International Journal of Engineering and Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 15 Issue 7 July 2026 || PP 09-17

Microstructural and Compositional Controls on Coalbed Methane Storage and Migration in Gondwana Coal of Sikni, Koel Valley Coalfields, Jharkhand, India: Insights from FE-SEM and EDS

Somesh Sengupta[1], Melvin A. Ekka[2], Hrishav Kumar Bhagat[3]
[1]*Department of Geology, St. Xavier's College, Ranchi – 834001, India*
[2]*Department of Geology, St. Xavier's College, Ranchi – 834001, India*
[3]*Department of Geology, St. Xavier's College, Ranchi – 834001, India*

ABSTRACT: *Storage and migration of coal bed methane within the coal deposits essentially depends on the pore-fracture system present within them. These pore-fracture system is significantly affected by the inorganic phases present inherently within the coal bodies. Consistent with these facts, this study investigated the characteristics of coal from the Sikni Coal deposits, Jharkhand, India, using field emission scanning electron microscopy (FE-SEM) coupled with energy-dispersive X-ray spectroscopy (EDS). The results obtained revealed presence of heterogenous pore network, characterized by the presence of slit-shaped, rounded, pear-shaped, and fracture-connected pores. The analyzed specimen also revealed presence of microfractures having variable width and openness and characterized with varying degree of interconnectivity. The primary inorganic phase, identified from the EDS results indicated presence of aluminosilicate clay minerals along with minor concentration of oxides, carbonates and sulphides. These occurred within the available pore spaces, fractures, as superficial deposits over the organic matrix as well as discrete crystalline grains with well-developed faces. The inorganic phases exerted a dual influence on the pore-fracture system by preservation of pore structures through their rigid framework and at the same time by restricting pore connectivity. It was observed that the methane storage and transport would essentially be governed by pore geometry, and their interconnectivity, available fracture network and volume of both organic and inorganic phases constituting the coal. The findings of this study thereby enable to understand the interaction of pore and inorganic phases in Gondwana coal of Sikni coal mines, North-Koel Gondwana basin, Jharkhand, India.*

KEYWORDS - *Energy-dispersive X-ray spectroscopy, FE-SEM, Fracture connectivity, Pore morphology, Sikni Coal deposits*

Date of Submission: 08-07-2026 Date of acceptance: 20-07-2026

I. INTRODUCTION

Coal represents a medium for both the generation and storage of coalbed methane (CBM). Mostly, methane gas is stored within the internal surfaces of the coal matrix. Some of the gas exists as free gas in bigger pores and fractures. Therefore, the amount and arrangement of pores are critical in determining the storage and flow of methane gas. The micropores are essential for storage because they offer the greatest surface area for adsorption. On the other hand, bigger pores and fractures facilitate the flow of gas through the coal (Moore, 2012).

The pore system of coal is highly heterogeneous. Firstly, the structure is affected by coalification processes, compaction, organic matter shrinkage, and mineralization. Secondly, previous studies revealed that coal composition, pore volume, size, degree of coalification, rank, pressure, hydraulic gradient, degree of deformation, and mineral matter play a significant role in controlling and predicting methane adsorption and flow capacity (Kim., 1977; Meissner., 1984; Ayers and Kelso, 1989; Levine., 1992, 1993; Schraufnagel and Schafer, 1996; Clarkson and Bustin, 1999a, 1999b). Similarly, the maceral composition of coal influences gas storage because vitrinite-rich coals tend to have more microporosity than inertinite-rich coals of the same rank (Lamberson and Bustin, 1993).

The influence of mineral matter on the pore system is equally critical. Different types of minerals such as clays, oxides, carbonates, and sulphides exist as discrete grains, coatings, and fillings in coal pores and fractures. Some minerals can resist compressive forces and can, therefore, be good pore space conservers. On

the contrary, minerals can also hinder gas flow if they develop densely consolidated seams. Additionally, post-depositional mineralization might lead to pore space and fracture blockages (Ward, 2002).

FE-SEM enables observation of pore geometry, surface morphology, fractures, and mineral matter distribution in coal. Mineral particles in coal can be investigated by scanning electron microscope and similar techniques (e.g. Stanton and Finkelman, 1979; Russell and Rimmer, 1979; Allen and Vander Sande, 1984; Corcoran, 1989; Martinez-Tarazona et al., 1992; Kwiecinska etal., 1992; Hower et al., 1994, 2000; Ward et al., 1996; Finkelman et al., 1998). Combined with EDS, FE-SEM allows analysis of the elemental composition pertaining to inherent mineral matters in coal. These two microstructural analyses are appropriate for evaluating coal pore systems, given their ability to resolve the heterogeneity that characterizes the pore system at different scales. For instance, FE-SEM analyses were performed to observe the morphology of coal samples from Sikni Mine. The techniques are essential in analyzing the pores because coal microstructures change abruptly over short ranges and cannot be represented by a single pore size or geometry (Mastalerz et al., 2012; Li et al., 2020). Therefore, the paper focuses on examining the main types of pores, fractures, and mineral matter associated with Sikni coal and how their distributions control methane storage and flow.

II. LITERATURE REVIEW

Coal represents a permeable medium that stores and generates coalbed methane. Methane gas is primarily stored within the internal surfaces of the coal matrix while some of it exists freely within bigger pores and fractures. Therefore, the amount of gas that can be recovered from coal is dictated by the pore structure's size and geometry as well as the connectivity of the pores and fractures (Clarkson and Bustin, 1999; Moore, 2012).

