

Petro-chemistry of Permian Coal Deposits from the Sohagpur Coalfield, Son Valley, Central India: Implications for Paleoenvironments and Coal Bed Methane (CBM) potential



Thesis submitted in partial fulfilment

For the Award of Degree

Doctor of Philosophy

by

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***Dedicated to the loving memory of my
beloved grandparents.....!***

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Preface

India possesses abundant fossil fuel resources and ranks fifth globally in terms of coal reserves. For decades, coal has been the backbone of the country's energy sector, supporting industrial development, electricity generation, and sustained economic growth. However, increasing concerns over climate change, environmental degradation, and greenhouse gas emissions have prompted a critical reassessment of conventional coal utilization. In this context, cleaner alternative energy sources associated with coal, such as coal-bed methane (CBM), have gained considerable attention. CBM is widely regarded as a comparatively cleaner and more environmentally sustainable energy option than direct coal combustion, thereby aligning with India's transition toward a low-carbon energy future.

The Sohagpur Coalfield, located in the central Indian state of Madhya Pradesh, represents one of the most significant Gondwana coal-bearing basins in the country. In addition to its substantial coal reserves, the coalfield exhibits promising potential for CBM generation. Despite its importance, comprehensive and systematic scientific investigations of the Sohagpur Coalfield remain limited. Earlier studies in the region have primarily focused on petrological, chemical, and trace elemental characteristics based on sporadic sampling. Other investigations include seismic imaging of selected coal blocks, geochemical, geophysical, and geomechanical characterization of organic deposits in the eastern part of the coalfield, as well as morpho-taxonomic analyses of macrofloral assemblages. However, detailed and integrated petrological and geochemical characterization based on pillar samples from currently operating coal mines has not been attempted so far.

The present study was undertaken to address this critical knowledge gap through a comprehensive investigation of coals from the Sohagpur Coalfield. By integrating coal

geochemistry, petrography, and advanced pore-structure characterization techniques, this research aims to elucidate coal formation processes, depositional environments, and reservoir properties. A major emphasis of the study is the evaluation of CBM generation potential, thereby contributing to India's broader objective of developing cleaner and more sustainable energy resources. The specific objectives of this research are to:

- i. Decipher the paleoclimatic and paleodepositional conditions of the Sohagpur coals.
- ii. Assess coal-bed methane generation potential and evaluate the feasibility of CO₂ sequestration for enhanced CBM recovery or long-term storage in abandoned coal mines.
- iii. Evaluate the potential industrial utilization of Sohagpur coal.

To ensure analytical accuracy, robustness, and reproducibility, coal samples were systematically collected from all workable seams of the Sohagpur Coalfield using the pillar sampling method. This approach was adopted to minimize contamination and to ensure representative sampling across the stratigraphic sequence. The samples were subsequently prepared into specific size fractions tailored to the requirements of individual analytical techniques. Proximate and ultimate analyses and FTIR spectroscopy were conducted on –72 mesh samples; XRF and XRD analyses on –100 mesh samples; Rock-Eval pyrolysis on –60 mesh samples; petrographic and vitrinite reflectance studies on –18 mesh samples; low-pressure gas adsorption and small-angle X-ray scattering (SAXS) on –230 mesh samples; and mercury intrusion porosimetry (MIP) on 0.5–1 cc coal chunk. This size-specific preparation enabled the precise determination of physical, chemical, and structural parameters critical for CBM assessment.

Petrographic analysis indicates that the Sohagpur coals are predominantly composed of vitrinite and inertinite maceral groups, with minor contributions from liptinite. Such maceral composition is favourable for CBM generation, as vitrinite plays a significant role in methane adsorption and storage. Vitrinite reflectance values suggest that the coals belong to the high-volatile bituminous rank, corresponding to a thermal maturity range considered optimal for methane generation. Textural variations observed within the coals reflect heterogeneity in maceral distribution and bonding characteristics, which may influence pore development and gas diffusion behaviour.

Geochemical investigations further corroborate the CBM potential of the Sohagpur coals. Proximate analysis reveals moderate volatile matter and relatively high ash content, while ultimate analysis confirms high carbon concentrations. Elemental ratios derived from CHNS data indicate the presence of humic-type kerogen, typically associated with terrestrial plant material and favourable gas generation potential. XRF and XRD analyses show that the mineral assemblage is dominated by clay minerals and quartz, suggesting deposition under humid conditions with significant clastic input. FTIR spectroscopy identifies diverse organic functional groups, including aliphatic and aromatic hydrocarbons, hydroxyls, and carbonyls, along with inorganic groups such as silicates and carbonates, providing insights into depositional conditions and gas adsorption behaviour. Rock-Eval pyrolysis data, particularly hydrogen index (HI) and $T_{\max}$ values, confirm that the coals are gas-prone and capable of methane generation under suitable burial and thermal conditions.

Pore-structure characterization offers critical insights into methane storage and transport mechanisms within the coal seams. Low-pressure gas adsorption analyses indicate that micropores (<2 nm) dominate the specific surface area, making them crucial for methane adsorption. Mesopores (2–50 nm), although contributing less to surface area, enhance gas

storage capacity and facilitate diffusion. Mercury intrusion porosimetry identifies macropores (>50 nm), which play a key role in permeability and gas migration. SAXS analysis reveals a multiscale, hierarchical pore network with interconnected pore systems, providing a comprehensive understanding of pore morphology and its influence on CBM recoverability. The integration of these techniques highlights the complex interplay between coal composition, mineral matter, and pore development that collectively governs methane sorption and production potential.

Paleoenvironmental interpretations based on petrographic and geochemical evidence suggest that the Sohagpur coals were deposited in humid, swamp-dominated settings under alternating oxic and anoxic conditions. The notable abundance of inertinite macerals indicates episodic wildfire activity during peat accumulation. Mineralogical and geochemical signatures further point to fluvio-deltaic and occasional lacustrine depositional environments influenced by periodic clastic influx.

