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Author **Arijit Sahu , ONGC , India**

Co-Authors **Milan Kanti Das**

Petrophysical evaluation of organic richness and brittleness of shale for unconventional hydrocarbon prospecting: A case study on Vadaparru Shale, Krishna Godavari Basin, India

Authors: Arijit Sahu, Milan Kanti Das

Abstract:

Objective: Shale has been a major destination for unconventional hydrocarbon resources for its wide stratigraphic coverage as well as high volumetric gas potential. Contemporary success in North American shale plays has intrigued operators worldwide in shale exploration. Organic matter richness has been a key factor to determine the potential of shale as it is proportional to the amount of free gas likely to be generated and stored in available spaces within the shale. The other important factor in this context is shale brittleness as it indicates how fracable the ‘potential’ shale is. Attempts are made here by strategically using standard wireline logs in order to evaluate potential of Eocene Vadaparru Shale in Krishna Godavari Basin, India qualitatively and quantitatively.

Methods: The technique used in this study involves identification of organic matter lean clean shale interval and establish a ‘clean shale’ relation of resistivity as a function of sonic transit time in the study wells. Using this relation a proxy resistivity log is generated in shale and compared with measured wireline resistivity. A positive separation between measured and calculated resistivity is then assessed as proportionate shale organic carbon richness owing to the combined effect of lower density of organic matter and higher resistivity from generated hydrocarbons. Shale brittleness is predicted from Young’s modulus and Poisson’s ratio using compressional and shear sonic velocities.

Results: The Eocene marine transgressive Vadaparru Shale is a dominant stratigraphy in KG basin as evident from seismics and drilling. The wireline log study in few subject wells indicated fair to excellent organic richness in Vadaparru Shale. Moreover the amount of positive separation between measured and calculated resistivity when combined with net vertical thickness and brittleness, quantitatively indicate excellent shale quality. Considerable thickness, Type-II, III kerogen content and geochemical measurements supports the study and highlight it as a potential ‘shale reservoir’ destination. In the context of rapidly growing energy demand of India Vadaparru Shale can be considered as serious unconventional player.

Novelty: Overall this study presents quick strategy for shale potential quantification, thus allowing operators to focus spatially in the quest of unconventional hydrocarbon exploration.

Keywords: *Shale organic richness, brittleness*

Introduction:

Krishna Godavari (KG) basin in India has been a focus for shale exploration in the context of unconventional hydrocarbon potential. As on date operators mostly kept their concentration in Cretaceous Raghavapuram shale including its bottom most High Gamma-High Resistivity litho unit. However the other geologically younger, prospective and spatially extensive Eocene Vadaparru Shale has not been explored to the extent of an unconventional player. The present study is thus aimed to develop strategies to evaluate potential of Vadaparru Shale using available wireline and geochemical data.

Unconventional shale potential is largely a function of organic carbon richness which commands directly on the volume of stored hydrocarbon either in ‘free’ or in ‘adsorbed’ form. ‘Free’ hydrocarbon determines the hydrocarbon-in-place factor of an unconventional system however ‘adsorbed’ hydrocarbon determines the life of such system. Clay richness according to Wang C-C et al. (2004) is one essential factor for unconventional play as they offer more adsorption site and surface area for hydrocarbons. Few authors (Ji L et al., 2012) showed that the gaseous hydrocarbon (C1) adsorption varies with clay mineral type and it decreases in the order of montmorillonite > illite/semectite mixed > kaolinite > chlorite > illite. However more recent studies (J. Tan et al., 2014) showed that TOC content has more positive correlation with hydrocarbon (C1) adsorption, over clay minerals in shale. Thus together clay and organic carbon richness can be considered as a longevity proxy for unconventional shale play.

In general micro-porosity, naturally existing micro fractures and bulk matrix are responsible to store available hydrocarbon in shale. But poorer natural permeability in shale is a hindrance in order to produce those stored hydrocarbons from shale. In order to cross that threshold of poor permeability shale is needed to be artificially fractured. As discussed by Zehnder (2012) it's important to identify brittle interval in shale as they are more likely to fracture, thus creating an artificial flow path within the shale. Therefore an effective unconventional shale interval would be a clay rich one yet brittle having significant TOC content. Hence in this paper we attempted to establish technique to practically identify such organic rich brittle intervals in Vadaparru Shale. The outcomes are also compared with geochemical studies on shale samples obtained during drilling.