The pore system of coal develops over a broad size range: the smallest pores are responsible for providing the greatest surface area for methane adsorption, whereas larger pores and fractures are important for facilitating diffusion and flow. Previous findings indicate that for many coals, especially those with a low degree of pore connectivity, a high percentage of total pore volume may occur in isolated pores with limited contribution to permeability. This consideration highlights the importance of pore connectivity, which largely controls the ability of coal to produce methane flow, like the total pore volume (Bustin and Clarkson, 1998; Mastalerz et al., 2012).

The coal quality influences the characteristics of the pore system in coal. According to Lamberson and Bustin (1993), the vitrinite-rich coal tends to have the greatest methane adsorption capacity due to the prevalence of a fine-pore structure, whereas the coal with high inertinite content is characterized by a larger pore size but lower surface area for methane adsorption. The significance of the organic matter composition of coal on its ability to store and release methane cannot be understated.

The mineral matter also affects the generation of coal pores and, consequently, its impact on gas flow through coal. In terms of influencing coal pore structure, clay minerals may be found as coatings on the surfaces of coal particles, whereas oxide, carbonate, and sulphide minerals may be discovered as inclusions within the coal's fissures. Moreover, dense mineralization may diminish the amount of pore volume while also restricting the flow paths for gas molecules. At the same time, mineral grains resistant to pressure may create room for the storage of gas molecules due to the voids between mineral fragments during compaction. Therefore, the effect of mineral matter on the pore structure of coal depends on the specific mineral composition, its distribution pattern, and location within coal (Ward, 2002). FE-SEM has become a popular technique for investigating the morphology of coal pores and fractures, as well as deciphering the distribution patterns of minerals. With the EDS analyses, the main metal components can be identified. According to the study conducted by Li et al. (2020), it is possible to evaluate such features as the variation in shape, particle arrangement, and mineral-controlled pores using the microscopic examination of the coal samples.

While numerous investigations have been conducted to determine the characteristics of coal reservoirs and the key factors affecting methane production and flow, the interrelationships between the properties of coal pores, fracture systems, mineral matter, and methane adsorption have received only limited attention. More specifically, there are few published works reporting the findings of a detailed mineralogical, petrological, and pore structural analysis of coal from the Sikni Coal Mine. Therefore, the current study aims to evaluate the impact of pore morphology, fracture patterns, and mineral matter on the potential for methane storage and flow in the Sikni coal using FE-SEM and EDS analyses.

III. STUDY AREA

The Sikni Coal Mine (Figure 1) is located near Chandwa in Latehar district, Jharkhand, at approximately 23°43′25.9″N 84°36′46.9″E. It is situated around 100 km to the northwest of Ranchi and is part of the Gondwana coal province. The mine was developed as an open-cast and has been abandoned. The exposed section contains coal seams and associated sandstone, shale, and carbonaceous deposits. The coal is fractured and weathered at the surface.

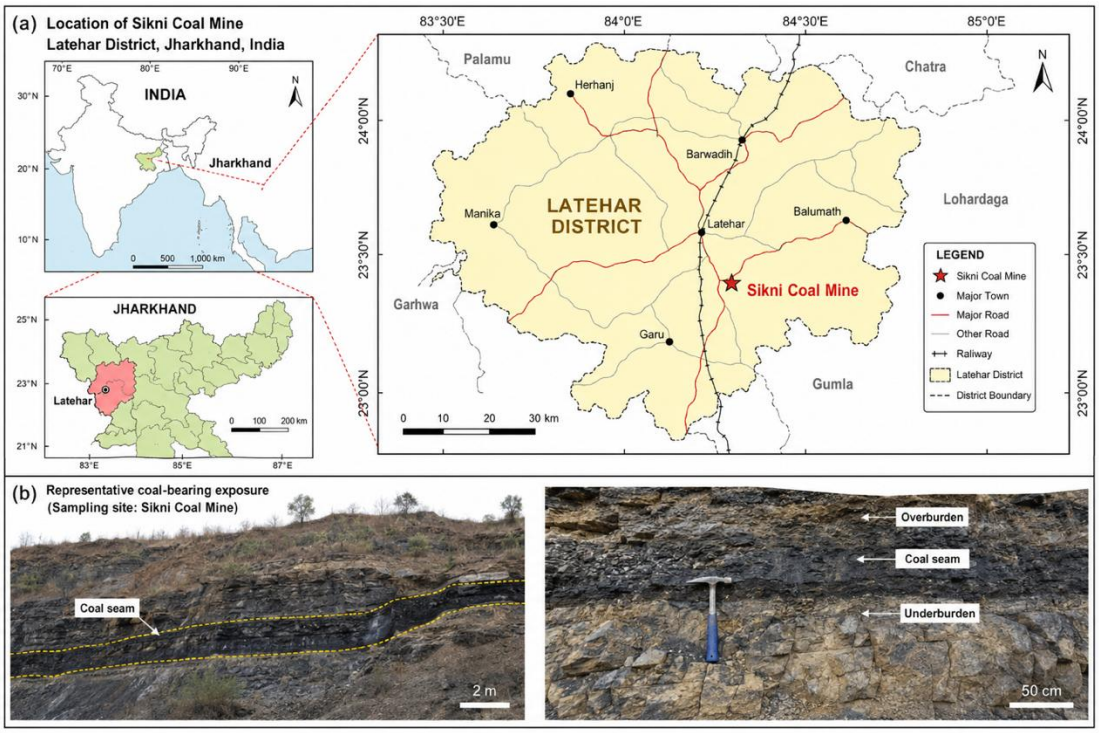

Figure 1. Study area of the Sikni Coal Mine: (a) location of the mine in Latehar district, Jharkhand; and (b) representative coal-bearing exposure from which the samples were collected.

