Characterization of Cleats by Integration of Micro-Resistivity Image Data and Cross-Dipole Array Acoustic Log in CBM Wells for Optimizing Completion Strategy

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Abstract

Cleats are micro-fractures present in coal seams which determine the potential of primary flow mechanisms of Coal Bed Methane (CBM) reservoirs. These cleats occur as mutually orthogonal fractures and are generally seen at very high angles or even perpendicular to the banding of the coal seams. The basic log suits, such as Resistivity, Gamma, Neutron, Density etc. provide petro-physical parameters of the seams; however, these logs and general evaluation strategies grossly remain short to define the cleat systems within the coal.
A CBM well may encounter multiple coal seams and only basic petro-physical evaluation methods is not sufficient to truly identify the prospect of the seams. Along with this the proper characterization of cleats can aid in production optimization as well as device better completion strategy. High cleat density in coal seams is of paramount importance as it defines fluid flow within the seam. Moreover, the azimuth of primary cleating in relation to in-situ stress azimuth makes an excellent tool to define flow potential.
In this study, the data from cross-dipole array acoustic log and high-resolution micro-resistivity image data from STAR log has been integrated to understand and characterize cleat systems in CBM wells of Bokaro field, Jharkhand. The idea is to analyze the variation of Compressional and Shear slowness, along with the variation of Stoneley reflectivity and transmission against the varying cleat density in different coal seams to delineate the better prospect for production. This aspect has also been validated with fracture analysis from high resolution micro-resistivity image data. Cleat orientation obtained from resistivity image has been integrated with maximum horizontal stress direction computed from azimuthal anisotropy analysis to identify seams having better capability of delivering fluid.
This study aims to devise a guideline to select a completion strategy in CBM reservoirs based on cleat characterization in relation to in-situ stress azimuth.

Introduction

Coal Bed Methane reservoirs consists of dual permeability system; where very low permeability matrix of the system and high permeable vertical to sub-vertical micro-fractures to the coal layers, known as cleats, form the entire flow network. In a cleat system the extended continuous micro-fractures are known as Face Cleats; while the subsidiary shorter micro-fractures (mostly orthogonal or sub-orthogonal to face cleats) are known as Butt Cleats. This interconnected network of cleat systems results in variation of path geometry and connectivity, which in turn gives rise to permeability anisotropy. Figure-1 displays a schematic of cleat network in a coal bed.

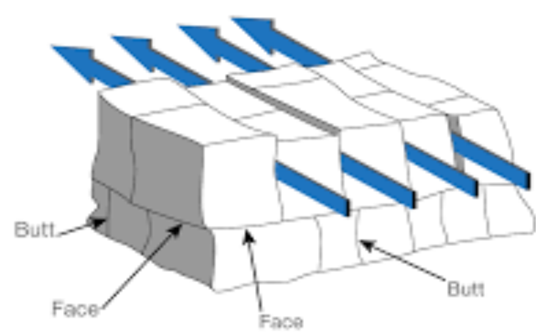

Figure-1: Schematic diagram of cleat syatem in coal

The geometry of cleat network and their relative connectivity varies from seam to seam and this has a significant impact in production characteristics even in commingled production scenario.
In this present study the well under consideration (Well#X) consists of nine (09) coal seams within an

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interval of 500.0 m. This paper describes an alternative approach to cleat characterization in relation to present day in-situ stresses; mainly based on full waveform sonic data and micro-resistivity image data, to select the coal seam with better flow capability and to optimize production.

Problem Definition

In general, basic logs such as density, neutron, resistivity and gamma are used to estimate the potential of a CBM reservoir. These logs are prone to be affected by the presence of secondary minerals, borehole environment etc. and does not depict the degree of cleating conclusively.
In the study well (Well#X) five (05) coal seams have been considered as objective in the interval A74-B72 m interval. The coal seams under consideration has the density in the range of 1.40-1.60 g/cc and compressional slowness varies from 112-130 µs/ft. Composite log data has been shown in figure-2 with objective seams marked in yellow. It is pretty much evident from the figure that based solely on basic log data it appears difficult to understand the role of different seams in commingled production.

Theory and Methodology

This section describes the methodology of cleat characterization based using resistivity image and acoustic data. In this study from top to bottom five objective seams (S-1 to S-5) are analysed.