Geological aspects:

Vadaparru Shale is located (figure-1) in the East Godavari sub-basin in KG and is of Eocene age. The shale and interlayered sandstone beds are largely known as Vadaparru play located to the south of Mori-Komarada fault system and has considerable average drilled thickness of 950m. As discussed by Sahu (2018) Vadaparru Shale itself is a source-reservoir system and mostly targeted for the conventional oil and gas in sandstone units contained within the shale. The sediments of Vadaparru Shale appear to be deposited in a marginal marine deltaic to shallow marine shelf condition.

Petrographic study of Vadaparru Shale indicated a shale system with high degree of heterogeneity owing to variable degree of occurrence of silt, sand and calcareous and carbonaceous matters. Shale is occasionally micaceous and overall has various degrees of lamination, fissility and micro discontinuities. X-Ray diffraction study in company's regional laboratory facility also revealed clay rich nature of Vadaparru Shale. It is also found that smectite/mixed clay & kaolinite is reduced and relative abundance of chlorite has increased consistently with depth in the subject wells.

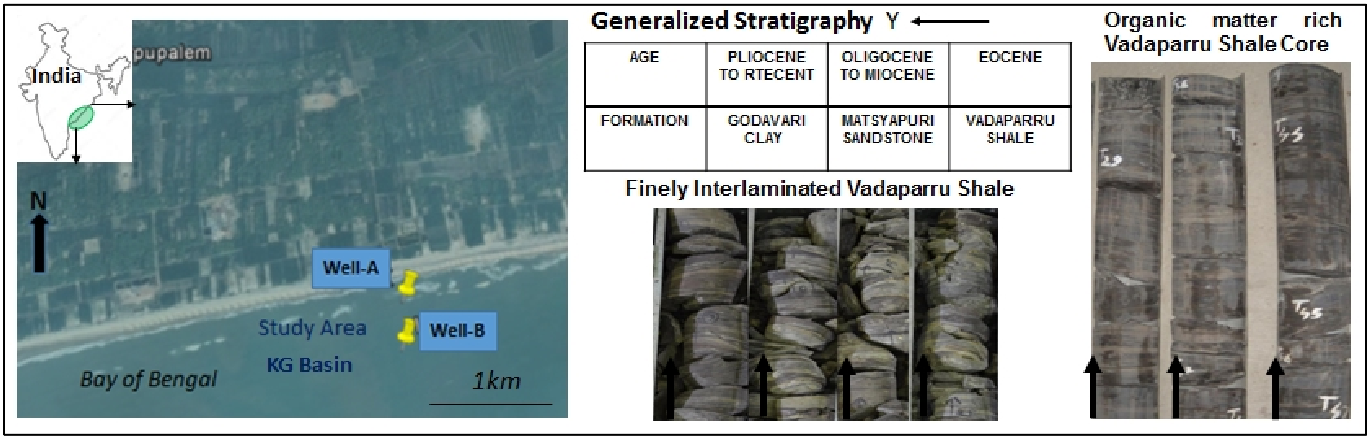

Figure-1: Location map of study wells and stratigraphy; also shows Vadaparru Shale core images from nearby area.

Methodical approaches:

In order to evaluate shale organic richness standard wireline logs of gamma ray (GR), deep resistivity (LLD) and compressional sonic transit time (DT) are used in this study. For the geomechanical aspects towards evaluating brittleness of shale strata dipole shear sonic log has been used. Sonic travel time and resistivity are essentially comparable and reliable logs as their behavioral patterns proportionately reflect changes in shale characteristics such as organic content. In general organic matter (OM) that occurs in shale matrix is relatively resistive and less dense. Hence comparing sonic and resistivity OM lean shale can be identified if properly scaled by 1 logarithmic decade of resistivity for 50 µsec/ft of sonic, as shown by Passey et al.(1990), after validating with gamma, neutron porosity and density responses. An organic lean 'clean' shale interval can be used therefore to establish a relation (equation-1a, 1b) of logarithmic resistivity as a function of sonic using cross plot method (figure-2). Reduced major axis regression method is applied here to obtain such relation as dependency of the two variables i.e. logarithmic resistivity and sonic must be symmetric for geological considerations.