IV. MATERIAL AND METHODS

From the collected coal samples, 20 representative specimens were selected for FE-SEM and EDS analyses based on their textural, mineralogical, and structural characteristics. The fresh aggregates were cleaned to avoid destruction of natural pores and fractures. The isolated fragments were mounted on an aluminium stub using conductive carbon tape and coated with platinum using JEOL JFC-1600 Auto Fine Coater. A ZEISS Sigma 300 field emission scanning electron microscope was used to characterise the microstructure. An InLens secondary-electron detector and operating voltage of 5.00 kV, together with working distances of approximately 4.4–7.8 mm, were used to acquire FE-SEM images at magnifications of 2500X–50000X.

Lower magnification was selected to capture an overview of the distribution of large pores, fractures and variations in matrix texture, while higher magnifications were used to identify slit pores, cavities, interparticle and intraparticle voids, and other fracture-related features. The EDS analysis was performed on mineral-rich regions at an accelerating voltage of 20 kV and a magnification of 2500x, as well as associated FE-SEM images. The FE-SEM images enabled a clear visualisation of the pore geometry, fracture distribution, and mineral matter. The observed variations in pore structure and fracture connectivity were then related to the potential for methane storage and migration.

V. RESULT AND DISCUSSION

Surface and pore characteristics

The FE-SEM results show a significant heterogeneity, in terms of surface morphology and pore architecture is considered. A wide variety of pore geometries were identified, which includes slit shaped pores, rounded pores, cavities along with network of microfractures.

Fig. 2a exhibits a fragmented coal surface, characterized with well-developed pore networks. The pore geometries range from slit shaped pore to irregular cavities. These aforesaid pore system and cavities are well

preserved due to presence of mineral matter that acted as the rigid support during the coalification process. This interconnected pore system would thus be an effective pathway for gas migration. Fig. 2b, exhibits that the coal has a more mature pore system, comprising primarily of interparticle pores with few organic matter hosted pores as well. It also shows indication of fragmentation, which has enhanced the pore connectivity. It can be therefore, concluded that the presence of spatial voids is directly related to the degree of fragmentation of the coal matrix.

Fig. 2c exhibits a relatively less porous system, dominated primarily by fracture porosity. Slit shaped pores occur in the juxtaposition of inorganic and organic phases, which subsequently developed into a narrow fissure like microstructure. In Fig. 2d, shows a pear-shaped deep pore with a large smooth cavity and relatively narrow throat; such a structure may allow for both methane storage and slow gas flow through the narrow region. The macrovoid having an irregular shape presented in Fig. 2e is 3–4 μm in size and is connected to a microfracture; thus, the structure may participate in both methane storage and methane migration processes.

The round pockets observed in Fig. 2f can be classified as local storage sites since their sizes are significantly bigger, ranging from 3 – 4 μm in diameter.