Chapter:1

Introduction

1.1 Introduction

Coal is one of the most important fossil fuels and has played a pivotal role in the global energy landscape for centuries. It is a naturally occurring sedimentary rock predominantly composed of carbonaceous material derived from the remains of ancient vegetation. Coal formation is a complex geological process that involves the accumulation, burial, and transformation of plant debris over millions of years under conditions of high pressure and temperature. This process progressively converts the original biomass into peat, lignite, sub-bituminous, bituminous, and ultimately anthracite coal, with increasing carbon content and energy density at higher ranks. The characteristics of coal, including its physical and chemical properties, depend on the rank and the geological environment in which it formed (Gupta, 2007; Dai et al., 2020). The genesis of coal is intrinsically linked to paleoenvironmental conditions conducive to the preservation of plant material. Typically, coal forms in swampy, anoxic environments where thick accumulations of vegetation are protected from rapid decay by water saturation and oxygen depletion. As sediment layers accumulate over the peat deposits, the resulting compaction, combined with geothermal heat and chemical reactions, alters the physical structure and chemical composition of the organic matter. This leads to a gradual increase in carbon content and a corresponding decrease in moisture and volatile matter. The process also involves the loss of hydrogen, oxygen, nitrogen, and sulfur through biochemical degradation and thermal decomposition, resulting in the formation of distinct coal ranks with varying fuel properties.

Coal is primarily composed of carbon, but it also contains significant quantities of other elements such as hydrogen, oxygen, nitrogen, and sulphur. These heteroatoms are bound

within complex macromolecular structures and mineral matter inherent to the coal matrix. The elemental composition greatly influences coal's combustion behaviour, pollutant emissions, and suitability for industrial applications. For example, sulphur content in coal can lead to the release of sulfur oxides (SO_x) during combustion, contributing to acid rain and respiratory health issues. Similarly, nitrogen and mercury contents impact the formation of nitrogen oxides (NO_x) and mercury emissions, respectively, which are regulated pollutants due to their environmental and health hazards. The quality and classification of coal are primarily governed by its rank, which reflects the degree of coalification and varies with geological history. Lignite, or brown coal, represents the lowest rank and contains relatively low carbon and high moisture and volatile matter content, resulting in lower calorific value and greater challenges for transportation and storage. Sub-bituminous and bituminous coals are of intermediate rank and are the most widely used for electricity generation and industrial processes, offering higher energy content and better combustion characteristics. Anthracite is the highest rank of coal, characterized by high carbon content, low moisture, and low volatile matter, making it highly efficient but less abundant. These variations influence not only the energy yield but also the environmental impact of coal use.

Coal contains several key components that are critical to its utilization. Moisture in coal can be categorized into inherent moisture, which is chemically bound, and surface moisture, which can be physically removed. Moisture adversely affects coal's heating value and combustion efficiency. Volatile matter consists of hydrocarbon gases and condensable organic compounds released when coal is heated in the absence of air, which play a critical role in ignition and flame stability during combustion. High volatile matter coals ignite more readily and burn with a luminous flame. Ash is the inorganic residue remaining after coal combustion, composed mainly of silicates, aluminates, and iron

oxides, along with trace amounts of other minerals. The quantity and chemical composition of ash are crucial in determining slagging and fouling behaviour in boilers and impact the environmental management of coal combustion residues (Choudhury et al., 2017; Mishra and Singh, 2017; Singh et al., 2021).

The spatial distribution and thickness of coal seams are highly variable and reflect the depositional environments of ancient peat bogs. Coal seams can range from a few centimetres to several meters in thickness and may extend over large lateral distances, reflecting widespread swampy conditions during specific geological periods. The geological setting and tectonic history influence the burial depth and subsequent coalification processes. Additionally, coal seams are often interbedded with other sedimentary rocks such as shales, sandstones, and limestones, which affect mining methods and coal quality. Understanding the geological context is vital for efficient coal exploration, extraction, and utilization (Dai et al., 2020).

The importance of coal as an energy source must be balanced with its environmental consequences. Coal combustion is a major source of air pollutants, including sulfur dioxide, nitrogen oxides, particulate matter, mercury, and carbon dioxide, the latter being the most significant greenhouse gas driving anthropogenic climate change. The environmental impacts of coal mining and combustion include land degradation, habitat loss, water pollution due to acid mine drainage, and health risks associated with airborne particulates and toxic emissions. Managing these impacts requires advanced technologies such as flue gas desulfurization, electrostatic precipitators, mercury control systems, and carbon capture and storage. Moreover, the environmental footprint of coal has motivated international efforts to transition towards cleaner and more sustainable energy systems, including renewables and natural gas (IPCC, 2021; IEA, 2023).

India has a rich history of coal mining, which began commercially in the late 18th century and has since become a cornerstone of the country's energy sector. The nationalization of coal mines in 1973 sought to unify the fragmented coal industry and enhance production to meet rapidly growing energy demands driven by industrialization and urbanization. Despite increasing investments in renewable energy, coal remains the dominant source of energy in India due to its availability, affordability, and established infrastructure. According to the Integrated Energy Policy Committee of the former Planning Commission, coal is expected to retain its central role in India's energy mix well into the mid-21st century (Planning Commission, 2006).

In 2018–2019, coal accounted for nearly 87% of the fuel used for electricity generation in India, highlighting its indispensability for the country's power sector. Beyond power generation, coal is essential to several key industries such as cement manufacturing, fertilizers, chemicals, and paper production, many of which rely on coal for process heat and energy. The growth of coal production in India has been substantial, with output increasing from approximately 675.40 million tonnes in 2017–2018 to 728.72 million tonnes in 2018–2019, reflecting a growth rate of around 7.9%. Meanwhile, lignite production experienced a slight decline of about 5.1% during the same period. India ranked second worldwide in coal production in 2018, underscoring its role as a major player in the global coal market (Ministry of Mines, 2021).