- **Resistivity Image Log Analysis**

Micro-resistivity image data has a very high resolution and thus the processed dynamic image from the log data enables us to observe the distribution of cleats, natural fractures and induced fractures and also to obtain their orientation by virtue of dip data. It also helps to identify the primary and secondary fracture sets, their relation and orientation. Natural fractures occur mostly as continuous fractures with varied orientation and morphology, while the direction of breakouts and drilling induced fractures depend on current in-situ stress azimuth.
Cleat genesis is caused by the causes like lithification, palaeotectonic stresses, desiccation and coalification and its range varies from ¼ to several inches. Amount of cleating and cleat spacing depends on coal rank, tectonics, vitrinite content, bed thickness and mineral content.

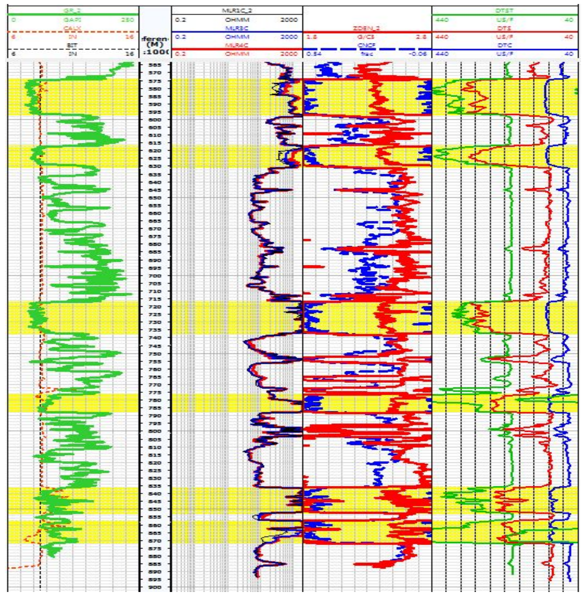

Figure-2: Composite Log of bulk density, neutron porosity, resistivity, gamma ray, compressional, shear and stoneley slowness along with objective coal seams

Firstly, the processed dynamic resistivity image of the well enables to identify two different types of cleat systems. Image of S-5 seam shows cleats of shorter length (Figure-3) while S-1 in networked by relatively longer cleats (Figure-4). This output has great implication as the longer cleats cut through multiple maceral bandings which enables better vertical connectivity.
Cleat network of the coal seams has been identified and plotted as fractures in terms of primary and secondary sets in processed resistivity image data. The cleat analysis has also been done for all the objective seams (S-1 to S-5) and it has been found that cleat density is more in seams S-1, S-2 and S-3 with highest cleat density at S-1.
This study also indicated in the orientation of the cleats, which has been plotted as tadpole plots for S-1 (Figure-5). This study infers that the general orientation of Face Cleats appears to be SW-NE.
Drilling induced fractures has also been interpreted in the well. These DIFs occur as tensile failures and seen in the direction of maximum horizontal stress. In this case it appears to be towards SW-NE direction,

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which eventually correlates with dominant direction of face cleats.

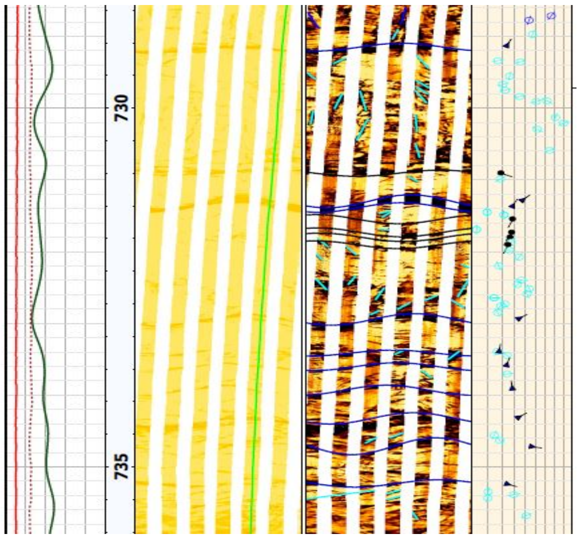


Figure-3: Short cleats confined within coal bands leads to less vertical connectivity

