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Estimation of In-Situ Stress from Cleat orientation for Coal Bed Methane Exploration, Jharia Coalfield, India

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Summary

This paper discusses cleat orientation and other structural features, observed in the outcrops of 14 major coal seams in Jharia coalfield and it's directional relationship with the in-situ stress orientation pattern. Cleat orientation mapping is critical to determine the maximum principal compressive horizontal stress (S_H) direction for coal bed methane exploration and exploitation, which in turn controls the direction of maximum gas or water flow through coal beds. Cleat orientation is found to vary laterally within same seam at the different locations, distributed from south-east part to north-western part of Jharia coalfield. Face cleat orientation of the 21 opencast coal mines and 2 under underground mins varies from N45°E to N45°W. Change of orientation of cleat, observed around the mining areas is related to the orientation of fault systems and to the orientation of igneous intrusions occurring within the coal bearing packet. Average permeability of the four major seams has been calculated from well logs of nine wells adjacent to Moonidih area and is correlated with the in-situ stress. An overall, NNE-SSW and NW-SE orientation of the S_H direction is predicted in the coal mines from cleat orientation mapping. The face cleat extends along S_H direction and the butt cleat along S_h direction (minimum principal compressive horizontal stress). S_H orientation is locally modified at places, close to the tectonic features and igneous intrusives. Finite element stress modeling is carried out near Moonidih area. Cleat orientation predicted stress direction matches well with the finite element stress results.

Introduction

Knowledge of the in-situ stress field in a Coal Bed Methane (CBM) reservoir in Jharia coalfield is essential to optimize drilling and production. Borehole stability, orientations of natural and hydraulically induced fractures, fluid flow anisotropies, among others, all depend critically on the present-day stress distribution. Several techniques ranging from dipmeter analysis of borehole breakouts to anelastic strain recovery and shear acoustic anisotropy analysis of core samples can be used to determine the in-situ stress orientations and relative magnitudes (e.g., Henk, 2005; Sperner et al., 2003). This valuable information will only become available after the well has already been drilled. Information on the regional stress orientations can be derived from large-scale data collections like, for example, the world stress map project (Sperner et al., 2003; Zoback, 1992).

Cleats are natural fractures in coal that usually occur in two sets, mutually perpendicular and also perpendicular to the bedding plane. The coal samples observed at different places of studied 21 opencast mines (OCM) and 2 underground mines (UGM) of the Jharia coalfield reveals that the cleat spacing and the length of the cleats vary from one place to another. The extensional stress regime existing in Jharia coalfield (Ghosh and Mukhopadhyay, 1985) developed fractures and cleats in the coal seams.

Unfortunately, no borehole imaging log data were available adjacent to the studied mining areas to determine the cleat orientation. Therefore, the present study aims to (a) estimate the in-situ stress orientation from cleat orientation mapping of 21 OCMs and 2 UGMs distributed over the Jharia coalfield, (b) correlation of cleat orientation with the geological structures in this Jharia basin and (c) comparison of predicted S_H orientation with previously established stress data.

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Data Collection

The Jharia coal basin located in the Singhbhum craton extends for about 38 km in an east-west direction and maximum of 18 km in north-south direction, and covers an area of about 456 km2 (Figure 1). The coal seams of present study belong to Barakar Formation of Permian age, which does not show any evidence of high intensity tectonic deformation except normal gravity faults of different magnitudes - both minor (throw less than 10 m) and major (throw 10 m to greater than 100 m) (Sengupta, 1980; Ghosh and Mukhopadhyay, 1985).

Cleat orientation data have been collected from the 12 mining areas operated by Bharat Coking Coal Limited (BCCL), India which includes total 21 opencast mines (OCM) and 2 underground mines (UGM) of Jharia coalfield (Figure 1).

Authors had already studied the cleat orientation pattern of four major coal seams (K, L, O and P) of 2 underground mines, i.e., Moonidih UGM of WJ area and Putkee Balihari UGM of PBP area of Jharia coalfield (Paul and Chatterjee, 2011).

Vertical stress magnitudes for the above mentioned four major seams (Figure 2) have been estimated from density logs of nine CBM wells adjacent to Moonidih UGM. The predicted coal bed permeability from well logs had been correlated with the vertical stress for this Moonidih area.