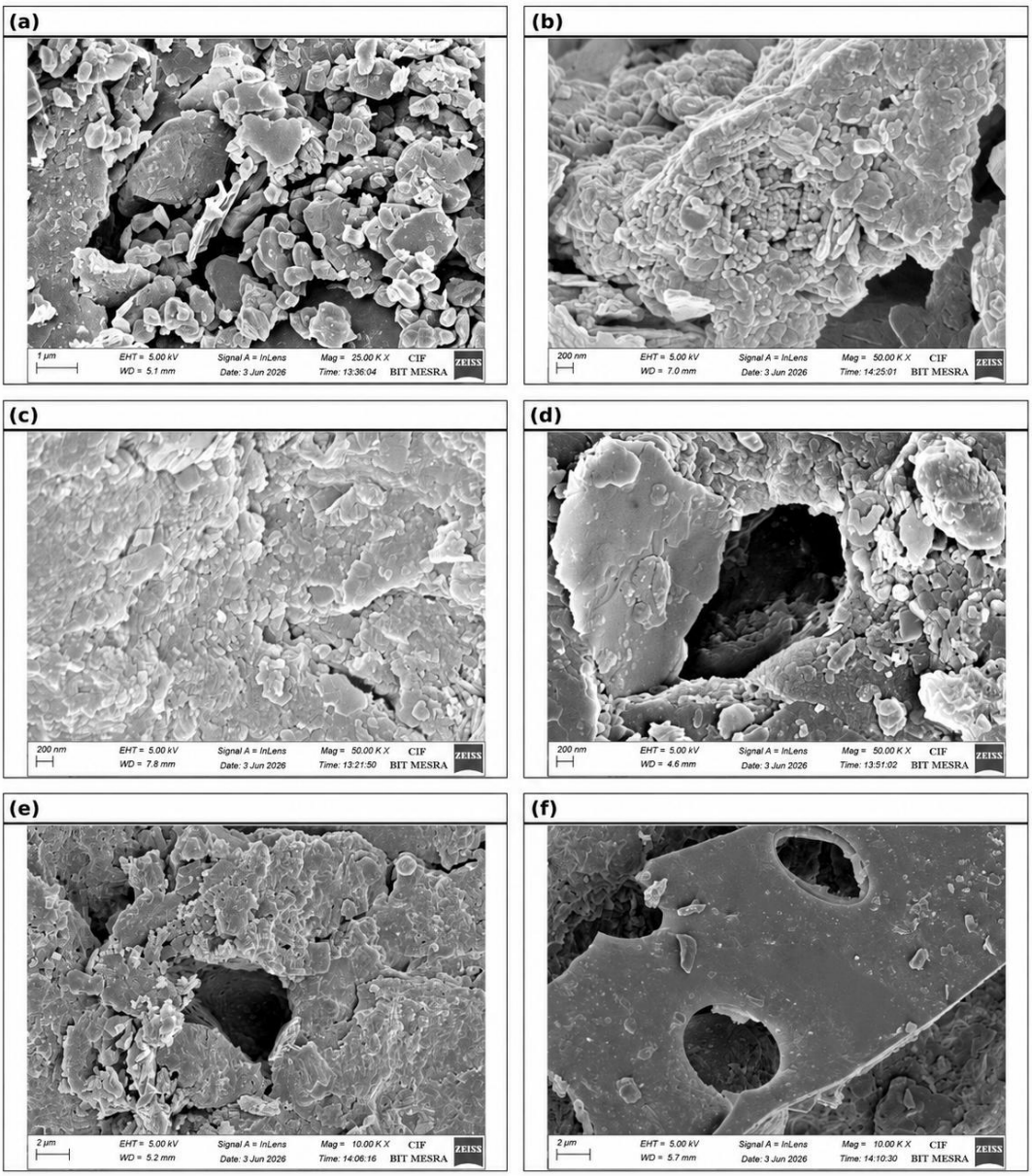

Figure 2. Selected surface and pore features: (a) (Fig. 2a), fragmented surface; (b) (Fig. 2b), compact surface; (c) (Fig. 2c), narrow mineral-related pores; (d) (Fig. 2d), pear-shaped cavity; (e) (Fig. 2e), fracture-connected macropore; and (f) (Fig. 2f), rounded pores

Fracture development

The fracture development varies from narrow microfractures to moderately wide and partially opened

cracks (Fig. 3a). The EDS analysis indicates oxide- and aluminosilicate-enriched inorganic phases in the fracture fillings, suggesting that the later mineral deposition decreased the initial width and openness of this fracture.

A heterogeneous pore system (Fig. 3b) could be envisaged, developed in between the grain boundaries. This system is observed to be constituted of pores of variable size ranging from 1100 – 2300 nm in diameter. The pores are generally deep in nature with smooth internal surfaces, that appears to be partially interconnected. A combination of these two attributes i.e., deep pores and interconnectivity make this system and efficient site for both methane accumulation and migration.

The isolated pore clusters revealed in Fig. 3c could limit gas migration. There is also evidence of development of secondary porosity, by virtue of dissolution along the grain boundaries. These together with the preserved primary porosity would contribute to enhanced methane adsorption.

A wide-open fracture with fragmented particles is observed in Fig. 3d. On the other hand presence of remnant channels, that are slightly open in nature, could serve as narrow preferential flow paths. Thus, the fracturing pattern, continuity, and mineral content control the connectivity of the fracture-pore system, in this case.

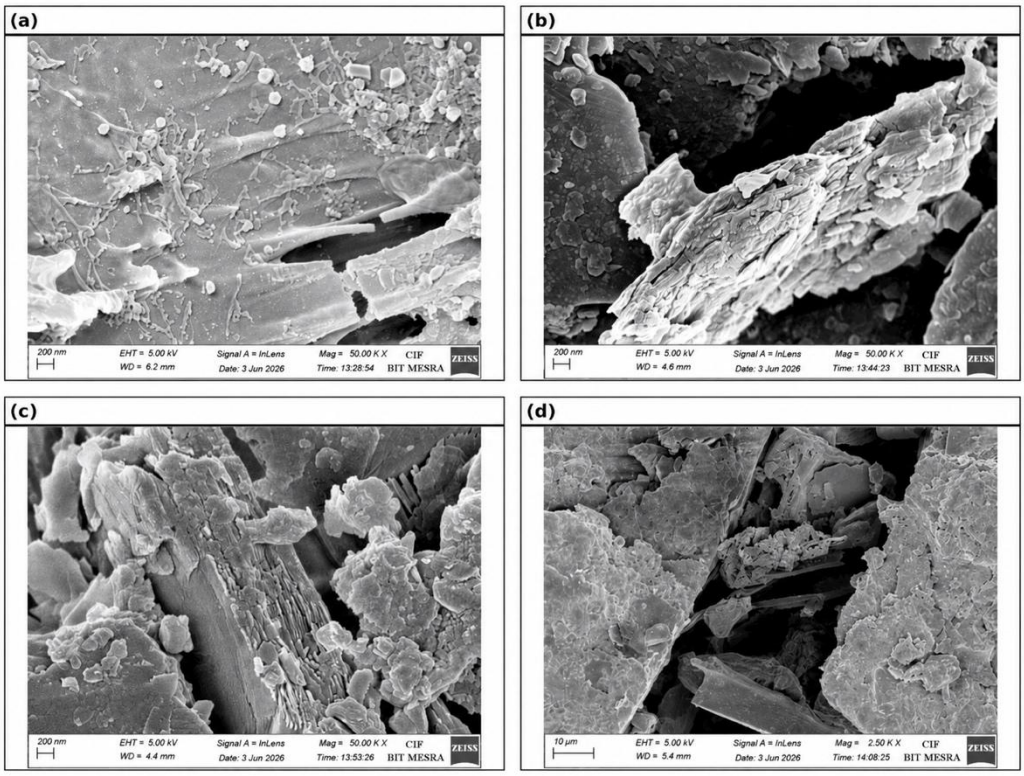

Figure 3. Fracture development: (a) (Fig. 3a), narrow mineral-filled fractures; (b) CS5_01 (Fig. 5.4b), connected boundary channels; (c) (Fig. 3c), partly filled fracture; and (d) (Fig. 3d), large open fracture

The inorganic phase in Fig. 4a contains plate-like, flaky, layered, blocky, and rounded particles, which were found in different parts of the analyzed material. The shape, size, arrangement, and location of these particles control the impact of mineral matter on the pore structure.

