# Prospective Coal Bed identification, Stress orientation determination and assessment of degree of fracture in coal seams and oriented perforation completion play favourable role in enhancement of CBM production

Dr.D.Haldar*, Sahadev Kumar*, Pinky Kumari*, Abir Banerjee*, H.S.Maity*

*Oil and Natural Gas Corporation Ltd., CBM Asset, Bokaro, India

halder_debashish@ongc.co.in

**Keywords:** Maximum Stress direction, Vp/Vs ratio, Degree of Cleating, Cleat Orientation, Breakout, Proximate analysis, Stoneley Transmission and Reflection Coefficient, Fast Shear Azimuth.

## Summary

Methane gas is adsorbed on the surface of coal matrix under hydrostatic pressure. On reduction of reservoir pressure (by dewatering) below the Critical Desorption Pressure, methane desorbs and migrates to the wellbore. However, presence of prospective coal seams alone does not warrant a well to be good CBM producer as adsorptive properties of coal leads to susceptibility from drilling mud, fracturing fluids and cement which might cause swelling and subsequent blockage. Apart from its Gas content and Gas Saturation, producibility from Coal largely dependent on the frequency and distribution of Cleats (i.e. extensive natural fracture system), cleats orientation and fracture induction in maximum stress direction. The aim of the study is to find out the prospective coal seams not only from resistivity, density and porosity parameter but also degree of fracture present in in-situ condition using Vp/Vs ratio and to characterise the fracture systems within the coal seams and to establish their relationship with the present day stress regime with a view to connect Cleats and to enhance as well as ensure sustainable flow of CBM to the well bore. Oriented perforation in maximum stress direction helps in generating enhanced permeability by increasing degree of fracture during Hydro-fracturing operations.

## Introduction

Coal bed methane (CBM) exists as monomolecular layer within the micro-pores of the coal. Coal acts as both source and reservoir for CBM. Coal acting as a CBM reservoir has dual permeability system, characterized by low permeability matrix part connected by high permeability orthogonal and sub vertical fractures (with respect to bedding) called cleats. The extended, continuous fractures are termed as face cleats and subsidiary shorter length fractures are classified as butt cleats. Shorter length butt cleats terminate against longer length face cleats. As a result of these geometric relationships, there is commonly a significant face and butt cleat permeability anisotropy in coal reservoirs. Cleats in coal can form by combination of stress and lithification. The relationship between maximum horizontal stress and the face cleat is such that, if maximum horizontal stress is parallel to the face cleat system, then the face cleats systems remain open and helps in primary flow and increases coal permeability.

The area of study is a CBM prospective area of Indian peninsula. Presently prospective coal seam identification is greatly dependent on laboratory analysis. Well log interpretation is an art to find out the effect & cause in the log characteristic. Log data shows high resistivity, high neutron & low density response against coal layer. Coal resistivity is a function of both physical and petrographic properties of the respective coal seams, the degree of metamorphism and the mineralogical composition. Density log has good relationship with gas bearing coal bed. Neutron porosity variation is insignificant against presence or absence of gas in coal seams. Detailed analysis of down hole physical parameters like Resistivity, Density and Neutron porosity data along with proximate analysis data is sufficient to reveal the CBM potential. Identification of potential coal seam does not ensure the possibility of exploitation/production of CBM unless permeability of the reservoir exists or possibility of enhancement. The permeability of the cleat system is a property which is obtained for presence of natural fracture system around the well bore. The degree of cleating, characteristics of cleat and relative connectivity of the cleat(natural fracture)/fracture system varies from one coal seam to the other and influences the permeability, hence production potential (McCulloh et al., 1974).

This study covers the conventional log analysis as well as advanced sonic log and high resolution resistivity image log data to characterize cleat system within coal seams including identification of maximum stress direction.