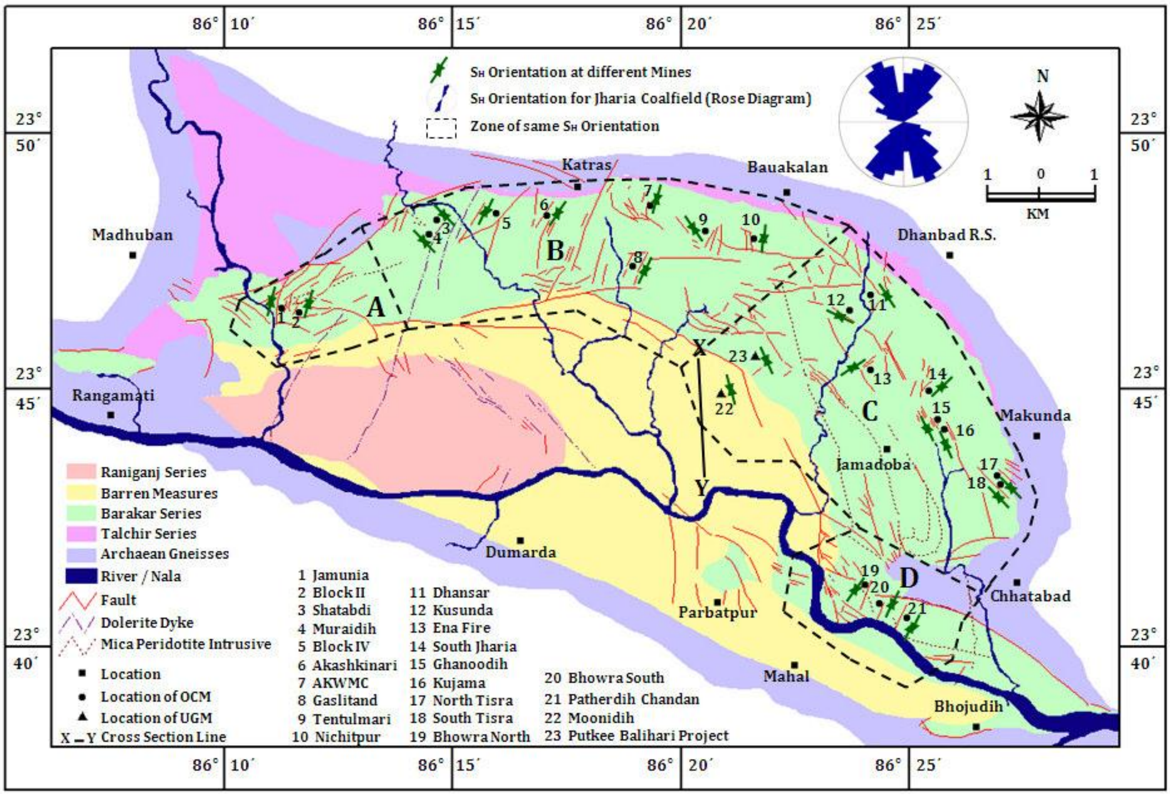

Figure 1: Stratigraphic and structural map of Jharia coalfield (after Sengupta, 1980) showing locations of opencast and underground coal mines and in-situ stress orientation of Jharia coalfield, India. Mean S_H orientation displayed in rose diagram is mostly N-S varying NNE to NNW.