Presence of some mineral associated pores could be observed in other wise dense, homogeneous, mass observed in Fig. 4a. Platy and flaky mineral matter could be observed to be closely packed having edge-to-edge and face-to-face contacts. This has resulted in formation of some interparticle pores, which has primarily developed along the interface between organic and inorganic phases.

Fig. 4c reveals some slit shaped pores developed within the inorganic phase. Inorganic mineral platelets could be observed to form interlaminar pores that exists irrespective of compaction. The pore spaces appear to be deep in nature with relatively rough internal surface. However, this do indicate having a high potential for methane adsorption as well as diffusion.

In Fig. 4d, the blocky and rounded inorganic particles occur embedded within the organic framework. The pore development is usually concentrated in the interface between organic and inorganic phases. The mechanical support from the inorganic phases seems to have provided the necessary support for the preservation, evolution and development of pores. These pores cumulatively increase the total available surface area for storage of gas. Fig. 4e provides valuable qualitative evidence regarding mineral occurrence, pore accessibility, and potential gas migration pathways. The image shows a dense aggregate of platy and flaky minerals together with crystalline mineral as well, inherently associated with dense, homogenous organic phase. The inorganic phase is represented by euhedral to subhedral grains ranging 0.2 – 1.0 μm in size. All the available primary pores, are filled up by authigenic mineral mass, leading to partial cementation of the pore network, leading to subsequent reduction of interconnected macropores. The surface of the studied sample clearly indicates presence of numerous nanoscale adsorption sites. However, lack of interconnection makes the entire system less permeable. The micrograph in Fig. 4f, shows a mass constituted by inherent association of organic and inorganic phases. The entire framework hosts numerous pores with presence some relatively large, localized pores about 2 μm in diameter. The entire system might together contribute to enhanced overall gas adsorption.

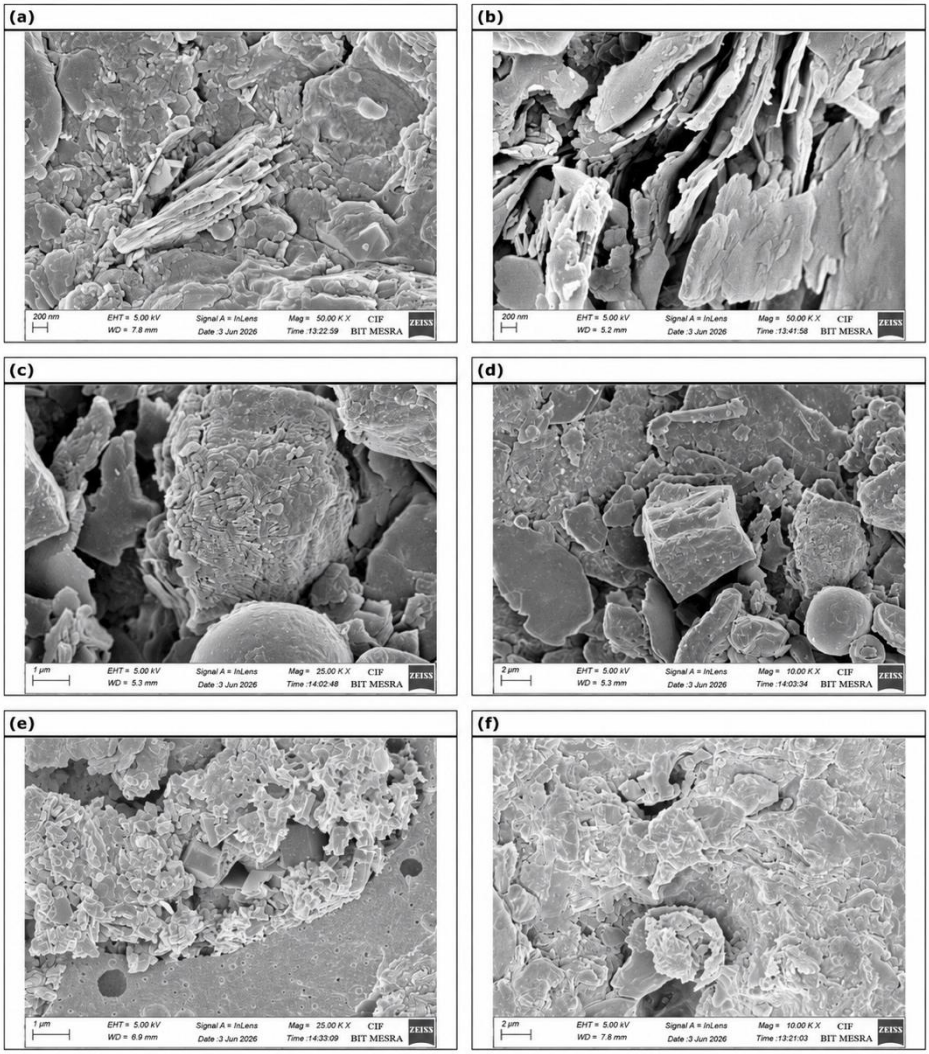

Figure 4. Mineral matter and related pore features: (a) (Fig. 4a), stacked plate-like particles; (b) (Fig. 4b), flaky sheets with slit pores; (c) (Fig. 4c), layered particles; (d) (Fig. 4d), blocky and rounded particles; (e) (Fig. 4e), mineral-filled cavity; and (f) (Fig. 4f), boundary and internal pores

