but the principles of the techniques presented here will apply equally well to other basins also.

REFERENCES


Figure-1: Variation in density in Cambay shale

Figure-2: Variation in GR in Cambay shale.

Figure-3: Cross-plot for estimation of ‘m’ for shale

Figure-4: Relative Frequency Distribution of ‘P’
Figure 5: Relative Frequency Distribution of ‘P’

Figure 6: Relative Frequency Distribution of ‘P’

Figure 7: Composite display of well logs and ‘P’ for zones corresponding to points not falling on normal distribution line. Black bands are carbonaceous layers.
Figure-8: Relative Frequency Distribution of ‘P’
Fig. 9: Showing presence of thin laminations in FMI Log w.r.t prospective zones of interest as shown by arrow in shale section.