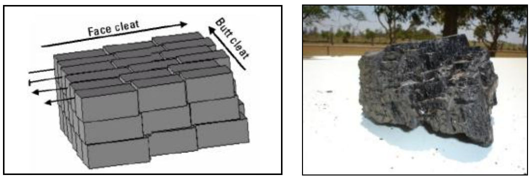


**Fig 1: Cleat system in coal. Face cleat and butt cleat form perpendicular to each other**

Maximum stress orientation and degree of pre-existing natural fracture including drilling induced fracture can be identified using acoustic and micro resistivity log. Any wave optical, electromagnetic or sound wave experiences partial transmittance and partial reflectance when the medium through which it travels suddenly changes. Acoustic log is affected by the presence of fracture and Vp/Vs ratio increases with increase of fracture density as well as cleat density. Sonic transmission coefficient decreases when cleat density increases. Stoneley Transmission coefficient as well as stoneley reflection coefficient plot also indicate the degree of fracture. Micro resistivity image log data is another tool to give numerous information of subsurface hole condition, cleat orientation, break out direction and fracture/cleat density, fracture aperture and fracture density. Break out study from FMI image has been studied to see the impact of breakouts and the consistency of it's azimuth. Breakout data from orthogonal calipers from the FMI and Breakout image have been integrated with fast shear azimuth data from DSI. The fast shear azimuth data indicates the maximum horizontal stress orientation.

## Problem Statement

Identification of prospective coal seam and cleat characterisation in coal seam is very critical for strategic completion criteria and optimization of CBM production. Presence of coal even after the presence of good natural fracture system can't ensure the production of CBM in good natural cleat system, favourable log characteristics, higher gas content (proximate analysis lab data) unless propagation of fracture system are aligned with the orientation of cleating system. Cleat density and direction of maximum shear stress controls the fracture ability of the coal seams and hence plays very important role in production optimization in CBM. Face cleats in coal seam form in the direction of maximum shear stress prevalent during dehydration period. But complete characterization of coal seams requires additional advanced logs. Moreover, open hole logs might be affected by presence of secondary minerals and nature of coal beds and borehole conditions, therefore might not be able to provide any conclusive difference among the different coal seams with different cleat properties.

It has been observed that production rates from similar coal seam (from two different locations) under similar completion design are not always the same. This is mainly attributed to the cleat properties and cleat densities which might be different for the same coal seam in two different stress environments.

## Theory and Methodology

Detailed methodology for prospective coal seam identification along with Cross plot of Resistivity vs Density (fig.2 – fig.4) shows the presence of coal and maximum resistivity of each coal seam. Gas content vs Density plot (fig5- fig.7) have been drawn to find out the relationship between the two. Production testing and laboratory proximate analysis data have been examined to observe the agreement of data for prospective pay analysis.

This section also describes in detail the methodology of fracture analysis of coal seams using advanced sonic log and high resolution resistivity image log.

### Prospective coal seam Identification

Rt Vs Density cross plots (Fig-2 to Fig.4) shows the limit of Rt value in each coal seams of Well A. Coal seams of Barakar formation Pay-I, IV & V are showing maximum resistivity limit less than 2000 ohm-m except very few data above 2000 Ohm-M , 2300 ohm-m and 2200 ohm-m respectively.

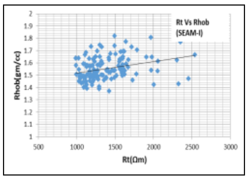


**Fig.2 Cross plot of Resistivity vs Density**

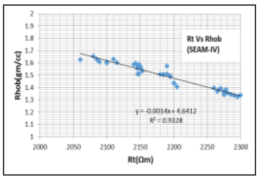


**Fig.3 Cross plot of Resistivity vs Density**

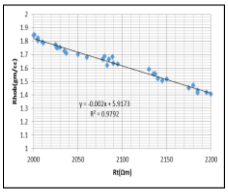


**Fig.4 Cross plot of Resistivity vs Density**

Density log has a great relationship with Gas content. Density decreases Gas content increases as well as ash content decreases. Gas content (daf) Vs Rhob plots in fig.5 to fig.7 are showing good correlation coefficient. Production testing result of the Well shows gas break from pay IV and V and no gas break from pay I fig.5.