The continued reliance on coal presents both opportunities and challenges for India's energy future. On one hand, coal supports economic growth, energy security, and employment. On the other hand, addressing the environmental and social impacts of coal mining and combustion is critical to achieving sustainable development goals. Strategies for cleaner coal utilization, enhanced efficiency, pollution control, and gradual

diversification towards renewable energy sources are essential components of India's evolving energy policy landscape.

1.2 Background and Motivation

The Permian coal deposits of the Indian Gondwana basins constitute an important archive of paleoenvironmental evolution and a significant component of the country's fossil fuel resources. These coal-bearing successions were formed in continental rift basins under diverse climatic and tectonic regimes during the assembly of Gondwana, making them particularly valuable for understanding coal genesis in relation to paleoclimate and basin dynamics (Mukhopadhyay et al., 2010). The Son Valley Basin of Central India represents one of the major Gondwana sediment deposits. The Sohagpur Coalfield lies in this basin and hosts thick and laterally persistent Permian coal seams, predominantly associated with the Barakar Formation (Raja Rao, 1987; Agnihotri et al., 2016; Mondal et al., 2020).

Petro-chemistry, encompassing coal petrography and geochemical characteristics, is a powerful tool for interpreting coal-forming environments, organic matter composition, and rank evolution. Petrographic constituents such as vitrinite, inertinite, and liptinite macerals provide insights into vegetation type, peat accumulation conditions, oxidation levels, and hydrological regimes prevailing during peat formation (Diessel, 1992; Taylor et al., 1998). Similarly, chemical parameters derived from proximate and ultimate analyses, elemental ratios, and volatile matter content reflect both depositional conditions and post-depositional coalification processes (van Krevelen, 1993; Suárez-Ruiz and Crelling, 2008). In addition to their paleoenvironmental significance, Gondwana coals have gained renewed importance due to their potential for coal bed methane (CBM), an unconventional and cleaner-burning energy resource. The occurrence, generation, and retention of CBM are strongly influenced by coal rank, maceral composition, moisture content, porosity, and geochemical maturity (Flores, 1998; Scott, 2002). Indian coalfields

such as Raniganj, Jharia, and Sohagpur have been identified as promising CBM provinces (Kumar et al., 2015; Prabhu and Mallick 2015; Kishor et al., 2023a) yet the understanding of coal quality and heterogeneity controlling methane potential remains incomplete. In the Sohagpur Coalfield, although CBM exploration has progressed, detailed petrochemical studies linking coal characteristics with methane potential have not done.

As there is very limited study done on the sporadic sampling of Sohagpur coals. The motivation for the present study arises from this gap in integrated petrochemical investigations of Permian coals from the Sohagpur Coalfield. A systematic evaluation of petrographic composition and chemical properties is essential to decipher the controls exerted by depositional environments, peat-forming conditions, and diagenetic processes on coal quality and CBM potential. By correlating petrochemical parameters with paleoenvironments, this study aims to improve the understanding of coal genesis while simultaneously contributing to CBM resource assessment. Such an integrated approach is crucial not only for advancing Gondwana coal research but also for supporting sustainable energy exploration and utilization in India's coal-bearing basins.

1.3 Occurrence of Coal in India

In India, there are primarily two different stratigraphic horizons that contain economically significant coal formations: the Cenozoic and Upper Palaeozoic Gondwana sediments (Figure 1.1). Government organizations, including the Central Mine Planning and Designing Institute (CMPDI), Mineral Exploration and Corporation Limited (MECL), Coal India Limited (CIL), and the Geological Survey of India (GSI) and its subsidiaries, among others, are responsible for conducting exploration efforts in India. These organizations have determined that the nation has 361.41 billion tonnes of coal resources up to a depth of 1200 m, considering coal seams with a thickness of 0.90 m or more (Ministry of Coal, 2022).