$[Y]\ \mathrm{Log}_{10}\,(LLD) = f\,(X) = f\,(DT)$ ------- (1a)

Log_{10} (LLD) = 2.2633 – 0.0233*DT------- (1b)

LLDdt = $10^{(2.2633 - 0.0233*DT)}$ ------- (1c)

Equation 1c is then used to calculate presumable clean shale response of deep resistivity '*LLDdt* (ohm.m)' for the shale dominant sections. As for Vadaparru Shale clay rich intervals can be determined easily by applying suitable Vclay cut off of 0.5 calculated from equation-2 using GR, with lowest 'clean' sand and highest 'unclean' shale end points.

Vclay (relative fraction) = (GR-GRclean) / (GRshale-GRclean) ------ (2)

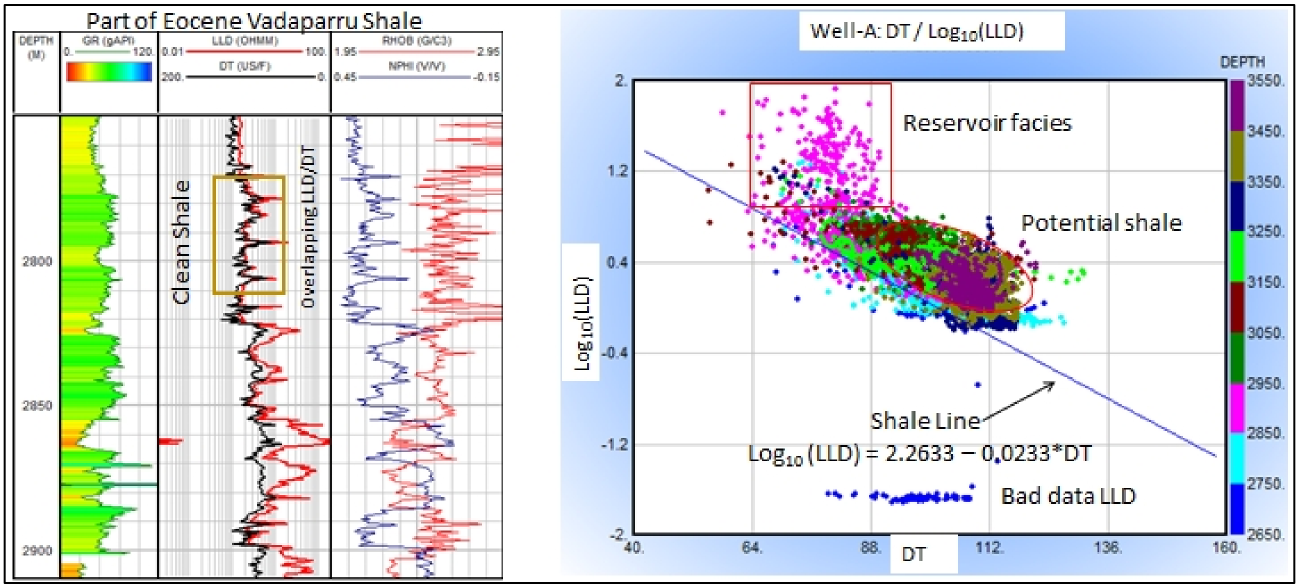

Figure-2: Identification of clean shale as found in Well-A of Vadaparru Shale in 2770-2800m and establishing clean shale line by relating LLD as function of DT using cross-plot and RMA regression within clean shale interval.

A positive separation of LLD from LLDdt is then assessed as proportionate shale organic carbon richness owing to the combined effect of lower density and higher resistivity of OM and generated hydrocarbons in clay dominant intervals. The positive separation of LLD and LLDdt is quantified as *LLDgap* in ohm.m (equation-3) and attributed to be proportional with combined shale organic potential and maturity. LLDdt and LLDgap are studied in two wells A and B for Eocene Vadaparru Shale.

