Sweet Spot Identification for Shale gas/ Shale oil Exploration through Seismic attributes and Pre Stack Inversion: A case study from Cambay Basin

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Keywords

TOC, Brittleness, Sweet Spot, Fracability

Summary

A successful shale exploration strategy entails identification of “sweet spots” or the places with maximum potential for shale oil/gas and desirable brittle behavior (fracability). The total organic carbon (TOC) and Brittleness Index (BI) are the two important parameters that can assist in identification of such locales. Higher TOC or total organic carbon is generally associated with shale sequences having good hydrocarbon storage while the rocks with high BI values are more amenable to fracturing. The identified sweet spot should therefore exhibit high TOC and high BI values. Although identification of these intervals through core analysis in laboratory-based measurements can be very accurate but these are in-turn very expensive and time consuming!! The paper presents an integrated workflow for identification of sweet spots within shale plays using wire-line logs and seismic derived rock physical properties. A synthetic TOC log has been derived using Passey’s method with the lab derived TOC values acting as calibration points. Good correlation in between synthetic TOC and log derived TOC values has been achieved. The relationship between total organic carbon (TOC) and seismically derivable rock properties have been estimated by cross-plot analysis. Bulk density (RHOB), Resistivity and Vp/Vs have been found to be responding to the TOC. Pre Stack inversion has been performed to generate volumes of elastic properties such as P-Impedance, Vp/Vs and RHOB. Using the relationships obtained from the cross plot analysis, the inverted volumes have been transformed to TOC and Brittleness volumes respectively. Resistivity volume was generated by Multi Attribute Regression analysis using EMERGE package of HRS suite The zones exhibiting high values for TOC, Brittleness and Resistivity have been identified as promising areas for future shale exploration in the study area.

Introduction

TOC content, maturation, gas-in-place, permeability, and brittleness are the parameters frequently used to characterize the shale gas/oil potential within shale sequences. However, of all the factors TOC and brittleness are the two most important parameters for characterization of shale plays. The shale plays in general, have low permeability and require frequent hydraulic fracturing in order to attain and sustain economic production. Rocks that are brittle (i.e. those that have a high brittleness index [BI]) values can be fractured more easily than rocks that are ductile i.e. have a low BI values, (Wang and Gale, 2009). In general, a high TOC is associated with a higher clay content; i.e. rocks with high TOC are ductile and are more difficult to fracture. Thus “sweet spot” is often characterized by laminated brittle-ductile couplets (Slatt and Abousleiman, 2011). The well is drilled and completed in the brittle rock that provides high-permeable pathways after fracturing into the associated high-TOC rock. (S.Verma et at., 2016)

The presence of TOC in shale formation is known to influence the response on the wire-line logs in several ways i.e. high uranium content in the organic matter may give rise to high GR response (Fertl and Chilingar, 1988), also the organic matter being less dense than matrix minerals results in lowering of bulk density (RHOB), (Schmoker and Hester, 1983) Additionally, transit times recorded on the P-sonic log may increase in the presence of organic matter (Passey et al., 1990; Sondergeld et al., 2010). Neutron logs on the other hand, may also provide a high response in the presence of organic matter (Sondergeld et al., 2010). Organic matter being nonconductive, the resistivity logs lead to high values for high TOC (Passey et al., 1990). While average brittleness can be expressed in terms of Brittleness Index (BI), which can be estimated from elastic properties such as Young’s modulus and Poisson’s ratio (Rickman et al. 2008). Hence, it is plausible to

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detect changes in TOC values and average brittleness from the changes in the recorded the elastic wire-line logs in 1-D and therefore through seismic derived elastic properties across a 3-D volume. The detailed workflow adopted for the current study is elaborated below.

Geology of the Area

Cambay basin is a narrow elongated intra cratonic rift basin along NNW-SSE Dharwarian trend and is situated in the western margin platform of the Indian craton in the north western part of Indian Peninsula in the state of Gujarat. Tectono stratigraphically, the basin is sub divided into South Cambay basin comprising of Narmada and Jambusar-Broach blocks and North Cambay basin comprising of Cambay-Tarapur, Ahmedabad-Mehsana and Patan-Sanchor blocks. The Study area lies in the in South Cambay Basin (Figure1&2). The basin hosts the sediments from Paleocene to recent. The sediments deposited in between Paleocene to Mid Eocene (Olpad and Cambay Shale) are the primary targets of shale exploration.