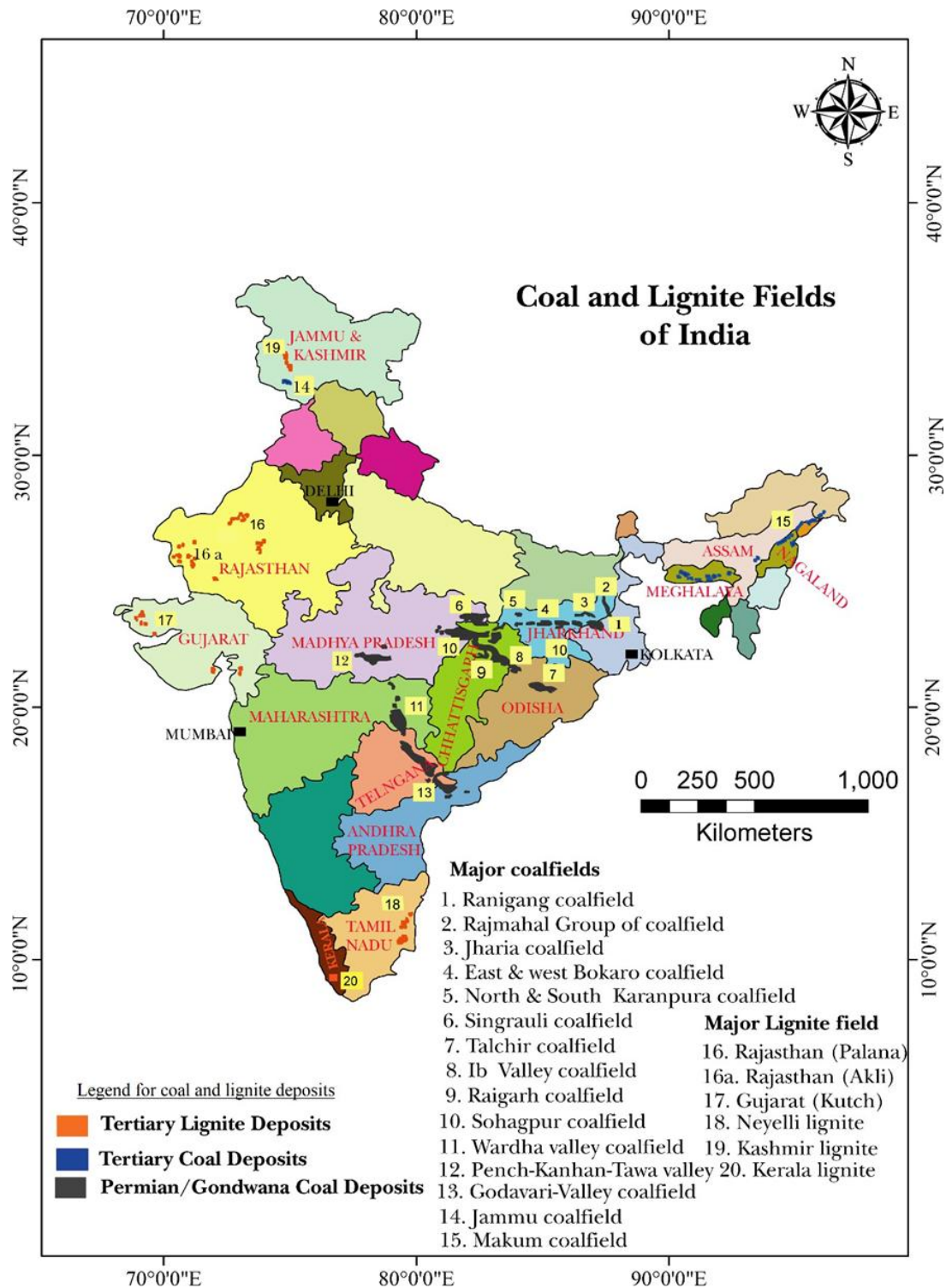


Figure 1.1 Major Coal and lignite fields of India (Kumar, 2021).

Out of the total 361.41 billion tonnes of coal, the Gondwana coal has 359.75 billion tonnes, while the Lignite has 1.66 billion tonnes of resources. This coal includes the total coal resources, including Measured, Indicated, and Inferred. Gondwana coal varies in types from prime coking, medium coking, semi-coking, and non-coking, while tertiary

coal is high in sulphur (Ministry of Coal, 2022). Table 1.1 shows the depth and category-wise value of Gondwana (Coking and Non-coking) and Tertiary (High sulphur) coal.

Table 1.1 Depth wise and category wise resources as on 01/04/2022 (values in billion tonnes)

Depth	Coking			Non- Coking			High Sulphur	Grand Total
	Prime	Medium	Semi coking	Superior (G1-G6)	Inferior (G7-G17)	Ungraded		
0-300	0	11.96	0.47	21.69	156.53	6.72	1.46	198.82
0-600	4.05	4.65	0	0.2	5.9	0	0	14.81
300-600	0	6.51	0.76	13.79	81.95	12.06	0.2	115.27
600-1200	1.26	4.96	0.48	3.43	16.99	5.39	0	32.51
0-1200	5.31	28.08	1.71	39.11	261.37	24.17	1.66	364.41

State-wise coal resource of India as of 01/04/2022 are shown in Table 1.2 (Ministry of Coal, 2022).

Table 1.2 State-wise coal resource (values show in million tonnes).

State	Measured (331)	Indicated (332)	Inferred (333)	Resource
Odisha	48572.6	34080.4	5451.6	88104.6
Jharkhand	53245	28259.7	5155.41	86660.1
Chhattisgarh	32053.4	40701.4	1436.99	74191.76
West Bengal	17233.9	12858.8	3778.53	33871.25
Madhya Pradesh	14051.7	12723	4142.1	30916.73
Telangana	11256.8	8344.35	3433.07	23034.2
Maharashtra	7983.64	3390.48	1846.59	13220.71
Bihar	309.53	4079.69	47.96	4437.18
Andhra Pradesh	920.96	2442.74	778.17	4141.87
Uttar Pradesh	884.04	177.76	0	1061.8
Meghalaya	89.04	16.51	470.93	576.48
Assam	464.78	57.21	3.02	525.01
Nagaland	8.76	21.83	447.72	478.31
Sikkim	0	58.25	42.98	101.23
Arunachal Pradesh	31.23	40.11	18.89	90.23
Total	187105	147252	27054	361411.46

1.3.1 Geological occurrence of Gondwana Coal in India

Gondwana coals were formed in Gondwanaland. Gondwana sediments are present in various parts of India, particularly in the eastern and central regions. These sediments are found sporadically in the northeast, especially in Assam and Sikkim. The northeastern region of India's peninsular plateau, which includes parts of Jharkhand, Chhattisgarh, Orissa, eastern Madhya Pradesh, and the western part of West Bengal that borders Jharkhand, has the highest concentration of coalfields. Large coal reserves can also be found in the eastern regions of Andhra Pradesh, Maharashtra, and Madhya Pradesh's southern regions. The Damodar (Jharkhand-West Bengal), Mahanadi (Chhattisgarh-Odisha), Godavari and Wardha (Maharashtra-Andhra Pradesh), Son (Madhya Pradesh Jharkhand), Indravati, Panch, Narmada, Koel, and a few other river valleys are home to the Gondwana coal mines. Table 1.3 shows state-wise coalfields and the total resource of Gondwana coals (Indian Bureau of Mines, 2021).

Table 1.3 State-wise coalfield and the total resource of Gondwana coals (Indian Bureau of Mines, 2021).