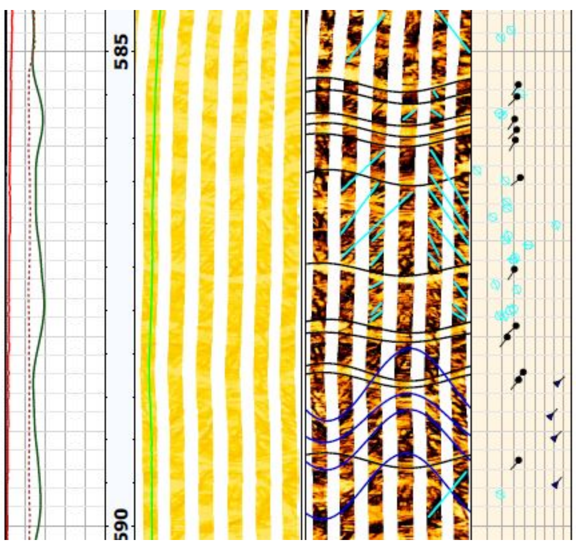
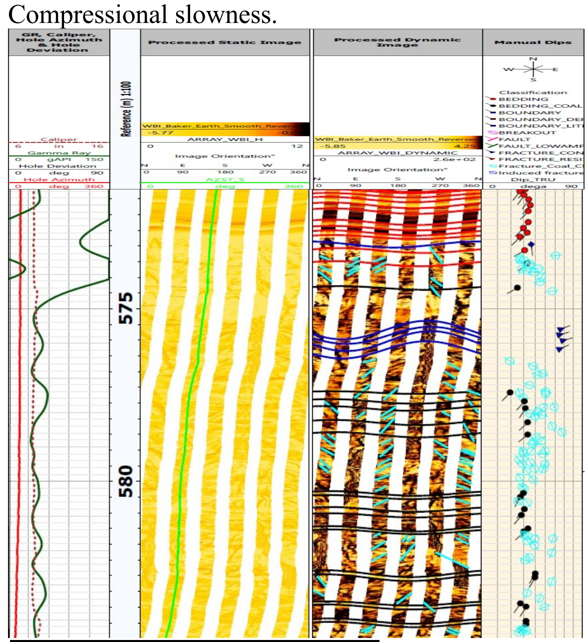


Figure-4: Longer cleats cross cutting maceral bands leads to good vertical connectivity

- **Acoustic Log Analysis**

The general study full waveform acoustic analysis for CBM aims to ascertain the stress profile along with delineation of the seams.

Coal being a very soft formation with Poisson ratio ranging around 0.38-0.42; shear slowness was not obtained from monopole source. Thus, from cross dipole array sonic processing shear and Stoneley slowness was extracted. The relation of compressional and shear slowness has been studied from the cross-plot of Vp-Vs ratio and Compressional slowness.



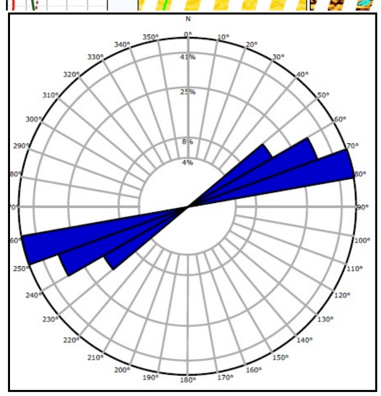


Figure-5: Highly cleated seam (S-1) shows dominant cleat strike towards SW-NE

As coal is a soft rock the elastic modulus of coal is low. If we take rigidity modulus in particular, which is a function of shear slowness, it has to be low in case of coal and it appears to be around 2-4 for the seams under consideration. So, if a coal seam has high degree of cleating it reduces the rigidity of the coal and increases shear slowness. This implies high degree cleating in the seam leads to high Vp-Vs ratio.

In our study, the highly cleated seams are S-1, S-2 and S-3 as obtained from micro-resistivity image data analysis. Vp-Vs ratio in these seams appears to be

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2.45-2.75. For the seams with less cleats (S-4 and S-5) it appears to be around 2.0-2.25.