LLDgap = LLD – LLDdt ------ (3)

Brittleness is studied in Well-B within the Vadaparru Shale. The organic rich shale must be fracable as it is required in low permeability regime to take out the production. Fracability of shale overall is largely dependent on mineralogy and sedimentary structures (fissility, variable lamination, natural micro fractures etc.) and can be realized through brittleness of shale. Brittleness controls fracture fairway geometry (Grieser and Bray, 2007) thus a brittle organic rich shale interval is desirable, for placing artificial fractures, to link to maximum 'potential rock volume'. Brittleness can be estimated (equation 4 to 11) from Young's modulus (YM in GPa) and Poisson's ratio (PR in fraction 0-0.50) as discussed by Grieser and Bray (2007). Higher YM (ability to retain fracture) and lower PR (ability to fail under stress) are accounted as brittle strata for their classical definitions. However occurrence of less brittle shale over more brittle organic rich shale can be considered as more beneficial as former tends to act as effective local cap in unconventional shale system (Rickman, 2008). As shown by previous authors (Potter and Foltinek, 1997; Al-Qahtani and Zillur, 2001) dynamic YM and PR can be estimated from dynamically recorded density (D kg/m3) and sonic compressional (Vp m/s) and shear (Vs m/s) velocities. Static YM conversion is needed for calculations as rocks are subjected to geologically longer static loading (Zoback, 2007). However for PR, dynamic and static components are found to be comparably same (Wang, 2001). There are various relations used for estimation of static YM from dynamic one, in absence of core with some obvious level of error, so we chose one as shown by Wang (2000).

$\mathrm{YM}_{\mathrm{dynamic}} = ((D*Vs^2)*((3*Vp^2)-(4*Vs^2)) / ((Vp^2)-(Vs^2)))/10^9$ ------- (4)

$\mathrm{PR}_{\mathrm{dynamic}} = ((Vp^2) - (2*(Vs^2))) / (2*((Vp^2)-(Vs^2))) = \mathrm{PR}_{\mathrm{static}}$ ------ (5)

$\mathrm{YM}_{\mathrm{static}} = (0.4145*\mathrm{YM}_{\mathrm{dynamic}})-1.0593$ ------- (6)

Shale is unique in a way that it behaves isotropic along its laminations/intercalations and anisotropic across the depth. This feature is known as transverse isotropy (Gholami, 2015). So in shale YM and PR is expected to differ in their respective horizontal and vertical components. The differences between static vertical and horizontal components of YM and PR are observed in study well-A. Dynamic vertical (V) and horizontal (H) YM and PR components can be calculated from dipole shear sonic velocities (Vsu = Vs upper dipole, Vsl = Vs Lower dipole, m/s) as discussed by Gholami, 2015 using following simplified equations.

$YM_{dynamicH} = ((D*Vsl^2)* ((3*Vp^2)-(4*Vsl^2)) / ((Vp^2)-(Vsl^2)))/10^9$ ------ (7)

$YM_{dynamicV} = ((D*Vsu^2)* ((3*Vp^2)-(4*Vsu^2)) / ((Vp^2)-(Vsu^2)))/10^9$ ------ (8)

$PR_{dynamicH} = ((Vp^2) - (2*(Vsl^2))) / (2*((Vp^2)-(Vsl^2))) = PR_{staticH}$ ------ (9)

$PR_{dynamicV} = ((Vp^2) - (2*(Vsu^2))) / (2*((Vp^2)-(Vsu^2))) = PR_{staticV}$ ------- (10)

YM static vertical and horizontal components can be calculated by using equation-6. As discussed by Grieser and Bray (2007); Waters (2011) vertical static YM and PR components are used to calculate brittleness % of shale.

$Brittlenes=100*[((YM_{staticV}-YM_{staticVmin})/(YM_{staticVmax}-YM_{staticVmin}))+((PR_{staticV}-PR_{staticVmax})/(PR_{staticVmin}-PR_{staticVmax}))]/2$---(11)

Where $YM_{staticVmin}$ is minimum and $YM_{staticVmax}$ is maximum values static vertical component of YM in the study interval (2960-3500m well-B) and stands at 0.25 GPa and 16 GPa respectively. Likewise $PR_{staticVmax}$ and $PR_{staticVmin}$ stand at 0.39 and 0.05 respectively for that interval.