Inorganic phase and EDS results

EDS analysis pertaining to Fig. 2c, shown in Fig. 5 below, demonstrates that the analyzed region is dominated by carbon (34.60 wt%) and oxygen (40.54 wt%), confirming the abundance of carbonaceous organic matter. Moderate concentrations of strontium (13.61 wt%) and zirconium (5.10 wt%), together with minor aluminium (2.31 wt%), calcium (1.63 wt%), magnesium (0.92 wt%), silicon (0.77 wt%), and zinc (0.52 wt%),

indicate the presence of dispersed mineral phases associated with the organic matrix. The enrichment of aluminium and silicon suggests minor aluminosilicate clay minerals, whereas calcium and strontium represent localized mineralization within the laminated structure. These results indicate that mineral matter occurs mainly as thin interlaminar bands and isolated inclusions rather than forming a continuous mineral framework.

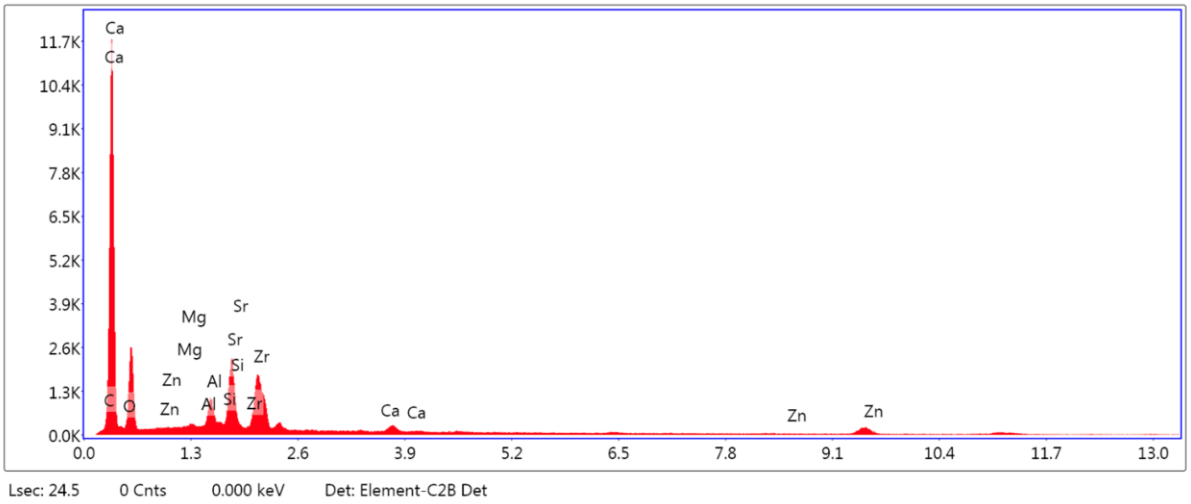

Figure 5. EDS spectra and elemental weight-percentage data for Fig. 2c

The EDS elemental analysis of the sample shown in Fig. 6, pertaining to the SEM image shown in Fig. 3b, indicates that the analyzed area of the sample is dominated by oxygen (40.87 wt%), strontium (37.19 wt%), and aluminium (10.96 wt%), together with minor zirconium (4.48 wt%), iron (3.00 wt%), silicon (0.55 wt%), magnesium (0.44 wt%), potassium (1.01 wt%), calcium (0.32 wt%), titanium (0.82 wt%), and zinc (0.35 wt%). The negligible carbon content confirms that this field of view is predominantly mineral-rich, with only a very minor contribution from organic matter. The enrichment of aluminium and silicon indicates the presence of aluminosilicate minerals, whereas iron and trace metallic elements occur as accessory mineral phases. The high oxygen content reflects the abundance of oxide- and silicate-bearing minerals within the laminated structure.