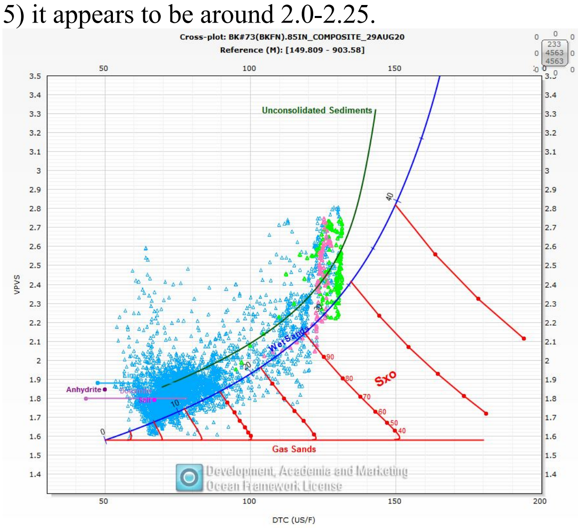

Figure-6: Vp-Vs ratio vs DTCO cross-plot for entire logged interval. Green and Pink points referred to S-1 and S-2 seams; DTCO shows negligible variation but Vp-Vs ratio varies

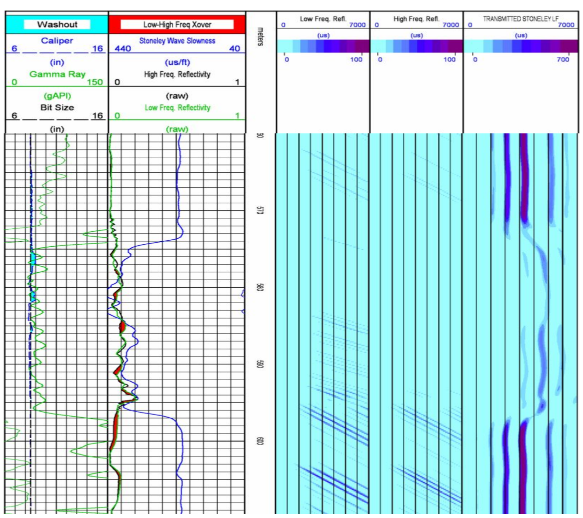

Figure-7: Less Stoneley transmission and reflectivity against seam S-1

The cross-plot of Vp-Vs ratio to DTCO for the entire section has been shown in figure-6, where green and pink dots representing seams S-1 and S-2 respectively. This indicates that these two seams are the most cleated ones. This output has been integrated with the resistivity image data and has been discussed in later sections.

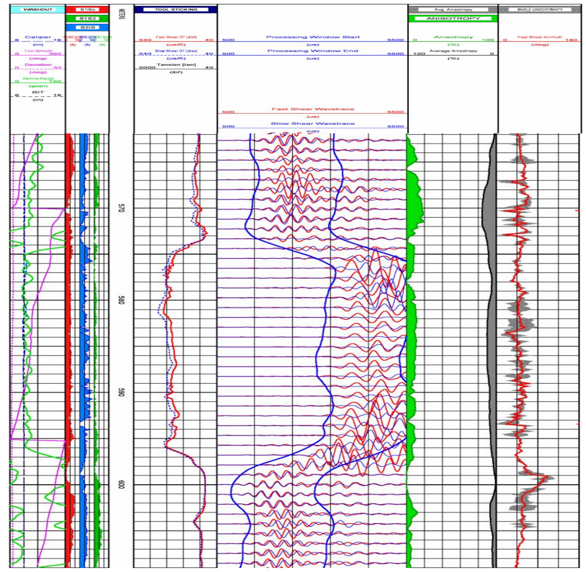

Figure-8: High degree of anisotropy against seam S-1. Note FACR trending towards SW-NE.

Stoneley wave in other hand travels along the surface of the borehole and is sensitive enough to the open fractures and irregularities of the borehole wall. Presence of open fractures tend to attenuate the Stoneley waves and thus, in coals with high degree of cleating attenuation will be maximum and reflection will be very less. In this study, Stoneley reflectivity and Stoneley transmission has been plotted for mostly cleated seam S-1 in figure-7. It has been found from the plot that Stoneley transmission is negligible and reflectivity is less. The similar overlay has also been done for other seams and has been correlated with Vp-Vs and DTCO cross-plot. It has been seen S-5 which is less cleated shown comparatively high reflectivity and transmission. Thus, these two analyses from full waveform sonic log paves a path for cleat characterization. These outputs have integrated with micro-resistivity image analysis for better confidence and the same has been discussed in next section.

Azimuthal anisotropy analysis from cross-dipole array acoustic log data has been used to determine the direction of fast shear azimuth (FACR). This represents the present day maximum horizontal stress direction. It has clearly indicated the anisotropic nature of the coal seams under study and their FACR trending towards SW-NE. (Figure-8)

Integration of Acoustic and Image Log

Integration of Acoustic and Image log analysis holds the core of this study. This enables us to build more confidence towards the conclusion.