State	Coalfield	Total Resources (in Million tonne)
Andhra Pradesh	Godavari Valley	2247
Assam	Singrimari	14
Bihar	Rajmahal	3464
Chhattisgarh	Sohagpur	104
	Sonhat	2671
	Jhilmili	267
	Chirimiri	362
	Bisrampur	2436
	East Bisrampur	165
	Lakhanpur	459
	Panchbahini	11
	Hasedo-Arand	5529
	Sendurgarh	279
	Korba	12976
	Mand-Raigarh	43761
	Tatapani-Ramkola	4403
Jharkhand	Raniganj	2036
	Jharia	19531
	East Bokaro	8284

State	Coalfield	Total Resources (in Million tonne)
Madhya Pradesh	West Bokaro	5218
	Ramgarh	1906
	North Karanpura	18967
	South Karanpura	7632
	Aurangabad	2997
	Hutar	250
	Daltonganj	144
	Deogarh	400
	Rajmahal	18852
	Johilla	481
	Umaria	181
	Pench-Kanhan	4056
	Pathakhera	447
	Gurunda	138
	Mohpani	8
	Sohagpur	8082
Maharashtra	Singrauli	16824
	Wardha Valley	7940
	Kamthi	3091
	Umrer Makardhokra	469
	Nand Bander	1405
Odisha	Bokhara	30
	Ib-River	32102
	Talcher	52776
Telangana	Godavari Valley	22851
Sikkim	Rangit Valley	101
Uttar Pradesh	Singrauli	1062
West Bengal	Raniganj	25578
	Barjora	201
	Birbhum	7298
	Darjeeling	15

1.3.2 Geological occurrence of tertiary coal

Northeastern coal, ranging in age from the Late Palaeocene to Early Eocene, occurring from the Mikir Hills of Assam to the Garo, Khasi and Jaintia Hills of Meghalaya in the northeastern, India, is renowned as the country's largest repository of Tertiary coal resources. In Assam, Arunachal Pradesh, and Nagaland, the Oligocene sediments are linked to coal seams. A small number of thin seams are known to exist in the sediments beneath the coal measures in Nagaland and Assam, particularly in the Makum, Dillileypore, and Nazira (or Borjan) coalfields. The coal seams in Meghalaya are thin

(0.2-2 m, sometimes up to 3 m thick), and laterally non-persistent. The coal seams in Nagaland, Assam, and Arunachal Pradesh are noticeably thicker (4–8 m) and comparatively more numerous in an easterly direction from the Miki Hills. In Meghalaya, the strata that support coal are either completely intact or have only experienced modest structural disruption. Conversely, the coal-bearing layers of Assam, Arunachal Pradesh, and Nagaland are exposed separately over a short linear strip that is depicted as a sequence of intricate and imbricate overthrusts, which is known as the "belt of Schuppen." This belt is home to the most significant Tertiary coal deposits in India, which are the coalfields of Nagaland (Nazira or Borjan and Changki-Valley), Assam (Dilli-Jeypore and Makum), and Arunachal Pradesh (eastern part of Makum and Namchik-Namphuk) (Misra, 2000). Table 1.4 shows the total resource of the tertiary coalfields (Indian Bureau of Mines, 2021)

Table 1.4 Total resource of the tertiary coalfields (Indian Bureau of Mines, 2021)

State	Coalfield	Total Resources (in Million Tonnes)
Assam	Makum	453
	Dilli-Jeypore	54
	Mikir Hills	4
Arunachal Pradesh	Namchik- Namphuk	84
	Miao Bum	6
Meghalaya	West Darangiri	125
	East darangari	34
	Balphakram-Pendenguru	107
	Siju	125
	Langrin	133
	Mawlong Shelia	6
	Khasi Hills	10
	Bapung	34
	Jaintia hills	2
	Borjan	10
Nagaland	Jhanzi-Disai	133
	Tiensang	3
	Tiru Valley	7
	DGM	293

1.4 Coal petrography and coal facies: why microscopic constituents matter

Coal petrography is the microscopic study of coal constituents, known as macerals, and their textural relationships, which provides fundamental insights into coal origin, composition, and utilization. Unlike bulk chemical analyses, petrography preserves information about the original plant material, depositional conditions, and post-depositional alterations that control coal quality and behaviour (Taylor et al., 1998; Suárez-Ruiz and Crelling, 2008). The three maceral groups: vitrinite, inertinite, and liptinite are derived from different botanical precursors and reflect varying degrees of preservation, oxidation, and microbial activity during peat accumulation.

Vitrinite macerals originate mainly from woody plant tissues and are commonly associated with water-saturated, reducing conditions that favour preservation of organic matter. High vitrinite content is typically indicative of stable peat-forming environments and plays a critical role in determining coal rank using vitrinite reflectance values and gas adsorption capacity due to the abundance of micropores (Diessel, 1992; Mukhopadhyay, 1986). Inertinite macerals, on the other hand, represent oxidized or charred plant material and are often linked to fluctuating water tables, wildfire activity, or periods of subaerial exposure. Elevated inertinite proportions are therefore interpreted as evidence of drier paleoclimatic conditions and increased oxidation during peat formation (Scott, 2002; Jasper et al., 2017). Liptinite macerals, derived from spores, cuticles, resins, and algal material, although generally present in smaller proportions in Gondwana coals, are significant contributors to hydrocarbon generation due to their hydrogen-rich nature (Taylor et al., 1998).

Coal facies analysis is used to reconstruct the environmental conditions under which peat accumulated. Facies models utilize maceral ratios, mineral matter content, and microlithotype associations to infer factors such as water depth, nutrient availability,

redox conditions, and peat accumulation rates (Diessel, 1992; Flores, 1998; Singh and Singh, 2000).

The microscopic constitution of coal has direct implications for its technological behaviour and resource potential. From an applied perspective, maceral composition strongly influences combustion efficiency, coking properties, and environmental performance. In the context of coal bed methane (CBM), vitrinite-rich coals with appropriate rank and microporosity are generally more favourable for methane adsorption and storage, whereas high inertinite content may reduce gas capacity due to lower micropore development as inertinite pores may be plugged with mineral matter. Thus, petrographic characterization forms a critical link between coal genesis, paleoenvironmental interpretation, and energy resource evaluation.