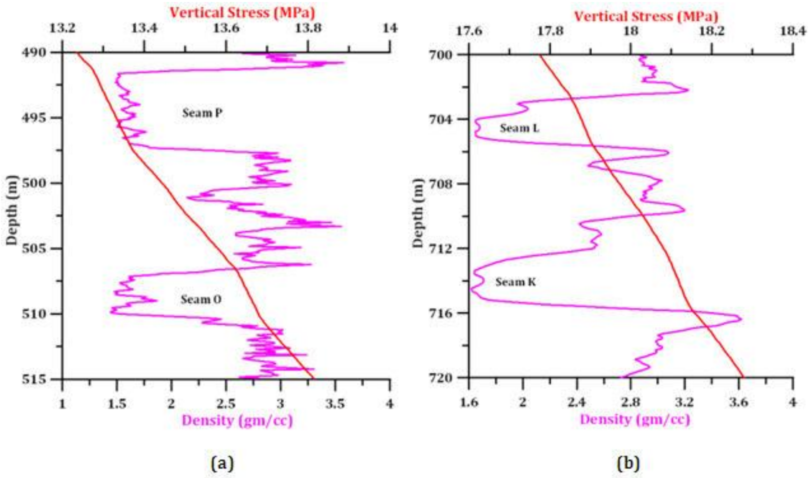

Figure 2: Density log signature from a CBM well indicates the major coal seams and the variation of vertical stress with depth against the identified coal seams.

Total 14 numbers of major coal seams namely; B, C, D, E, F, G, H, I, J, K, L, N, O and P from 21 OCMs and 2 UGMs have been studied to prepare the cleat orientation map of Jharia coalfield. Out of 14 numbers of studied seams the oldest seam, "B", is exposed to the surface near the northern boundary of the Jharia coal basin at Nichitpur OCM (Sijua area), Dhansar OCM (Kusunda area) and Patherdih Chandan OCM (East Jharia area) and the youngest seam, "P", is encountered at the inner part of the Jharia coal basin at Moonidih UGM.

Correlation between in-situ stress and geological structures in Jharia Coalfield

To investigate the cause behind the changes in cleat orientations across the Jharia coalfield as a whole, the cleat orientation map of Jharia coalfield has been correlated with the fault patterns of Jharia coalfield (Sengupta, 1980). The variations of face cleat orientation throughout the coalfield provide a clue to correlate the in-situ stress orientation with the geological structures of the basin. In-situ stress orientation map (Figure 1) is prepared for the Jharia coalfield from the maximum average face cleat orientation data of each mine. Predominant fault directions in different zones, as observed from the structural map (Sengupta, 1980) and the orientation of the face cleats and SH in the same zones (Figure 1) are summarized below in Table 1 to show the correlation between these elements.

Location within basin	Fault Trend	Intrusive Trend	Mean Face Cleat Trend	Mean S_H Trend
Zone A	NNE-SSW	NE-SW	N15°E	N15°E
Zone B	NNE-SSW	NNE-SSW	N10°E	N10°E
Zone C	NNW-SSE	NNW-SSE	N20°W	N20°W
Zone D	NNE-SSW	NNW-SSE	N35°E	N35°E

Table 1: Orientation of geological structures and in-situ stress in Jharia coalfield, India

Comparison of predicted stress orientation with the other stress data

The total numbers of face cleat orientation data (1782) are plotted in the rose diagram to indicate the mean orientation of SH in the Jharia coalfield (Figure 1). The mean orientation of SH of the total face cleat azimuth gives almost N-S with two dominant orientation of NNE and NNW.

The previous authors (Ali et al., 2008) had observation of face cleat orientation from FMI log for a single well in Parbatpur area, located at the southern part of the Jharia coalfield. The orientation of SH predicted from FMI log is directed towards NW-SE, varying between N30°W and N60°W. Recording of borehole image log like FMI from drilled well at different locations is very expensive and time consuming, whereas the cleat data collections in the field are less expensive. Therefore in absence of borehole image log data, SH orientation predicted from face cleat and fracture mapping is more useful as a whole than the estimated orientation provided by Ali et al., 2008 from a single well data.

A review of local earthquake activity near the study area under Singhbhum craton revealed that a magnitude of lower than 3.0 seismic event occurred twice in the month of November, 2007 within 8 km to 10 km from Jharia coalfield. A source solution study indicates that this earthquake originated from a depth of about 26 km and defines a strike slip faulting environment with dominant N-S compressional and E-W tensional stresses (Kayal et al., 2009). Based on the seismicity, Chandra (1977) inferred a NNE-SSW Singhbhum seismic zone beneath the Singhbhum craton. Mean SH orientations in three zones namely; A, B and D, in Table 1 matches well with the regional compressive stress direction. Thus, corroborating information derived from cleat orientation in the coal beds and from focal plane solutions of two recent earthquakes implies that the orientation of in-situ stresses has not been changed much over time, from mean SH direction of about N-S during Permian deposition and coalification to a present day N-S direction. The continental movement of Indian Plate towards NNE direction is also supporting the present day stress orientation.