Image log analysis has shown that S-1, S-2 and S-3 seams have highest cleat density and longer cleats, cross-cutting the maceral bandings of the coal, leading to more vertical connectivity. Whereas seams S-4 and S-5 are less cleated and cleats in these seams are mostly short ones.

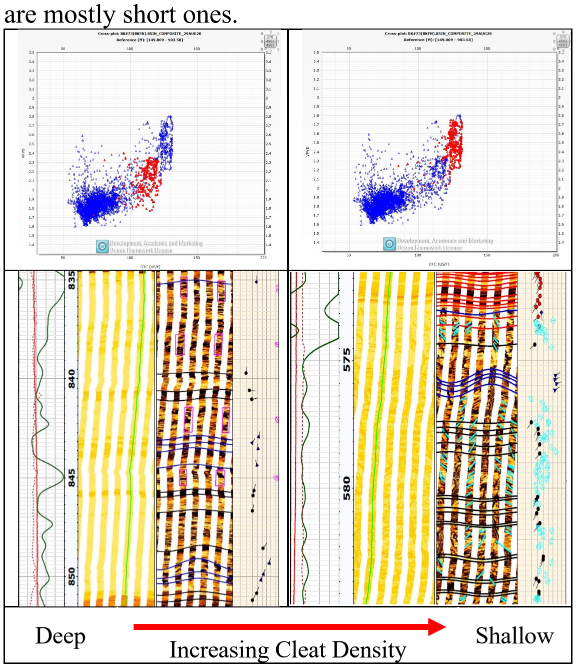

Figure-9: Increase of Vp-Vs ratio with cleat density. Vp-Vs ratio vs DTCO cross-plot response (red highlight) for deeper seam S-5 to shallower seam S-1. (Plotted in same scale as figure-6)

It has been discussed in earlier sections that high cleat density is leads to high to Vp-Vs ratio. Acoustic log analysis upheld this view by depicting that, Vp-Vs ratio has been highest for seams S-1 and S-2 followed by S-3. Vp-Vs ratio for these seams ranges from 2.45-2.75; while for seam S-4 and S-5 it is 2.0-2.25. A correlative diagram is shown with image logs in association with Vp-Vs DTCO cross-plot in figure-9.

Analysis of Stoneley reflectivity and transmission shows the same trend as depicted in figure-10.

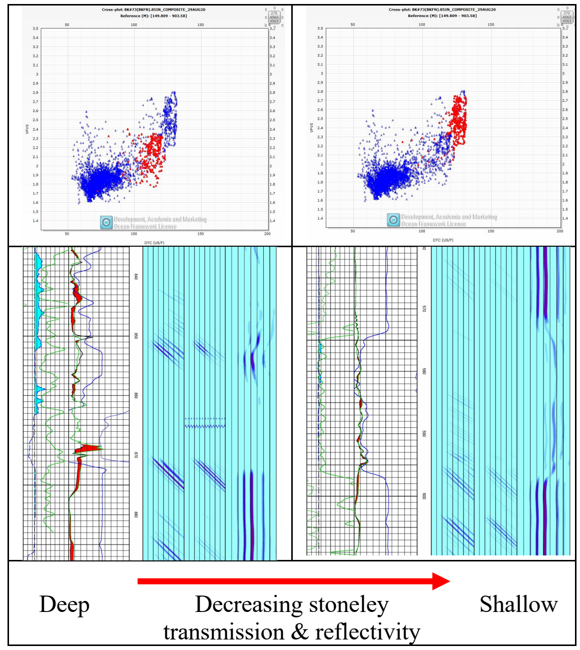

Figure-10: Stoneley reflectivity and transmission for deeper seam S-5 to shallower seam S-1; plotted in conjunction with Vp-Vs ratio-DTCO cross-plot (Plotted in same scale as figure-6)

This draws a correlation to categorize the seams on the basis of cleat characterization. Seams S-1, S-2 and S-3 occur at shallow depths of the well and are more cleated in comparison to seams S-4 and S-5, which are deeper coal seams.

Acoustic and Image log analysis are two independent techniques and both complements each other in terms of cleat density. Stoneley transmission and reflectivity analysis adds more confidence that S-1, S-2 and S-3 seams have different nature in comparison to S-4 and S-5.