1.5 Coal geochemistry and mineral matter: links to provenance, diagenesis, and reservoir quality

Coal geochemistry and mineral matter composition provide critical insights into the origin of inorganic constituents, post-depositional processes, and the overall quality of coal as a reservoir for gas storage and flow. Unlike organic petrographic components, the inorganic fraction of coal reflects the combined influence of source rock composition, sediment supply pathways, depositional environment, and diagenetic alteration within the basin. Consequently, geochemical and mineralogical analyses serve as essential tools for reconstructing sediment provenance, understanding coal–mineral interactions during burial, and evaluating reservoir properties relevant to CBM potential (Ward, 2002; Dai et al., 2010).

The mineral matter in coal is derived from both detrital and authigenic sources. Detrital minerals, such as quartz, feldspar, and clay minerals, are transported into peat-forming environments from surrounding highlands and therefore retain signatures of source

lithology and weathering intensity (Rimmer et al., 2000; Dai et al., 2012). Trace element ratios and rare earth element (REE) patterns have been widely used to constrain provenance, tectonic setting, and paleoclimate, as they are relatively resistant to organic processes and preserve geochemical fingerprints of source areas (Seredin and Dai, 2012). Authigenic minerals, including carbonates, pyrite, and certain clay minerals, form within the peat or during early to late diagenesis as a result of geochemical reactions between organic matter, pore waters, and dissolved ions. Pyrite formation, for example, is commonly associated with reducing conditions and microbial sulfate reduction, providing evidence for waterlogged, anoxic peat environments and marine or brackish influences (Berner, 1984; Ward, 2002). Diagenetic transformation of clay minerals and precipitation of carbonates can modify pore structure, reduce permeability, and influence gas migration pathways, thereby exerting a strong control on reservoir quality (Bustin and Clarkson, 1998; Busch and Gensterblum, 2011).

Bulk coal geochemistry, including major oxides, major, minor and trace elements, and elemental ratios, complements mineralogical data by elucidating the extent of diagenetic alteration and organic–inorganic interactions. Elements such as Fe, Ca, Mg, and S are particularly sensitive to redox conditions and diagenetic processes, while alkali and alkaline earth elements may indicate detrital input or fluid-mediated redistribution during burial (Dai et al., 2015). In CBM reservoirs, elevated mineral matter content generally reduces adsorption capacity by diluting the organic fraction and blocking micropores; however, certain clay minerals may enhance gas storage by contributing additional surface area, depending on their type and distribution (Clarkson et al., 2011; Chandra et al., 2020).

Reservoir quality is highly dependent on the composition and distribution of mineral matter influence porosity development, cleat integrity, and permeability evolution. High

ash content tends to degrade reservoir performance, whereas low mineral matter, vitrinite-rich coals are typically more favourable for methane adsorption and desorption (Flores, 1998; Scott, 2002; Clarkson et al., 2011).

1.6 Pore systems and adsorption: why multi-technique characterization is necessary

The pore system of coal plays a fundamental role in controlling gas storage, adsorption, diffusion, and permeability, and therefore directly governs the CBM potential of coal seams. Coal is a highly heterogeneous, dual-porosity medium in which pores occur across a wide range of scales, from nanometer-scale micropores to macroscopic fractures and cleats. Pores in coal are of two main types: open and closed pores (Figure 1.2). These pores differ not only in size and geometry but also in origin, connectivity, and surface chemistry, making their characterization inherently complex (Gan et al., 1972; Clarkson and Bustin, 1998). Coal pores are classified into three types as per International Union of Pure and Applied Chemistry (IUPAC): micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm), each contributing differently to gas behaviour. Micropores provide the majority of surface area and are primarily responsible for methane adsorption, while mesopores and macropores facilitate gas diffusion and flow toward cleat systems (Sing 1985; Busch and Gensterblum, 2011).

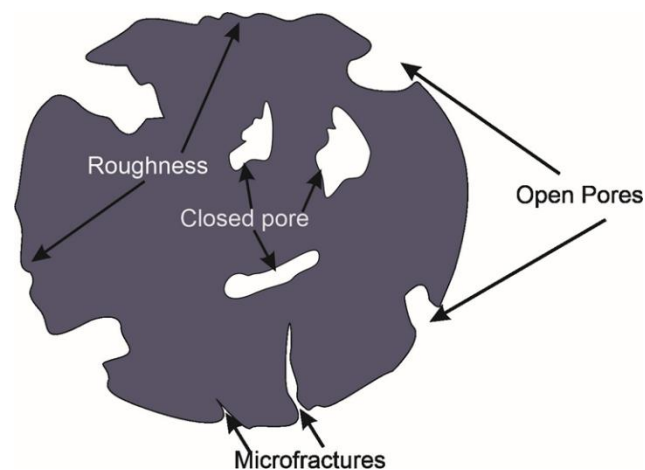


Figure 1.2 Illustration of open pores, closed pores, microfracture and roughness of pores in a coal particle.

A single analytical technique is not capable of fully capturing the multiscale and heterogeneous nature of coal pore systems. As fluid intrusion can only detect the open pores, while scattering techniques can detect open as well as closed pores present in coal particles. Low-pressure gas adsorption methods, such as N₂ adsorption and CO₂ adsorption, are effective for quantifying mesopores and micropores, respectively, but provide limited information on larger pores and fracture networks (Sing et al., 1985; Hu et al., 2023). Mercury intrusion porosimetry (MIP) is widely used to characterize macropores and pore throat distributions; however, it may underestimate microporosity and can alter fragile coal pore structures due to high intrusion pressures (Kumar et al., 2025b). Similarly, scanning electron microscopy (SEM), provides direct visualization of pore morphology but is limited in quantitative pore volume estimation and may not adequately resolve nanometer-scale pores. Advanced techniques such as nuclear magnetic resonance (NMR), small-angle X-ray scattering (SAXS), and micro-computed tomography (μ -CT) have further enhanced the understanding of coal pore networks by providing information on pore size distribution, connectivity, and spatial arrangement in three dimensions (Yao et al., 2010; Hu et al., 2023). However, each of these methods operates over a restricted pore size range or requires assumptions about pore geometry and fluid behaviour. Consequently, reliance on a single method can lead to incomplete or biased interpretations of pore structure and gas storage capacity.