Stress Orientation Modeling

Two-dimensional (2D) finite element stress modeling for the Jharia basin aims to illustrate the effect of the applied stress in the SH direction (N-S) and the variations in mechanical rock properties for the available section: X-Y (Figure 1) in the study area. The 4545m long X-Y section paralleling N-S direction passes through the Moonidih area where sediment depth exceeds 1.4 km (Sengupta, 1980). For the generalized finite element modeling (FEM) purposes, the sedimentary column underlying the section X-Y is broadly divided into 9 layers including four major coal seams (L, M, N and O), overlying and underlying sediments (Figure 3).

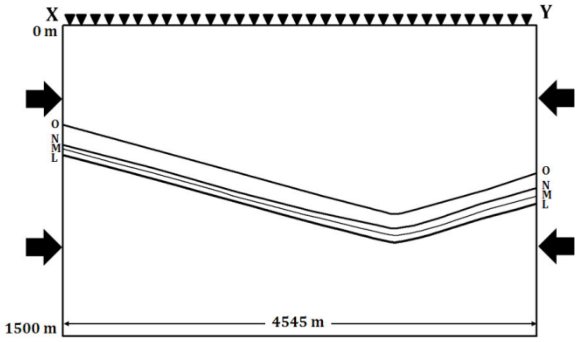

Figure 3: 2-D model for the X-Y section. Four coal seams (L, M.N Model is constrained at the top boundary.and O) are identified. Solid arrow indicate the applied stress,

An average horizontal compressive stress of 15 MPa has been applied at the vertical boundary of the solid FEM model with constraining the top boundary. The mechanical rock properties for the coal seam and overlying/underlying sediments for the FEM model have been assumed (personal reliable source) as provided in Table 2.

Layers	Young's Modulus (MPa)	Poisson's Ratio	Average Density (kg/m^3)
Coal seams	2000	0.32	1450
Overlying / underlying sediments	20,000	0.26	2350

Table 2: Rock mechanical properties assumed in the 2D FEM for X-Y section of the Jharia coalfield, India.

Finite element grids for the underlying X-Y section consisting of 8777 numbers of 6-noded triangular elements are generated and stress trajectories are calculated using ANSYS (University Intermediate Version 7.1) finite element software. Finite Element Model (FEM) predicted SH orientations are displayed in Figure 4. Stress orientation in three rectangular boxes namely; A, B and C in Figure 4a have been illustrated in zoomed mode through Figures 4b, 4c and 4d respectively. It is observed from the Figure 4b that SH direction for the four seams at the left part (box A) of the X-Y section is oriented towards NW-SE whereas SH direction at the middle (box B) and right part (box C) of the same section is oriented towards NNE-SSW (Figure 4c and 4d). The FEM predicted SH orientation (NW-SE) at coal seam "O" is matching well with the SH orientation (N45°W) at the same seam at the Moonidih UGM (Paul and Chatterjee, 2011 and Table 2). FEM results also indicate rotation of SH direction within coal seams though it is aligned N-S at the deeper part.

Application of Stress orientation in CBM Exploration

Sub-surface data on cleat / fracture orientation, is exceedingly sparse, hindering well planned development through optimized well placement or directional drilling for CBM exploration in this coalfield. As the fractures act as release paths for the CBM, trapped in the coal seams i.e CBM reservoirs, knowledge of the preferred orientation of those natural fractures is key to cost-effective and successful CBM exploration and exploitation (Bachu and Bell, 2001; Bachu and Michael, 2003; Bell and Bachu, 2003; Beekman et al., 2000).

In the CBM reservoirs, permeability is controlled by cleat network / natural fractures. Therefore, evaluation of such reservoirs need accurate information on (1) the spatial distribution of faults and fractures, (2) orientation of those structures, and (3) quantitative estimation of permeability, provided by those faults and fractures. Locally, however, the stress field can vary in magnitude and direction, the major influence being faults and basement relief (Laubach et al., 1998; Moon and Roy, 2004). It requires ascertaining the correlation of the variation of SH direction with the predominant fault / fracture orientation.