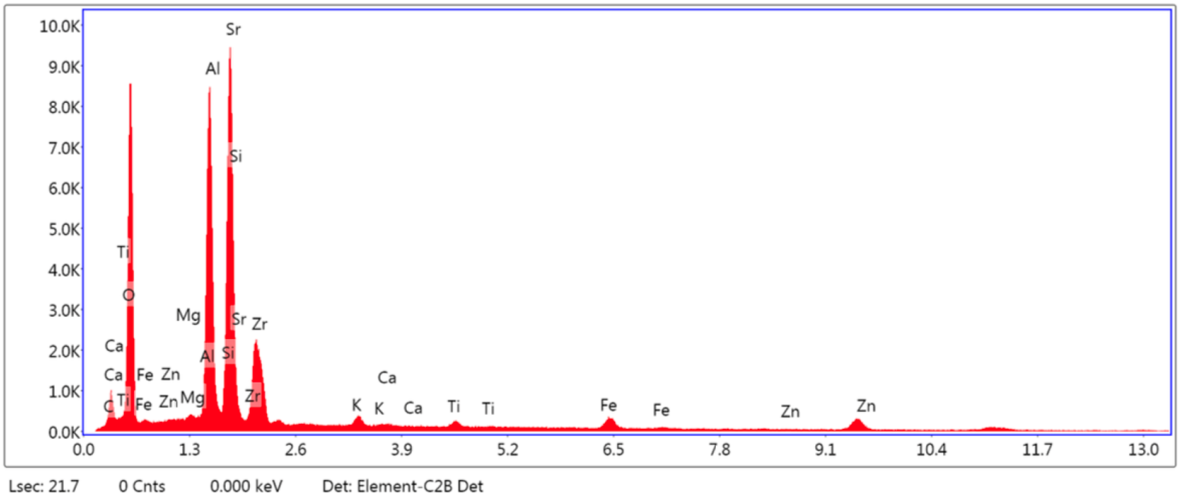

Figure 6. EDS spectra and elemental weight-percentage data for Fig. 3b

The EDS elemental spectrum in Fig. 7, pertaining to the SEM image presented in Fig. 4b, shows that the major elements identified are oxygen (39.20 wt%), zirconium (20.09 wt%), silicon (18.69 wt%), and aluminium (15.33 wt%), accompanied by minor concentrations of iron (2.07 wt%), zinc (1.72 wt%), magnesium (1.06 wt%), calcium (1.02 wt%), and potassium (0.81 wt%). The abundance of aluminium and silicon indicates the presence of aluminosilicate clay minerals, whereas zirconium-rich domains represent accessory heavy mineral phases. Minor iron and calcium suggest localized oxide and carbonate mineralization, reflecting secondary diagenetic processes.

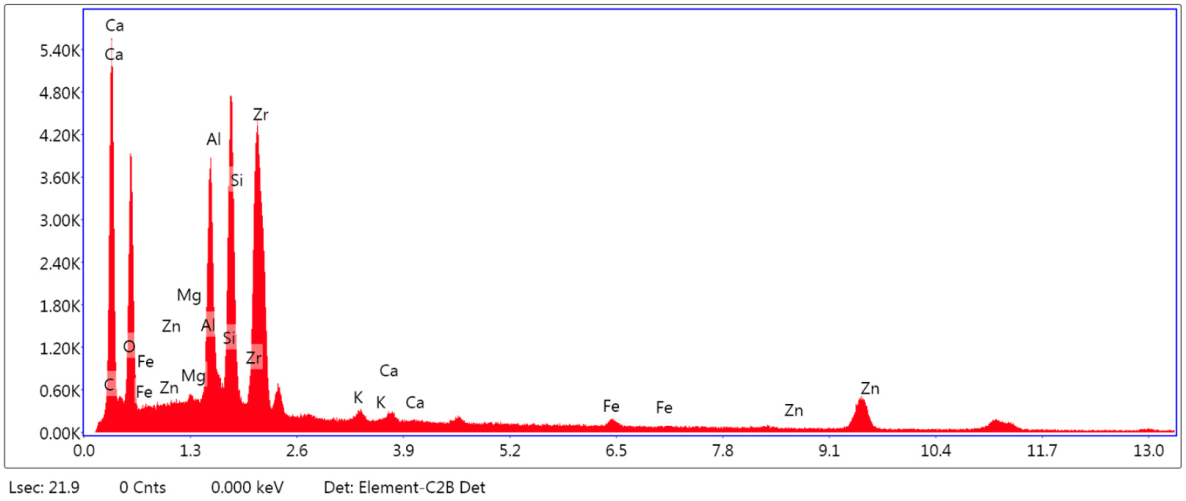

Figure 7. EDS spectra and elemental weight-percentage data for Fig. 4b

Implication for methane storage and migration

The findings suggest that the role of methane in the investigated coal is controlled primarily by the composition and constitution of both organic and inorganic phases, by virtue of availability of storage sites and their interconnectivity facilitating gas migration. While, organic phases comprising of interconnected slit-shaped pores, would provide most favourable conditions for both adsorption as well as desorption of gases. On the other hand, inorganic phases with well-developed fracture network, were observed to primarily enhance the permeability of the entire system. One of the important role played by the inorganic phase is by virtue of their relatively rigid nature, that facilitated the preservation of interparticle pores during the compaction, diagenesis and subsequent coalification process. The findings clearly indicate that the samples showing a balance between organic matter abundance, mineral composition, pore geometry, and fracture development, influences the coal microfabric functions predominantly from methane storage medium and migration pathway point of view.

VI. CONCLUSION

This study presents an exhaustive microstructural and compositional study of coal from, Sikni coal mines, North Koel Gondwana Basin, using FE-SEM, together with EDS to assess the primary controls influencing coal bed methane storage and migration. This assessment revealed coal characterized with a highly heterogeneous pore network along with associated fracture systems. The primary pores and fractures of interest observed were slit shaped pores, rounded pores, pear shaped pores, interparticle and fracture-connected pores. Wide variety of microfractures with variable aperture and continuity were also envisaged in this study, which were observed to have significant influence on gas migration. Based on this heterogeneity, it could be concluded that methane adsorption in these coal deposits is governed by pore abundance, their interconnectivity and associated fracture network. The inorganic phase was observed to be dominated primarily by aluminosilicate minerals, with minor concentration of oxides, carbonates and sulphides, occurring as pore infilling material, superficial deposits and discrete grains, with developed crystal faces. This mineral matter played a dual roe in evolution of pore system. On one hand, they supported primary pore preservation during diagenetic and subsequent coalification process, by virtue of their rigid framework, thereby sustaining potential gas adsorption sites. And, on other hand, precipitation of these authigenic minerals, have been observed to block pores and fractures, thereby effectively reducing the permeability of the coal reservoir and hence their migration. So, it could be concluded that the effectiveness of these coal deposits, both for storage and migration is directed by balance between preserved pores and mineral induced blockage. Future studies integrating quantitative pore-size distribution analyses, X-ray micro-computed tomography and methane adsorption/desorption experiments would further establish the relationship between pore architecture, mineralogical heterogeneity, and reservoir performance, of the Sikni coal deposits, thereby improving predictive models for CBM exploration and production.