A multi-technique characterization approach integrates complementary methods to capture the full spectrum of pore sizes and their functional roles in adsorption and transport processes. By combining gas adsorption analyses, scattering, and imaging techniques, it becomes possible to establish more reliable relationships between pore structure, coal composition, and methane adsorption behaviour. Such integrated analyses are especially critical in Gondwana coalfields, where strong heterogeneity in maceral

composition and rank can result in significant spatial variability in CBM potential (Singh, 2016; Kishor et al., 2025a).

Based on the complexity of coal pore systems and their central role in methane adsorption necessitate a multi-technique characterization strategy. This approach not only improves the accuracy of pore structure assessment but also strengthens predictions of CBM storage and producibility. Understanding pore systems through integrated methodologies is therefore essential for both fundamental coal reservoir studies and effective CBM exploration and development.

1.7 Review work on Sohagpur Coalfield

The Sohagpur coalfield is a part of the Son Valley basin of the Gondwana deposit and the main coal-bearing area of South Rewa. The name for Sohagpur Coalfield was given by Hughes (1871). Many investigations have been done by several authors on the coal of the Sohagpur described below-

Navale and Tiwari (1967) conducted palynological investigations that demonstrated that the coal in the study area predominantly comprises durain. Their results further established stratigraphic equivalence with Lower Gondwana units observed in analogous sedimentary basins, thereby facilitating regional correlation. Following this, Bharadwaj and Srivastava (1970) performed a detailed palynological analysis on spore assemblages derived from borehole coal samples, successfully delineating eight discrete coal seams, enhancing the stratigraphic resolution of the coal-bearing sequences. Pareek (1987) employed petrographic techniques focusing on microlithotypes and maceral composition, reporting vitrinite reflectance values ranging between 0.46 and 1.05% (oil reflectance basis), indicative of low to medium rank bituminous coal and thermal maturity levels. Chakrabarti (1992) investigated the subsidence patterns within the coalfield through structural and sedimentological analyses, concluding that depositional environment

exerts a primary control on coal seam morphology and continuity. Ram-Awatar et al. (2004) validated the Late Permian age through palynological assemblage analysis, which is consistent with the middle Pali formation in the South Rewa basin and thereby refining the chronostratigraphic framework of the basin. Dhanam et al. (2013) integrated high-resolution seismic reflection profiling with borehole sonic log data, revealing syn-sedimentary subsidence processes and faulting characterized by steeply dipping normal faults. The study also identified the presence of a thick Barakar Formation sequence, thus contributing to a more comprehensive understanding of the tectono-sedimentary evolution of the Sohagpur Gondwana basin. Agnihotri et al. (2016) investigated megafossil assemblages and identified floristic similarities between the Sohagpur Coalfield and Barakar Formation coal deposits from other Gondwana basins across India, supporting paleoecological and paleoclimatic continuity. Gautam et al. (2016) applied palynological zonation techniques to distinguish well-defined assemblage zones corresponding to late Permian and early to late Triassic ages, refining biostratigraphic subdivisions within the basin. Jasper et al. (2017) utilized scanning electron microscopy (SEM) to identify microscopic evidence of paleo-fire events within peat-forming environments, elucidating paleo-environmental dynamics influencing coal formation. Agnihotri et al. (2018), through detailed palynological investigations, inferred that extensive coal seam thickness resulted from prolific vegetation accumulation during Barakar Formation deposition, emphasizing the role of lush paleo-vegetation in coal seam development. Mondal et al. (2020) applied geophysical monitoring to quantify microseismic activity associated with large-scale coal extraction and surface blasting in conjunction with the presence of hard roof strata, establishing the relationship between mining-induced stress redistribution and seismicity in the longwall roof. Subsequently, Mondal et al. (2021) combined geochemical, geophysical, and geomechanical datasets to

evaluate reserve quality, roof strata properties, and gas content, providing a multi-disciplinary characterization of coal seam integrity and gas potential. Modi et al. (2022, 2024) focused on geochemical characterization, particularly quantifying rare earth elements (REEs) within coal samples. They reported mean concentrations of critical REEs, including Yttrium (51.49 ppm), Neodymium (79.34 ppm), Europium (2.67 ppm), Terbium (1.71 ppm), and Dysprosium (9.76 ppm), highlighting the coal's potential as an unconventional resource for critical elements. Bhapkar et al. (2023) employed X-ray scattering techniques combined with high-resolution imaging to demonstrate a progressive reduction in mesopore volume and specific surface area with increasing depth, influencing the coal's gas adsorption and transport properties.

1.8 Research problem, knowledge gap and rationale

The Permian coal deposits of the Sohagpur Coalfield constitute a geologically and economically significant resource, with importance for both paleoenvironmental reconstruction and assessment of Coal Bed Methane (CBM) potential. Although petrographic and geochemical investigations have been conducted in several Indian coalfields, detailed and systematic petrochemical characterization of the Sohagpur Coalfield remains limited. Previous studies in this coalfield have largely focused on petrological, chemical, and trace elemental analyses based on sporadic sampling, along with seismic imaging, geochemical, geophysical, and geomechanical characterization of organic deposits in the eastern part of the coalfield, as well as morpho-taxonomic studies of macrofloral assemblages. However, these studies do not adequately address the comprehensive petrological and geochemical variability of the coal seams and CBM potential of this coalfield.