Cambay Basin is one of the few Indian sedimentary basins which is believed to hold good potential for shale gas & shale oil. The Cambay Shale Formation bears resemblance in geological and geo-chemical characteristics to the commercially producing global analogues. In general, the TOC value of Cambay shale section falls in the range of 2-3 %. VRo in the range of 1 – 1.2 % and it is mature as confirmed by Tmax values. Hydrogen Index values indicate the kerogen to be gas prone. The Modified Van Krevelen diagram for the Cambay shale source rock intervals shows the Cambay Shale Formation to contain mixed kerogens of types II and III. Thus, geochemical parameters fall well within the threshold values for a potential shale gas play. For that reason, the basin has been prioritized for shale gas and shale oil exploration with a slew of efforts aimed towards gauging the envisaged potential of the basin from the point of view of shale exploration (Source: Report on Petroleum System Modelling for assessing the unconventional resource potential of Broach depression, Cambay Basin, KDMIPE, ONGC, 2017).

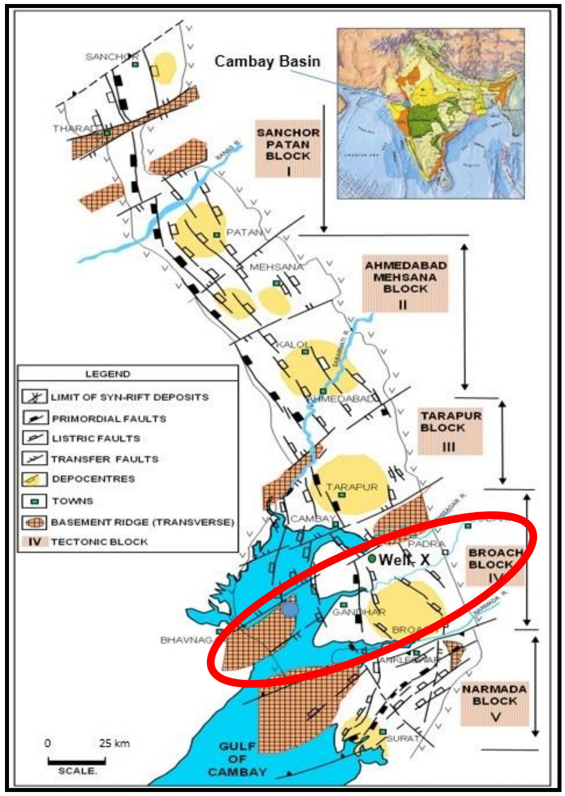

Figure1: Tectonic map of the Cambay Basin with area of study highlighted by red ellipse

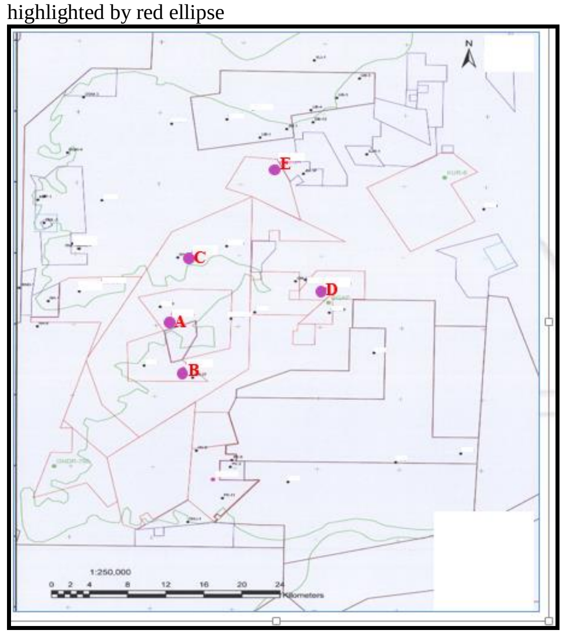

Figure2: Basemap showing the position of the wells A, B, C, D, E used for the present study

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Methodology

A three step methodology has been employed for the present study. In the first step we generate a synthetic TOC log by correlating the core measured TOC values with wire line log measurements using Passey's equation, (Passey et al., 1990). In the second step we deduce rock physical relationship in between the seismically derivable elastic properties and TOC values. Next we use the relationship established in the second step to transform the outputs from Pre Stack Inversion to the TOC volume and Brittleness Index volumes.