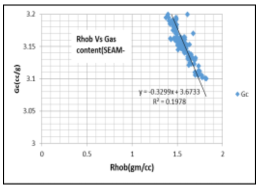


**Fig.5 Cross plot of Density Vs Gas Content**

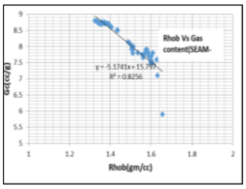


**Fig.6 Cross plot of Density Vs Gas Content**

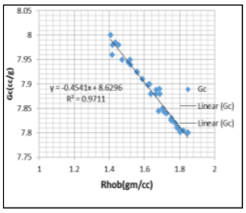
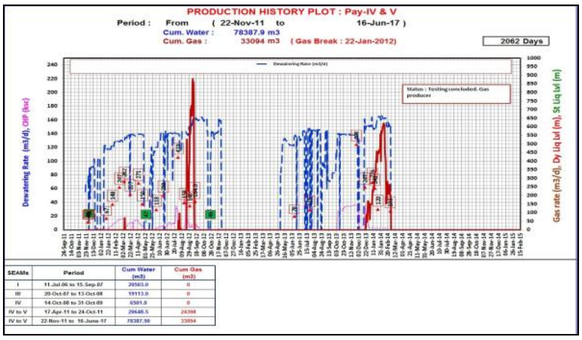


**Fig.7 Cross plot of Density Vs Gas Content**

Coal seam wise cross plot of Gc(daf) vs Rhob in fig. 5 to fig. 7 show Gas content as well as coal property are different in the well at different pay intervals. All the coal seams in the well are not equally prospective due to their variation in resistivity, density and porosity. In this Well all the coal seams have been tested but no pay is found to be prospective on production testing except Pay-IV & V. All the coal seams identified by log motif depending on resistivity in the range of 1100 - 2300 ohm-m, rhob varies in the range 1.86 to 1.30 and neutron porosity 49 – 82 PU. However coal seams having resistivity in the range of 2000 and above ohm-m, density less than 1.55 gm/cc and Neutron porosity variation lies within the porosity range 40 – 60 PU produced significant amount of gas on production testing culminates to identification of prospective coal seams (Pradip et al. 2012). Production testing results fig.8 of the well proves that resistivity alone can distinguish between prospective and non-prospective pay. High resistive coal having resistivity more than 2000 Ohm-m shows good coal characteristic and resistivity less than 2000 ohm-m is devoid of gas.



| SEAMs | Period | Cum Water (m3) | Cum Gas (m3) |
|---|---|---|---|
| I | 11-Jul-06 to 15-Sep-07 | 20503.0 | 0 |
| III | 20-Oct-07 to 13-Oct-08 | 19113.0 | 0 |
| IV | 14-Oct-08 to 31-Oct-09 | 6501.0 | 0 |
| IV to V | 17-Apr-11 to 24-Oct-11 | 20648.5 | 24398 |
| IV to V | 22-Nov-11 to 16-June-17 | 78387.90 | 33094 |

**Fig: 8 Production testing Data.**

Till date Well log is not a good tool to predict presence of gas bearing coal beds unless proximate analysis is done in the laboratory. Proximate analysis data for the well is given in Table-I. Hence our attempt is to characterize the well log after comparing all available data of wells like resistivity, density and neutron porosity. Density and Neutron porosity value didn't vary remarkably with the presence or absence of gas within coal seams. Density variation in coal is observed in the entire well within the range of 1.86 – 1.30 gm/cc and neutron variation is seen in the range 48 – 82 PU. Depending on the observation of the resistivity, density and neutron log, cut off values have been taken to characterize the prospective pay. Prospective pay should have density less than 1.55 gm/cc, neutron porosity more than 40 PU and resistivity more than 2000 OHM-m.

| Sl.No. | Pay No. | Gas Content cc/g daf | | | | Proximate Data(Avg.) | | |
|---|---|---|---|---|---|---|---|---|
| | | Count | Min. | Max. | Avg | Moist | Ash | VM, daf |
| 1 | V | 2 | 7.8 | 8.0 | 7.9 | 4.4 | 30.6 | 46.8 |
| 2 | IV | 3 | 5.9 | 8.8 | 7.7 | 3.1 | 21.0 | 36.5 |
| 3 | III | 2 | 3.7 | 4.1 | 3.9 | 1.7 | 25.0 | 37.7 |
| 4 | II | 5 | 2.7 | 4.9 | 3.8 | 1.3 | 34.0 | 35.5 |
| 5 | I | 2 | 3.1 | 3.2 | 3.2 | 1.6 | 22.0 | 32.9 |