VII. Acknowledgement

The authors express their sincere gratitude to the Principal, St. Xavier's College, Ranchi, for providing generous financial support that made this research work possible. The authors are also deeply thankful to the Central Instrumentation Facility (CIF), Birla Institute of Technology, Mesra, for providing access to the Field Emission Scanning Electron Microscope (FE-SEM), Energy Dispersive X-ray Spectroscopy (EDS), and other

laboratory facilities essential for carrying out the experimental investigations. Their continued support and technical assistance are gratefully acknowledged.

REFERENCES

[1] Allen, R.M., Vander Sande, J.B., 1984. Analysis of sub-micron mineral matter in coal via scanning-transmission electron microscopy. Fuel 63, 24 – 29.
[2] Corcoran, J.F., 1989. The use of SEM/EDS techniques in studies of coal and associated mineral matter. Proceedings of Mineralogy – Petrology Symposium, MINPET 89. Australasian Institute of Mining and Metallurgy, Sydney, pp. 85 – 87.
[3] Ayers, W.B., Kelso, B.S., 1989. Knowledge of methane potential for coalbed resources grows, but needs more study. Oil and Gas Journal 87, 64–67.
[4] Bustin, R. M., & Clarkson, C. R. (1998). Geological controls on coalbed methane reservoir capacity and gas content. International Journal of Coal Geology, 38(1–2), 3–26.
[5] Clarkson, C. R., & Bustin, R. M. (1999a). The effect of pore structure and gas pressure upon the transport properties of coal: A laboratory and modeling study. 1. Isotherms and pore volume distributions. Fuel, 78, 1333–1344.
[6] Clarkson, C. R., & Bustin, R. M. (1999b). The effect of pore structure and gas pressure upon the transport properties of coal: A laboratory and modeling study. 2. Adsorption rate modeling. Fuel, 78, 1345–1362.
[7] Finkelman, R.B., Bostick, N.H., Dulong, F.T., Senftle, F.E., Thorpe, A.N., 1998. Influence of an igneous intrusion on the inorganic geochemistry of a bituminous coal from Pitkin County, Colorado. International Journal of Coal Geology 36, 223 – 241.
[8] Hower, J.C., Andrews, W.M., Wild, G.D., Eble, C.F., Dulong, F.T., Salter, T.L., 1994. Quality of the Fire Clay coal bed, southeastern Kentucky. Journal of Coal Quality 13, 13 – 26.
[9] Kim, A.G., 1977. Estimating methane content of bituminous coalbeds from adsorption data. US Bureau of Mines Report of Investigations 8245, 22 pp.
[10] Kwiecinska, B.K., Hamburg, G., Vleeskens, J.M., 1992. Formation temperatures of natural coke in the Lower Silesian coal basin, Poland: evidence from pyrite and clays by SEM-EDX. International Journal of Coal Geology 21, 217 – 235.
[11] Lamberson, M. N., & Bustin, R. M. (1993). Coalbed methane characteristics of Gates Formation coals, northeastern British Columbia: Effect of maceral composition. AAPG Bulletin, 77(12), 2062–2076.
[12] Levine, J.R., 1992. Influence of coal composition on coal seam reservoir quality: a review. Coalbed Methane Symposium, Townsville Australia, 1992, I to XXVIII.
[13] Levine, J.R., 1993. Coalification: the evolution of coal as source rock and reservoir. In: Law, B.E., Rice, D.D. Eds. , Hydrocarbons From Coal. American Association of Petroleum Geologists, AAPG Studies in Geology, 38, pp. 39–77.
[14] Martinez-Tarazona, M.R., Spears, D.A., Palaicios, J.M., Martinez- Alonso, A., Tascon, J.M.D., 1992. Mineral matter in coals of different rank from the Asturian Central Basin. Fuel 71, 367 – 372.
[15] Mastalerz, M., He, L., Melnichenko, Y. B., & Rupp, J. A. (2012). Porosity of coal and shale: Insights from gas adsorption and SANS/USANS techniques. Energy & Fuels, 26(8), 5109–5120.
[16] Meissner, F.F., 1984. Cretaceous and lower Tertiary coals as sources for gas accumulations in the Rocky Ž . Mountain area. In: Woodward, J., Meissner, F.F., Clayton, J.L. Eds. , Source Rocks of the Rocky Mountain Region. Rocky Mountain Association of Geologists, 1984 Guidebook, pp. 401–431.
[17] Moore, T. A. (2012). Coalbed methane: A review. International Journal of Coal Geology, 101, 36–81.
[18] Russell, S.J., Rimmer, S.M., 1979. Analysis of mineral matter in coal, coal gasificaiton ash, and coal liquefaction residues by scanning electron microscopy and X-ray diffraction. In: Karr, C. (Ed.), Analytical Methods for Coal and Coal Products, vol. 3. Academic Press, New York, pp. 133 – 162.
[19] Schraufnagel, R.A., Schafer, P.S. 1996. The success of coalbed methane. In: Saulsberry, J.L., Schafer, P.S., Ž . Ž Schraufnagel, R.A. Eds. , A Guide to Methane Reservoir Engineering Gas Research Institute GRI Reference Number GRI-94r0397 , Chicago, IL, pp. 1.1–1.10.
[20] Stanton, R.W., Finkelman, R.B., 1979. Petrographic analysis of bituminous coal: optical and SEM identification of constituents. Scanning Electron Microscopy 1, 465 – 471.
[21] Ward, C. R. (2002). Analysis and significance of mineral matter in coal seams. International Journal of Coal Geology, 50(1–4), 135–168.
[22] Ward, C.R., Taylor, J.C., 1996. Quantitative mineralogical analysis of coals from the Callide Basin, Queensland, Australia using X-ray diffractometry and normative interpretation. International Journal of Coal Geology 31, 211 – 229.