Step1: Generation of Synthetic TOC logs

Out of the several methods of quantifying total organic carbon (TOC) from well logs, ΔlogR technique (Passey et al, 1990) is the most common and widely used method. The method require one of three porosity logs viz, Density, neutron and sonic, along with resistivity log to calculate the ΔLogR using the following equation:

$$\Delta LogR = \log_{10}(RTD/RTD_b) - 2.5 * (RHOB - RHOB_b)$$

Where RTD & RHOB are the deep resistivity (Ωm) and bulk density (g⁄cm3) in any zone, RTD_b and $RHOB_b$ are the deep resistivity baseline value and bulk density baseline value of the organic lean zone respectively. Whereas LOM is the level of thermal maturity which is lab derived, with the values typically varying in between 6-14. For the present study LOM value has been taken as 10.

TOC is then computed using the formula:

$$TOC = \Delta logR * 10^{(0.297-0.1688*LOM)}$$

For the present study, five wells A, B, C, D and E (Figure2), had measured TOC data from core and cutting samples of the target shale section. Synthetic TOC logs using ΔlogR technique (Passey et al, 1990) was computed using Sonic (DT) and Density (RHOB) logs respectively (Figure3). TOC log generated using Density (RHOB) gave the best correlation with the lab derived TOC values. Hence, in the present study TOC log generated from RHOB log has been considered for all the analysis.

Step2: Establishing rock physical relationship

The relationship of synthetic TOC log vis-à-vis elastic properties such as P-Impedance, Resistivity (Deep), Density and Vp/Vs has been studied. While P-Impedance appears to be insensitive to TOC, Resistivity (Deep), Density and Vp/Vs show a very good correlation with TOC i.e. while the Resistivity increases with increase in TOC values, density and Vp/Vs decrease with increasing TOC values. (Fig4, 5 6& 7)

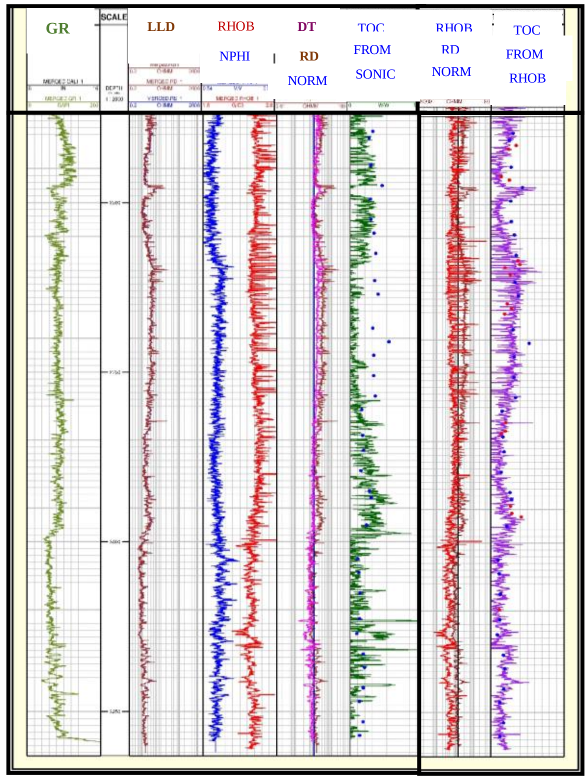

Figure3: Synthetic TOC log generation using Sonic (DT) and Density (RHOB) (Extreme right); cutting TOC and core TOC plotted as dots

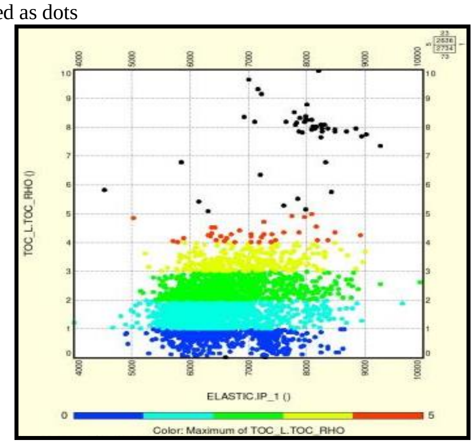

Figure4: Cross-plot of P-impedance (X-axis) and Synthetic TOC log (Y-axis); colored with TOC values (Z-axis).

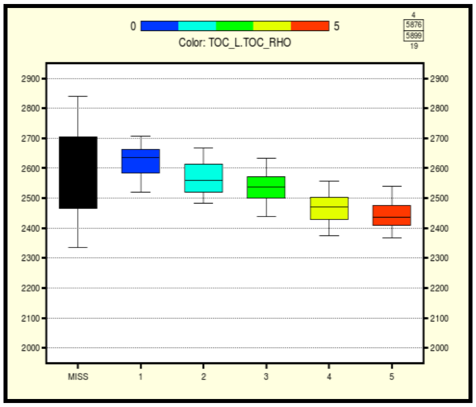

Figure5: Box Whisker plot of RHOB in Kg/m3 (Y-axis) and TOC (X-axis) colored with TOC showing decrease in RHOB vis-à-vis increasing TOC.