**Table-I: Proximate Analysis**

### Image log analysis

High resolution resistivity image logs (fraction of an inch) processed data is an effective way to depict and identification of cleat and fracture network and also to compute their orientation in terms of dip data. Dip data analysis enables to identify dipping direction of the bed as well as distinguish the primary and secondary fracture present, their direction and mutual relationship in three dimensions. Natural fractures are primary fractures and secondary fractures are mechanically induced fractures and their geometry can be clearly distinguished using image logs. Natural fractures appear more continuous on the image logs generally occurring in more than one direction and have varied morphology. Borehole breakouts or drilling induced fractures tend to occur in some preferred direction, depending on the nature of present day local stresses and the orientation of the borehole. Cleat genesis is commonly caused by the interdependent influences of desiccation, lithification, coalification, and paleotectonic stress. Cleating in coal may range in spacing from ¼-in to several inches. Cleat spacing is affected by coal rank and bed thickness.

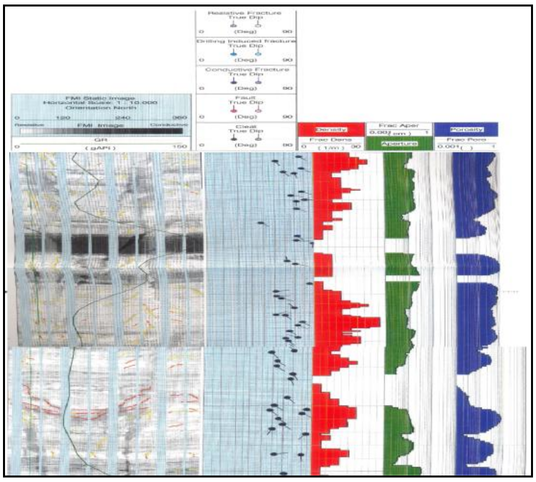


**Fig 9: High resolution resistivity images showing high cleat density.**

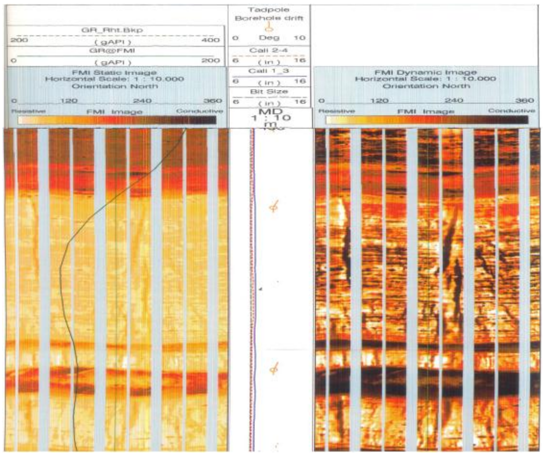


**Fig 10: High resolution resistivity images showing presence of Breakout.**

The development of cleats and degree of variation is clearly visible on the image logs. In Fig 9, numerous small scale cleats can be seen in the above image including cleat orientation, fracture density, fracture aperture and facture porosity (Lithi and Souhaite, 1990).

Identification of the possible primary and secondary cleat sets and their orientation are some other critical outputs possible only through image log analysis. Cleat orientation from image logs were picked as fracture traces as plotted in Fig.9 and their orientation displayed as tadpole plots, indicating dip and strike of the cleat faces. In this study the Face (primary) cleat orientation in best coal seams is found to be in NW-SE direction.

Break out image in fig.10 shows the minimum stress direction in NE-SW which is clearly indicating the maximum stress direction orthogonal to minimum horizontal stress in NW-SE direction has agreement with cleat orientation.

### Sonic log analysis

Array Sonic log is traditionally used in CBM to find out stress profile, delineate coal beds and its anisotropy etc. Using advance processing methods on array sonic tool, an effort is to characterize the coal seams in terms of cleat as well as fracture density.