Results and Discussion:

The study carried out in KG basin Eocene Vadaparru Shale in order to evaluate the organic richness as well as brittleness is presented through figure 2 to 5. In well-A and B the organic richness has been assessed using the strategy of calculating LLDdt (figure 2 and 4) in Vadaparru Shale. LLDdt is indicative of possible deep resistivity behavior in subject shale as if it were OM lean. LLDgap or the positive separation of LLD from LLDdt is measured for clay rich sections (determined by Vclay cut off of 0.5 in this case). As shown in figure-3 in well-A LLDgap (color coded in middle track) in negligible or nil in section above 2950m. However LLDgap exists (A, B & C figure-3) in deeper shale section punctuated by arenaceous intervals.

Laboratory studies (pyrolysis) of 5m interval cuttings Vadaparru Shale of Well-A reveal type-II/III kerogen and TOC content varies in the range of 0.80-10% with average of 4%, S1 varies from 0.02-0.44 mg HC/g with average of 0.1 mg HC/g, S2 varies from 0.80-30mg HC/g with average of 7mg HC/g, HI varies from 73 to 293 mg HC/g with average of 153 mg HC/g and Tmax varies from 434-448°C with average of 440°C. Since Tmax is indicative of thermal maturity it can be converted to Vitrinite Reflectance (VR) as discussed by Jarvie and Lundell (2001) using following equation-12.

$VR = (0.018 * Tmax) – 7.16$ -------- (12)

Well-A VR calculated varies from 0.65-0.90 with average of 0.79. These geochemical lab results are shown in right most track of figure-3. It can be seen from figure-3 that intervals A, B and C are having early to peak maturity, good HI with fair to excellent TOC content. Palynological study in well-A reveals presence of maximum flooding surface at 3205m and a sequence boundary at 3100m supporting TOC behavior of the shale.

Interestingly LLDgap is also prominent in the same (A, B, C figure-3) intervals. Comparing magnitude variation of LLDgap with geochemical findings in well-A, LLDgap is attributed to be directly related with combined shale richness and maturity. Similarly LLDgap is studied in well-B (figure 4 & 5) and it shows presence of major potential shale in the interval of 3356-3485m. Two essential components of unconventional shale play- free and adsorbed hydrocarbons are related to organic richness of shale and maturity with which LLDgap is associated. So we suggest LLDgap can be used with confidence as a parameter for unconventional shale potential for Vadaparru Shale. Heterogeneity as discussed in geological aspects coupled with OM richness are two important factors which makes Vadaparru Shale a favourable unconventional target.

Brittleness study has been carried out in well-B for dipole sonic data being available for the entire drilled Vadaparru Shale through equations 4 – 11 (figure-5). For Vadaparru Shale based on brittleness responses values >65 is classified as highly brittle facies and mostly represented by arenaceous or 'non-shale' facies. Brittleness of 45-65 range is classified as brittle, 45-30 is