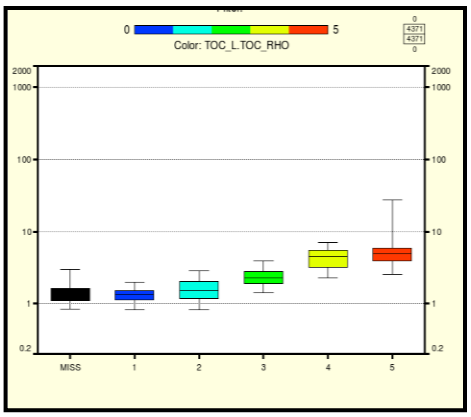

Figure6: Box Whisker plot of Deep Resistivity (Y-axis) and TOC (X-axis) colored with TOC showing increase in Resistivity vis-à-vis increasing TOC

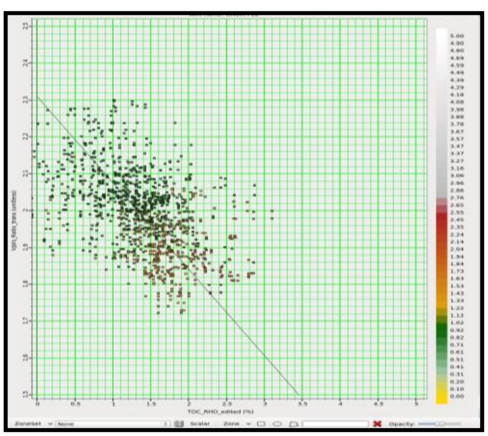

Figure7: Cross plot of TOC (X-axis) and Vp/Vs (Y-axis) colored with Resistivity showing decrease in Vp/Vs vis-à-vis TOC

Assessing Quality of P-sonic and Density data

To further investigate the probable reason of P-impedance not being impacted by TOC, P-sonic (DT) and Density (RHOB) were cross plotted to examine the quality of recorded P-sonic and Density data (Fig8). It was observed that although the trend /correlation between the two properties (DT & RHOB) is linear but the P-sonic values exhibits a wide range of variation corresponding to range of Density values (2.4 g/cc to 2.7 g/cc) with in which it varies vis-à-vis TOC (as seen in Figure5). Thus the finer variation as seen in Density values vis-à-vis TOC variations are not perceptible in P-sonic values. Furthermore, this may be the probable reason for P-impedance which is a product of the two (DT and RHOB) being insensitive to TOC.

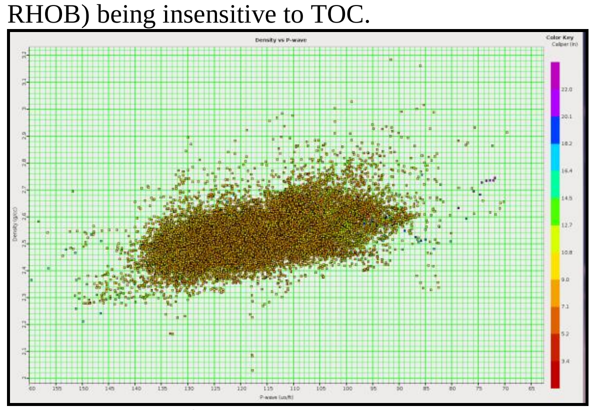

Figure8: Cross plot of P-Sonic (X-axis) and Density (Y-axis) colored with Caliper to ascertain the log data quality

Step 3: Pre Stack Inversion and Transformation of inverted outputs into TOC and BI volumes

After having established the elastic parameters sensitive to the TOC values following workflow was adopted for generating TOC volume and Brittleness Index volumes respectively:

- Pre Stack Inversion.
- Generation of TOC volume from Vp/Vs
- Generation of Brittleness Index volume from Young's Modulus and Poisson's Ratio.
- Generation of Resistivity volume using EMERGE
- Validation TOC volume from Resistivity volume.
- Identification of probable brittle zones and High TOC zones (Sweet Spots) from TOC and Brittleness Index volumes.