Coal being a soft rock, monopole source could not provide shear slowness. Shear slowness was extracted from dipole flexural waveform using dispersive bias corrected STC processing. It was found, density correlated well with compressional slowness variation. The plot of vp/ vs ratio w.r.to depth shows the presence of coal seams and degree of cleating and fractures. High vp /vs ratio is expected in coals with high degree of cleating fig.11. Vp/Vs ratio plots with respect to depth have shown presence of good vertical fracture when ratio is greater than 2.3.

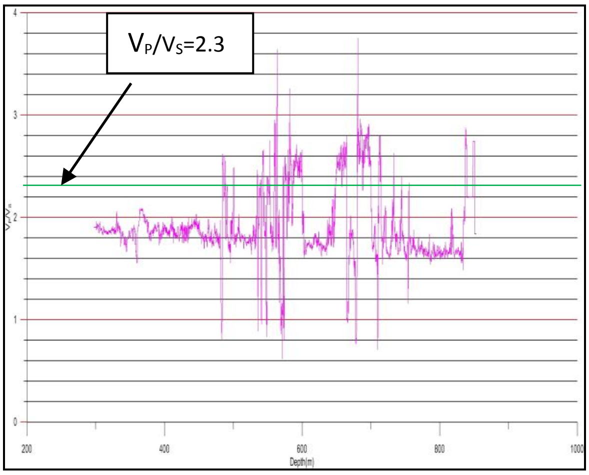


**Fig 11: Well Depth vs Vp/Vs ratio plot.**

Stoneley waveform is sensitive to the interface of formation to borehole. It is known that presence of open fractures and permeability affects the slowness and causes attenuation in the Stoneley waveform. Stoneley reflectivity analysis (Hornby et al., 1989) is being used to identify conductive fractures based on Stoneley reflectivity analysis. However in very highly cleated coal seams, most of energies are attenuated and the reflected energies are negligible. In this environment, transmission coefficient (STTC), measurement of attenuation of energy provides better indicator of fracturing or degree of cleating. In fig.12 low transmission coefficient (STTC) and low reflection coefficient (STRC) indicates very high attenuation which is caused due to high degree of cleating. In fig.12 reduction in STTC and insignificant STRC represents the presence of high density cleat systems.

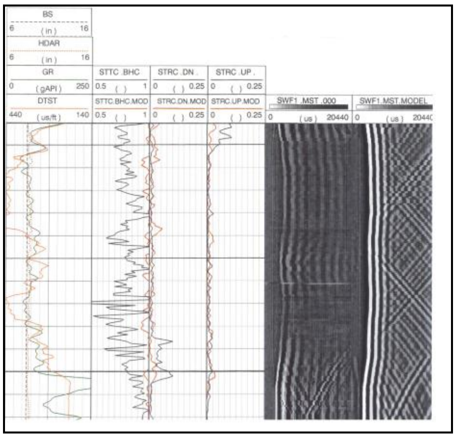


**Fig. 12 Reduction of STTC**

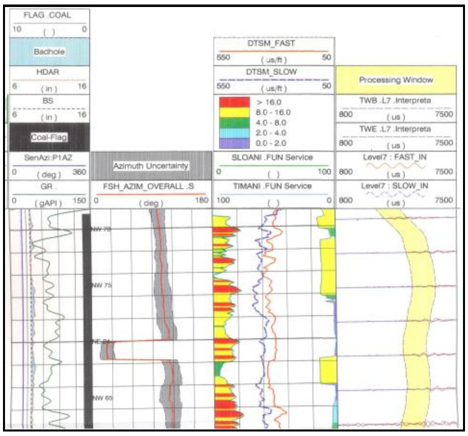


**Fig.13 Fast Shear Azimuth Direction**

Acoustic anisotropy analysis (Alford,1986) using cross dipole flexural waveform have been used to compute fast shear azimuth direction, which in general indicates present day maximum horizontal stress direction. This study shows that coals are anisotropic and computed fast shear azimuth trending towards NW-SE (Fig13).