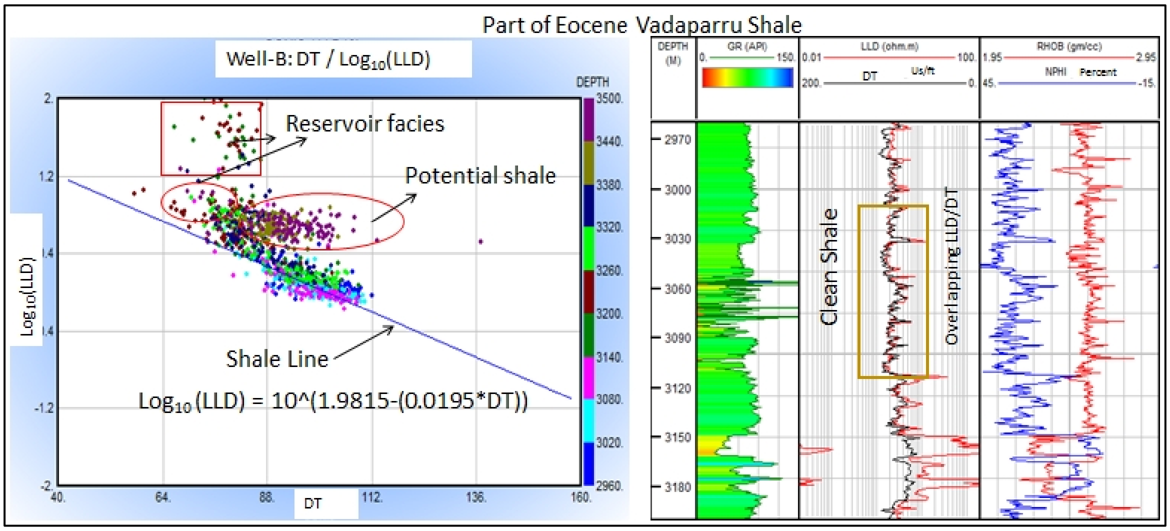

Figure-4: Identification of clean organic lean shale from Well-B in Vadaparru Shale in the interval of 3033-3100m and establishing clean shale line by relating LLD as function of DT using cross-plot and RMA regression within clean shale interval.

classified as transitional between brittle-ductile and <30 is classified as ductile facies. It is observed that shale brittleness in Vadaparru Formation ranges from 6-62 thus ductile, transitional and brittle all three types are present in the formation. It is observed that brittle organic rich shale 'sweet spot' (indicated by LLDgap carrying a cut of 0.5 for Vclay) exist in the interval of 3356- 3420m (brittleness 45-54) with few fringes of transitional shale. The transitional fringes in between an organic rich brittle shale interval might be advantageous as it could be responsible locally if not regionally, to restrict the migration of generated hydrocarbon. Interval 3420-3485m is having few thin (1-5m) potential (supported by LLDgap) brittle organic rich shale intervals. It is also observed that few brittle shale intervals exist in the interval of 3050- 3356m but lower ranges of LLDgap values discard their eligibility to become potential organic rich shale.