Pre Stack Inversion

Pre-stack time migrated gathers were conditioned and the fidelity of amplitude response of these gathers was quality checked with the synthetic gathers generated using well logs. Satisfactory data quality within the zone of interest was available for carrying out simultaneous inversion. A low frequency model using the log data from the input wells was prepared and a model based inversion was performed to generate P-impedance, S-impedance Density and Vp/Vs volumes respectively.

Generation of TOC volume

As concluded from the rock physics analysis carried out earlier (Fig4, 5, 6 & 7); while the P-impedance was insensitive to TOC, Density, Resistivity and Vp/Vs were seen to be having good correlation with the TOC. However, for estimating the TOC volume, Vp/Vs was preferred over Density since it provided a greater dynamic range of variation in values i.e. from 1.7 to 2.4 as against comparatively narrow range of variation in Density values i.e. 2.4 g/cc to 2.7 g/cc. A regression equation relating Vp/Vs and TOC was obtained from the combined cross plot of Vp/Vs and TOC for all the wells taken together (Figure7). TOC can be expressed in terms of Vp/Vs as follows:

$$\mathbf{TOC = -(((Vp/Vs)-2.10)/0.109914)}$$

Inverted Vp/Vs volume was converted to TOC volume using the above relationship (Figure9).

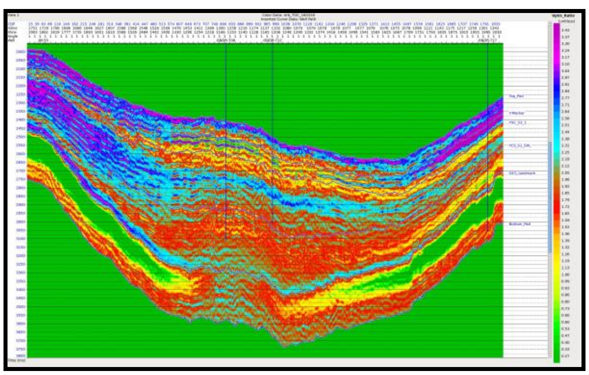

Figure9: Arbitrary Profile through generated TOC volume

Generation of Brittleness Index Volume

The term Brittleness Index (BI) is a lithology indicator, which implies that the rocks characterized by high BI exhibit a high Young's Modulus (E) and low Poisson's ratio (ν) (Rickman et al 2008); i.e. high BI is indicative of sandstone (quartz rich lithology) while low BI indicates shale (clay rich lithology). Thus Brittleness Index can be expressed as a function of (E & ν) as:

BI (%) = [w $((\nu_{max} - \nu) / (\nu_{max} - \nu_{min}))$ + (1-w) $((E - E_{min}) / (E_{max} - E_{min}))$] X 100; where w is weight factor; varying from 0 to 1. ν_{max} and ν_{min} are minimum and maximum Poisson's ratio while E_{max} and E_{min} are minimum and maximum Young's modulus respectively.

Young's Modulus (E) and Poisson's ratio (ν) volumes were generated by transforming inverted Vp/Vs and inverted Density volumes as following relationships:

$\nu = (\gamma-2) / 2(\gamma-1)$ where $\gamma = (Vp/Vs)^2$

$E = \rho Vs^2 (3\gamma-4)/\gamma-1$ where ρ =Density & $\gamma = (Vp/Vs)^2$

Brittleness Index (%) volume using the above relationship was computed (Figure10).

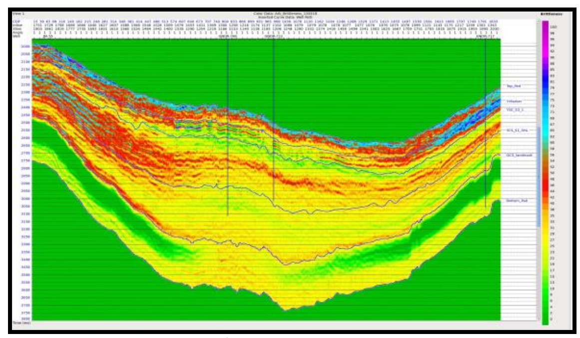

Figure10: Arbitrary Profile through generated Brittleness Index volume

Generation of Resistivity volume using EMERGE

Resistivity (deep) was another parameter which showed a direct correlation with TOC (Figure4). With a view to corroborate the computed TOC volume with Resistivity. The Resistivity (Deep) volume was also generated as an additional attribute for QCing the TOC volume as the zone which exhibit high TOC values should also exhibit by high resistivity values (Figure12). Resistivity volume was generated using multi regression analysis using EMRGE. Multi regression analysis showed that S-impedance had maximum contribution in the regression relation of Resistivity volume with training correlation of 87% with and validation correlation of 75% respectively (Figure11).