The study and analysis of well log data only can help in identification of stress direction regionally as well as locally for directional perforation and enhancement of CBM production significantly. It has been observed that coal quality, coal thickness, gas content and good designing of hydro fracture jobs are not only the main criteria for good CBM production but also perforation along maximum stress direction is most important to assure additional permeability and hence enhanced production.

### Completion strategy

Good numbers of studies have been carried out to understand the production behavior of CBM reservoirs. An integrated reservoir description is essential for incorporation during planning of the completion type for production optimization. Apart from geo-mechanical properties which are key input for engineered completion design, present day stress orientation and relation with face cleat orientation is also important (Ali et al.,2008; Haldar et al.,2015).

Cleat density as well as fracture have very important role in determining the connectivity behaviors of coal beds and subsequently the planning of completion strategy. In the present study, cleat orientation and maximum horizontal stress direction is found to be parallel in the selected coal seams as explained. The completion strategy for the coal seams compared here is suggested to be based on cleat density. Coal seam with high cleat density depending on the Vp/Vs ratio is recommended to be perforated as connectivity would be very good in these seams in comparison to the coal seams with lower cleat density. The strategy for fracturing and perforating should take into account the cleat density of the coal seam. Induction of this method of completion, maximum horizontal stress and direction of face cleats which can be incorporated while perforating and fracturing the coal seam to optimize the production from the identified coal seam (Mavor et al.,1991 and Manrique et al.,2001).

### Conclusion

This study clearly shows that identification of prospective coal is of primary importance. Presence of good cleat density can't assure the presence of CBM unless log characteristics are favorable. Presence of breakout and fracture analysis can easily reveal the stress orientation as well as cleat orientation and array sonic log signatures varies from one coal seam to another based on density of cleat development and the nature of cleat network. Stress direction from Resistivity log and Array sonic log matches for definite interpretation required for completion strategy. A careful selection of completion method is necessary to optimize production in CBM.

## References

1) Alford, R.M.,1986, Shear data in the presence of azimuthal anisotropy; Soc. Expl. Geophys. 56th Ann. Internal .Mtg , 476-479.
2) Ali, M., Sarkar, A., Sagar, R., Klimentos, T. and Basu, I.,2008, Cleat Characterization in CBM wells for Completion Optimization; SPE Indian Oil and Gas Technical Conference and Exhibition, 4-6 March, Mumbai, India, 113600 (2008), 1-10.
3) Haldar, D., 2015, Cleat characterization using Advance Sonic- Image logs for Production Optimization in CBM wells: case studies from Damodar coal belt, India; 3rd CEWELL Symposium.
4) Hornby E., Johnson D. L., Winkler K. W., Plumb R. A., 1989, Fracture evaluation using reflected Stoneley wave arrivals; Geophysics,54, 1274-1288.
5) Luthi, S.M., Souhaite, P.,1990, Fracture apertures from electrical borehole scans; Geophysics,55, 821-833.
6) Manrique, J.F., Poe Jr., B.D., England, K., 2001, Production Optimization and Practical Reservoir Management of Coal Bed Methane Reservoirs; Society of Petroleum Engineers, 67315, 1-13.
7) Mavor, M. J., Close, J.C. and Pratt, T.J.,1991, Western Cretaceous Coal Seam project Summary of the Completion Optimization and Assessment Laboratory (COAL) site; Gas Resource Institute Tropical Report No. GRI-91/0377.
8) McCulloh, C. M.,Duel, M.and Jeron,T. W., 1974, Cleat in bituminous coal beds; U. S. Bureau of Mines Report of Investigation 7910, 25-31.
9) Pradip, S., Haldar, D., Dubey, P., Roy, S.,2012, Prospective Coal Seam Identification and Characterization by wire line logs and validation by Laboratory Study and core images: A case Study; 2nd CEWELL Symposium 2012.

## Acknowledgement

Authors are thankful to Regional Laboratory, Bokaro for providing Lab data analysis report. Authors acknowledge kind help of the Geology, SST, Bokaro for providing Geological data. Authors are really thankful to Reservoir Team, Bokaro-CBM for providing production testing results. Authors are highly indebted to Asset Manager, CBM Asset for support and inspiration during the preparation of the paper. Authors convey their profound gratitude to CLS, Mumbai to give the opportunity to prepare this paper.