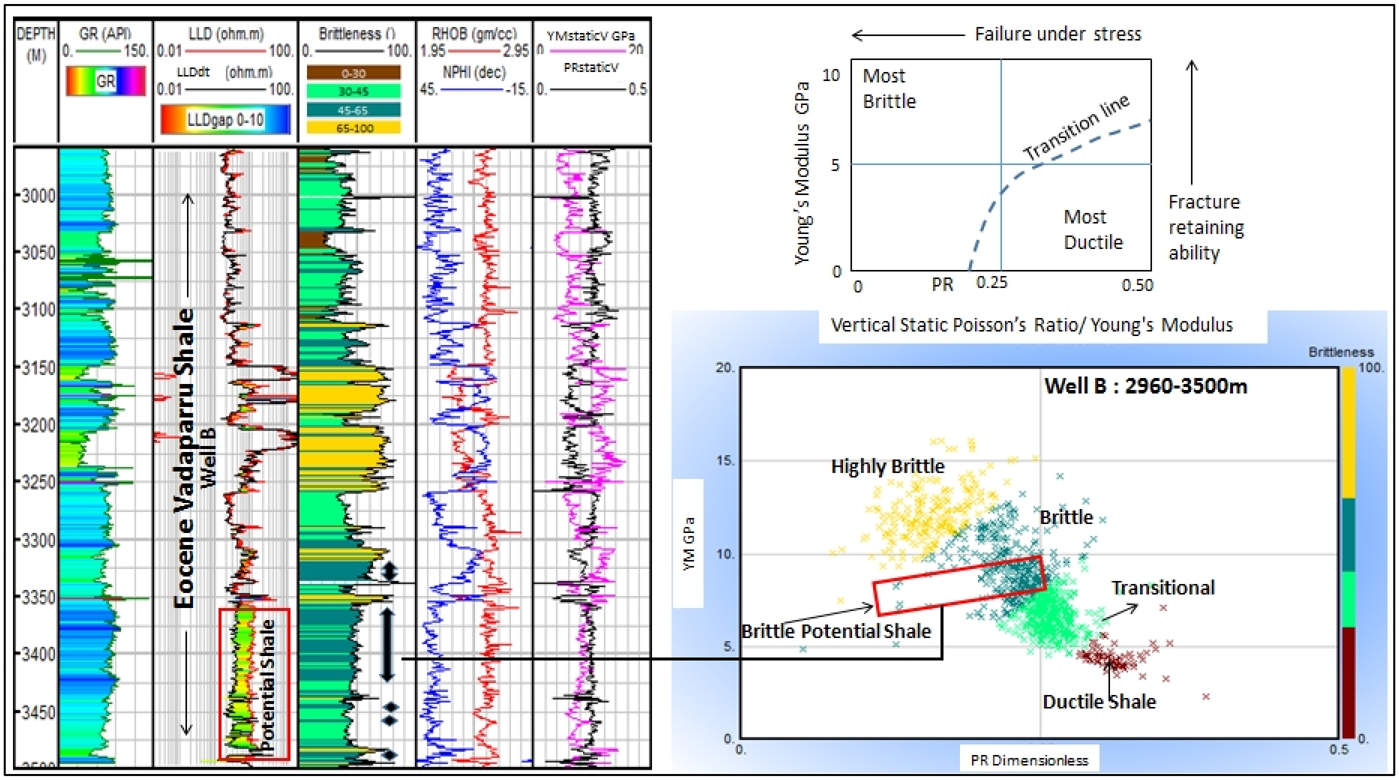

Figure-5: Brittleness and shale richness study in Vadaparru Shale Well-B. 'Non-shale' highly brittle facies are distinct. Potential shale exists within 3356-3485m and appears brittle in 3356-3420m and in few thin intervals from 3420-3485m.

Above 3356m few brittle shale exist but not potential as indicated by poor LLDgap magnitude. Static vertical components of Young's modulus and Poisson's ratio determined from dipole sonic data are displayed on the right most track.

Quantification of potential shale:

LLDgap can be used as a correlation tool of organic rich potential shale intervals over geological area of interest as shown in figure-6. Since LLDgap is proportional to shale organic richness it's application can be extended in shale potential quantification through equation 13-14. Whenever LLD exceeds LLDdt in clay rich interval average LLDgap is to be calculated and called as AVG_{LLDgap}. True potential thickness of shale over which LLDgap is >0 is then calculated as H_{TP} and true thickness of total drilled shale is calculated as H_{TD}. Relative shale organic potential (RSOP in ohm.m) and Volumetric shale organic potential (VSOP in ohm.m^2) are defined as-

$RSOP = AVG_{LLDgap} * (H_{TP}/H_{TD})$ -------- (13)

$VSOP = AVG_{LLDgap} * H_{TP}$ ---------- (14)

RSOP and VSOP are designed in to provide quick information of comparative shale organic richness for a drilled well and thus can be mapped from different wells over an area to get overview of possible orientation of unconventional shale system. RSOP values for well-A and well-B stand at 2.07 and 2.06 while VSOP values stand at 1870 and 910. RSOP signifies the development of identical shale potential in both well. Since true drilled thickness through potential shale is more in well-A, it yields higher VSOP.

Brittle (brittleness>45) organic rich potential for Vadaparru shale is also defined for well-B by equation-15 and 16. Effective brittleness ($Brit_{Eff}$) is calculated by subtracting 45 from calculated brittleness (equation-11). When $Brit_{Eff}$ is >0 and LLDgap is >0 average of both is calculated as $AVG_{BritEffP}$ and $AVG_{LLDgapB}$. True thickness (H_{TBP}) of Interval over which such conditions occur is then calculated. Relative ($RSOP_B$ in brittle ohm.m) and volumetric ($VSOP_B$ in brittle ohm.m^2) organic rich brittle shale potential is defined as-

$RSOP_B = AVG_{BritEffP} * AVG_{LLDgapB} * (H_{TBP}/H_{TD})$ ------- (15)

$VSOP_B = AVG_{BritEffP} * AVG_{LLDgapB} * H_{TBP}$ ---------- (16)

$RSOP_B$ and $VSOP_B$ address relative and volumetric abundance of brittle-organic rich shale for a well and can be mapped over to visualize distribution of effective shale distribution. For well-B $RSOP_B$ and $VSOP_B$ values are calculated as 18.4 and 8101.5.