The average permeability of four major seams in Moonidih area varies from 0.7 to 3.06 md. The directional permeability of coal is directly related to the face cleat/S_H orientation in this part of the coalfield. Regression analysis between permeability and vertical stress of the coal seams indicated second order polynomial, as the best fit curve with R^2 = 0.65 (Paul and Chatterjee, 2011). The in-situ stress regime can have a strong influence on CBM production, coal permeability, hydraulic fracturing pressure and the borehole stability while drilling horizontal wells. Knowledge of these features is essential to effective development of CBM resources. The stress trajectories

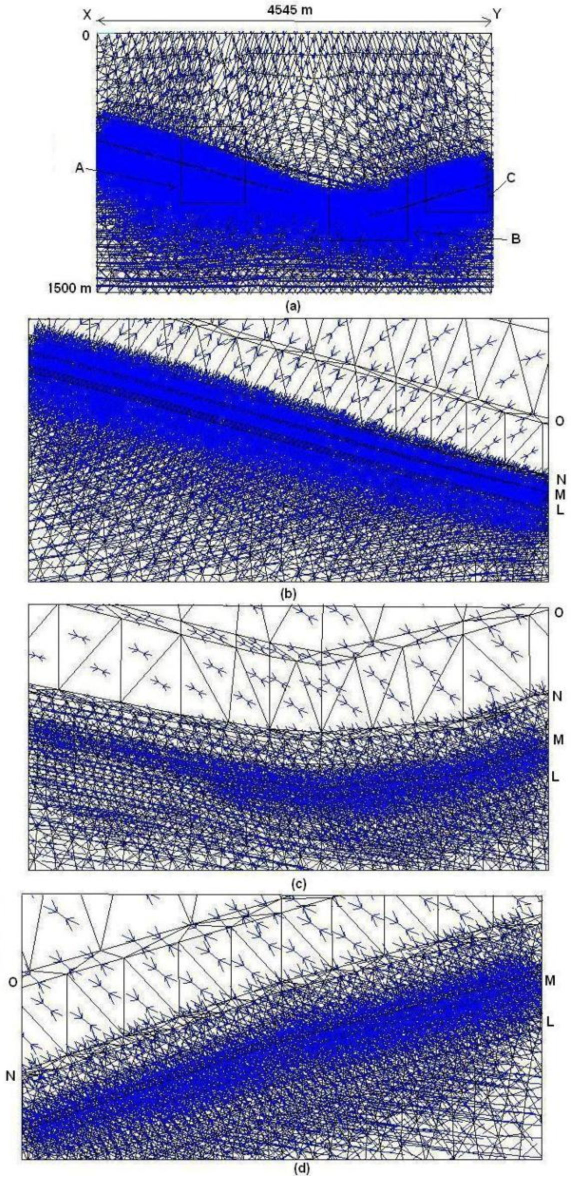

Figure 4: (a) SH orientations are illustrated in the finite element gridded model. A, B and C are indicating the three rectangular boxes, (b) SH orientation for the box A at the zoomed mode, (c) SH orientation for the box B at the zoomed mode and (d) SH orientation for the box C at the zoomed mode.

indicated on the map (Figure 1) as well as FEM predicted results (Figure 4) can be used for predicting the orientation of induced hydraulic fractures in different parts of Jharia basin.

Conclusions

In this study, cleat and joint orientation data have been collected from 14 major coal seams from the area around 21 opencast mines and 2 underground mines across the Jharia coalfield. Face cleat orientation varies from NE-SW to NW-SE within the same seam. In-situ stress (SH) orientation is parallel to the face cleat direction and has two prominent directions of N25°E and N25°W respectively. The orientation of SH is strongly related with the orientation of faults in this basin, as shown by overall parallelism between the major regional lineations, the face cleat and the joint direction.

An overall NNE-SSW oriented SH measurement in mines and inferred from earthquake events at depth of 26 km is a regional phenomenon which locally modified close to the geological structures. The FEM predicted SH orientations agrees well with the cleat orientation predicted SH direction at the Moonidih UGM. It is very important to emphasize here that finding of this study does not replace or reduce the need for detail drilling investigation, which would provide additional data to map the local variation and fine tune the well designs for CBM production.

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