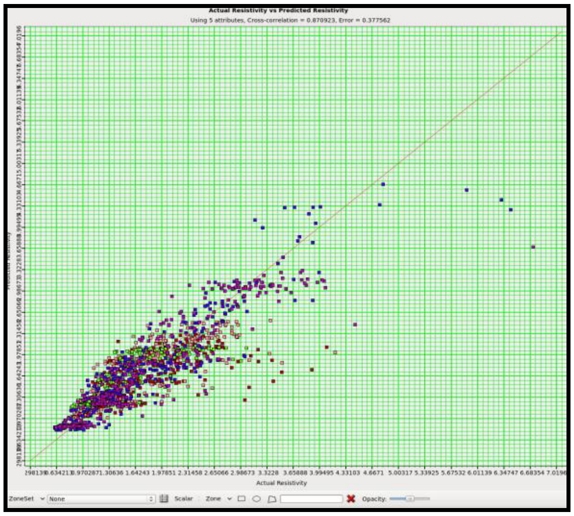

Figure11: Cross plot of Resistivity (Deep) log (and Resistivity log predicted using Multi Regression Analysis (EMERGE) showing correlation of about 78%.

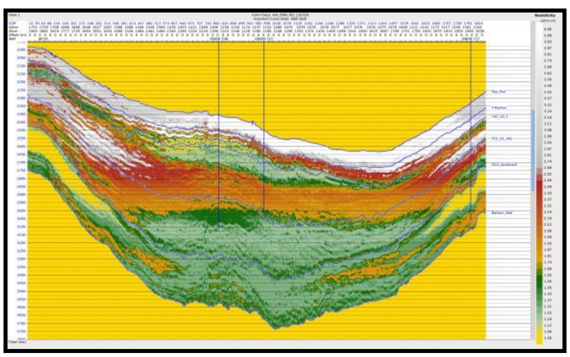

Figure 12: Arbitrary Profile through generated Deep Resistivity volume. The volume corroborates very well with the generated TOC and BI volumes.

Identification of probable High TOC and brittle zones (Sweet Spots) from TOC and Brittleness Index volumes

To scout for regions exhibiting high TOC & high BI values (probable sweet spots), several horizon slices of each of the property volume were generated and analyzed for different levels. However, with a view to integrate all the three properties in a single map, all the three property volumes (TOC, BI and Resistivity) were first normalized and then super-imposed over each other so as to come up with a composite map where the high value in the map will correspond to the high values for all the three properties. One such map is reproduced below in (Figure13).

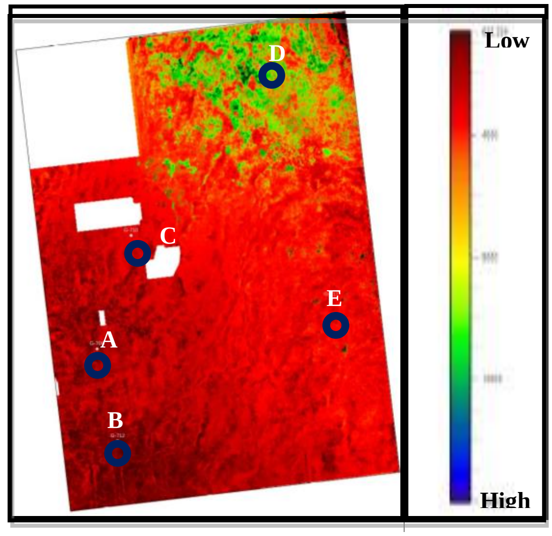

Figure 13: Composite map of normalized TOC, BI and Resistivity. Depicting that high value corresponds to high TOC, high BI and high Resistivity

Conclusion

The study shows that Passey's method can be used when there is no core available in the study area to give a reasonable TOC estimation with the help of wireline logs. In the study area P-impedance was insensitive to TOC, while Density and Vp/Vs exhibit negative linear correlation vis-à-vis TOC. Resistivity (Deep) behaved linearly proportional to TOC. TOC volume has been generated by transforming inverted Vp/Vs volume into TOC by using linear regression equation obtained from cross-plotting TOC and Vp/Vs. Brittle ness Index volume has also been calculated for the study area. The areas exhibiting high TOC, high Resistivity values and high Brittleness Index (BI) have been identified as prospective locales for future efforts.

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