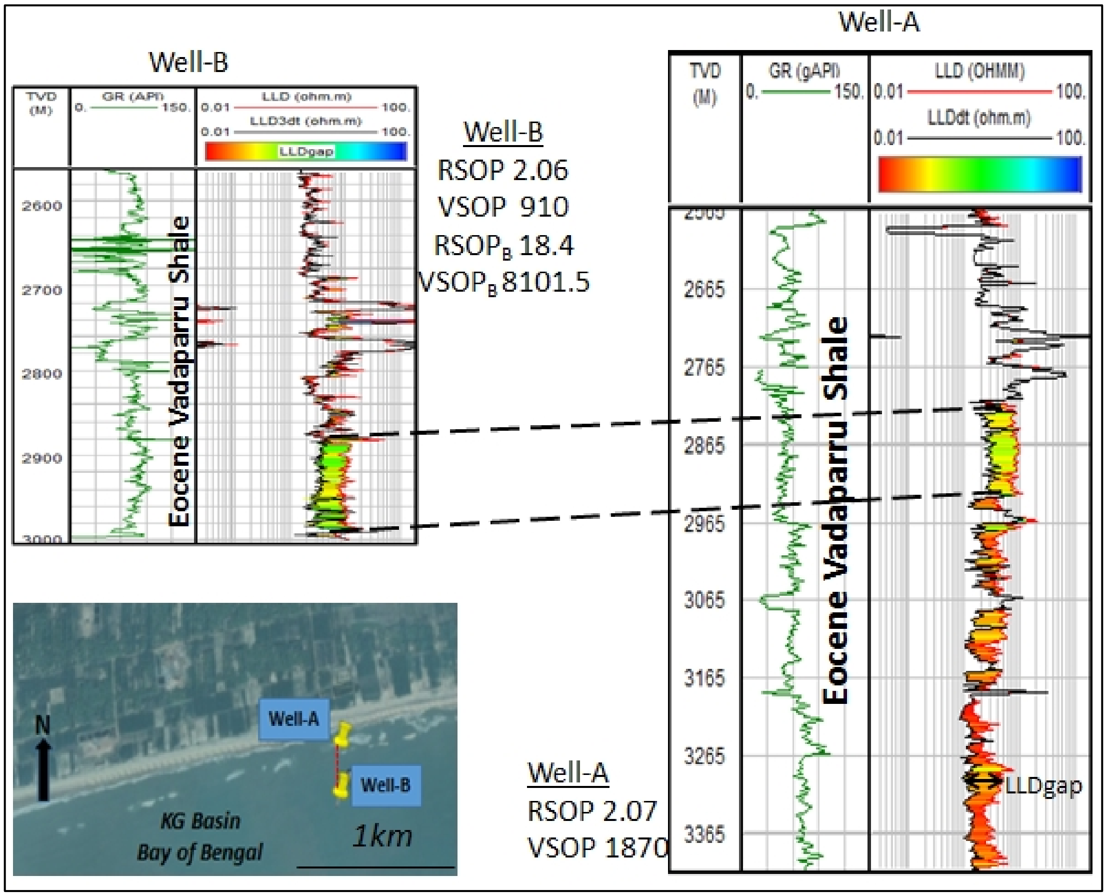

Figure-6: Correlation of organic shale in Well-A and B from LLDgap color coded on the right tracks.

Summary:

‘LLDdt’ and ‘LLDgap’ are useful approaches from the perspective of evaluating shale organic richness as discussed above. It’s easy to develop once clean shale is identified. However in the absence of such OM lean shale, LLD and DT relationship may be established from adjacent formations. In Vadaparru Shale clean shale exist as shown above so LLDgap can be practiced with confidence for potential shale identification, quantification and correlation. Vadaparru Shale brittleness varies a lot owing to its geological heterogeneity. Nevertheless thick brittle organic rich shale intervals exist in association with fringes of transitional shale. Overall combining LLDgap and brittleness analyses in wells combined with geochemical parameters, Vadaparru shale is found to be potential as unconventional player. There are further scopes to study this Eocene shale of KG basin in order to understand its geomechanical stress regime and distribution of organic richness associated with geological controls.

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