Moreover, both logs suggest that the direction of maximum horizontal stress is towards SW-NE and it coincides with the dominant direction of face cleats. This keeps the cleat systems open and aid the primary flow through the seam and raises the permeability.

Conclusion and Completion Strategy

The general modus of operandi in CBM wells of Bokaro field is to hydro-fracture all the objective coal seams; flowed by testing and thereafter to put the wells under commingled production. As our study suggested the shallow seams (S-1, S-2 and S-3) has different nature compared to deeper seams (S-4 and S-5), this idea of producing from all the seams may not be prudent. Because cleat systems and flow behaviour of shallower (S-1, S-2, S-3) and deeper (S-4 and S-5) coal seams appears to be different all together, which means these two groups may require different drawdowns and may show influxes differently.

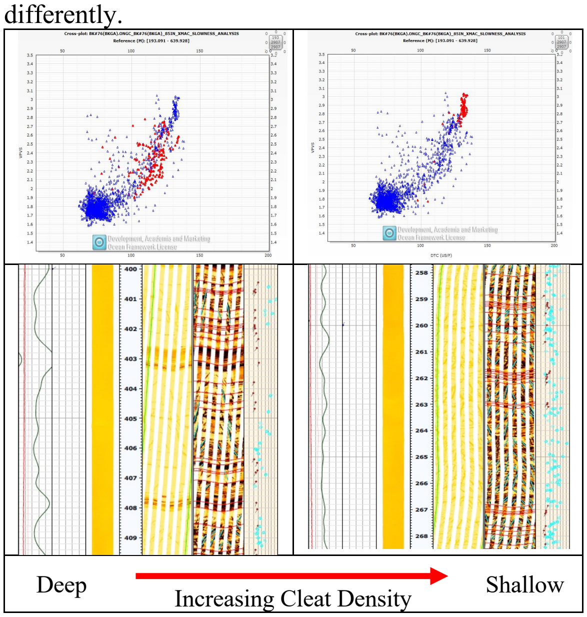

Figure-11: Increase of Vp-Vs ratio with cleat density. Vp-Vs ratio vs DTCO cross-plot response (red highlight) for deeper seam S-5 to shallower seam S-3. (Plotted in same scale as figure-6)

To obtain more certainty about the discussion above, the similar study has also been done in another Well#Y in the area and in this well also the integrated approach of cleat characterization reveals the similar trend as in Well#X. The results are shown in figure-11.

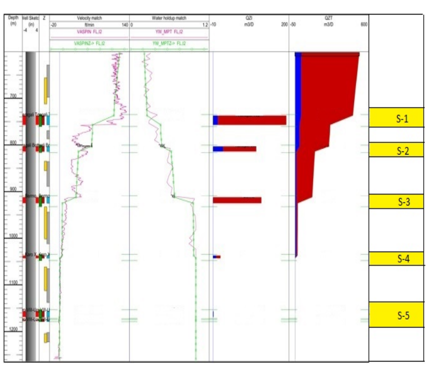

Figure-12: Production profile of Well#Z showing production from S-1, S-2 & S-3 only

Well#Z in the nearby area was put under gas lift and self-flow of CBM has been established in the well. Under such condition full set Production Log data has been recorded during commingled production. The results are shown in figure-12. The data showed that only the seams S-1, S-2 and S-3 are producing, while S-4 and S-5 remains inactive.

In such scenario it makes more sense to treat these two groups of seams separately and to facilitate this, two different completion strategy is being suggested. This may be adopted based on techno-economic viability.

1. Separate wells to be drilled for shallower and deeper seams to keep their testing and production approach separate, Or
2. The wells may be put under dual completion; putting separate tubing for two groups, which may require revision of casing policy.

Unconventional reservoirs such as CBM requires in depth knowledge of cleat systems to understand and predict the flow behaviour of the seams. This study has taken an approach by integrating two independent measurements of acoustic and resistivity image data to characterize cleat systems and their mutual relation with present day near wellbore stresses to share some lights of primary flow behaviour of the CBM reservoir.

This study has been concentrated on a particular section of the field as per the availability of the data and has not considered other geological and geo-chemical factor. Thus, it must not be used in isolation; rather it should be used in conjunction with other parameters such as: saturation, gas content, maceral content, reservoir pressure, hydro-dynamic conditions etc. for more prudent results.

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