Based on this, there is a clear knowledge gap in the absence of detailed petrological and organic geochemical characterization based on representative pillar samples from

currently operating coal mines in the Sohagpur Coalfield. Such samples are crucial for accurately evaluating coal maceral composition, organic matter type, and thermal maturity, which directly influence CBM generation and storage potential.

Given the growing national emphasis on meeting rising energy demands and transitioning toward cleaner energy resources, a focused assessment of CBM potential in Indian coalfields is a strategic priority. Therefore, this study is rationalized by the need to generate robust petrochemical and organic geochemical data from systematically collected pillar samples, thereby providing a scientific foundation for improved CBM exploration strategies and refined paleoenvironmental interpretations of the Permian Sohagpur coals.

1.9 Objective and Scope of the Current Work

The previous study on the Sohagpur coalfield was done for the petrological, chemical and trace elemental by sporadic data. The seismic imaging of coal block, geochemical, geophysical and geomechanical characteristics of the organic deposits on eastern Sohagpur is also done, while the morpho-taxonomic study of macrofloral assemblage was also studied for a few coal mines. However, there are no attempts made for the detailed petrological and geochemical characterization of the Sohagpur coalfield based on pillar samples of the currently operating coal mines. There is a research gap on Coal Bed Methane potential and pore size occurrence and distribution, Hydrocarbon source rock potential and CO₂ adsorption on these coal samples.

The present study has been undertaken with the following key objectives:

- To conduct detailed petrological and geochemical characterization of coal samples from the Sohagpur coalfield using representative pillar samples from active mines.

- To decipher the paleo-depositional and paleoclimatic conditions of coal formation through multiple geochemical, petrographic, and mineralogical proxies.
- To evaluate the hydrocarbon source rock potentiality of the Sohagpur coals by integrating organic geochemical and petrographic parameters.
- To assess the coalbed methane (CBM) potential of the Sohagpur coalfield, with emphasis on adsorption behaviour in relation to maceral composition and mineral matter distribution.

This study examines the detailed paleodepositional and paleoenvironmental conditions of Sohagpur coals. Coalbed methane potential is also discussed with reference to current operable coal seams. The major finding of this study is the behaviour of carbon dioxide (CO₂) adsorption in relation to the petrographic constituents of Sohagpur coal.

By addressing these objectives, the present work provides the first systematic, multi-proxy investigation of the Sohagpur coalfield based on representative pillar samples. It establishes detailed insights into the paleoenvironmental conditions of coal formation, quantifies the hydrocarbon and CBM potential, and highlights the role of petrographic constituents in governing pore characterization and gas adsorption behaviour. The findings of this study are directly relevant for both academic understanding of Gondwana coals and the applied energy sector, where CBM and CO₂ sequestration are of increasing importance.

1.10 Assumptions of the study

This thesis is primarily based on laboratory measurements of coal petrography (maceral analysis, microlithotype analysis, reflectance), coal geochemistry (proximate and ultimate analysis), mineral chemistry and mineralogy (XRF, XRD), microstructures (SEM), pore system metrics (BET, adsorption, SAXS, MIP), and adsorption behaviour

(N₂ and CO₂). The assessment of CBM potential is therefore framed as a screening-level evaluation of storage-related attributes and pore accessibility/connectivity indicators.

1.11 Significance of the study

This study is significant as it addresses the existing gaps in detailed petrographic and geochemical characterization of the Sohagpur Coalfield, which is crucial for reconstructing Permian paleoenvironmental conditions and understanding coal formation processes. By employing a multi-analytical approach, including petrographic, geochemical, and pore structure analyses, the research will provide comprehensive insights into coal maceral composition, organic matter types, thermal maturity, and the nature of coal porosity, which directly influences Coal Bed Methane (CBM) storage and migration. Analysing pillar samples from currently operating mines will enhance understanding of reservoir quality, support efficient resource exploration and management, and promote sustainable energy development. The findings will also serve as a valuable reference for future geological, geochemical, and energy-focused research in Indian coalfields.

1.12 Organization of the thesis

The thesis is organized into seven chapters, which start from the overview of coal resources to the geology of the study area, methodology, results, discussion and conclusion of this study.

Chapter 1 provides an overview of India's coal reserves, a detailed literature review on the Sohagpur coalfield and outlines the objectives and scope of the present work.

Chapter 2 deals with the regional geology of the Sohagpur coalfield, including its geographical location, communication networks, physiography, topography, drainage, climate, vegetation, and the occurrence and distribution of coal seams.

Chapter 3 explains the methodology adopted in this research, covering the coal sampling method, petrographic investigations, geochemical analyses, and gas adsorption-pore characterization techniques.

Chapter 4 presents the detailed results of these analyses, focusing on the occurrence, distribution, and variation in petrographic and geochemical attributes, as well as findings from gas adsorption and pore-structure studies.

Chapter 5 addresses the maturity and source rock potential of the studied coals, with special emphasis on their coal bed methane potential.

Chapter 6 integrates and discusses the results, elaborating on coal genesis, multiscale pore characterization, the influence of petrographic constituents on pore structure and gas adsorption, and the industrial applicability of Sohagpur coals.

Chapter 7 summarizes the key findings and conclusions of the study and also provides recommendations for further work.

All cited references are compiled in the reference section at the end of the thesis.

Chapter:2

Geological and Stratigraphic Framework of the Sohagpur Coalfield, Madhya Pradesh, Central India

2.1 Introduction

The Gondwana coal basins represent one of the most significant repositories of Permian-age coal resources and form a critical component of the global carbon cycle during late Paleozoic–early Mesozoic time. The evolution of Gondwana coal basins is closely linked to large-scale tectonic reorganization, climatic shifts from glacial to post-glacial conditions, and changes in sedimentary environments associated with continental rifting and subsidence (Veevers, 1984; Scotese, 2001). The initiation of Gondwana sedimentation is generally attributed to Late Carboniferous–Early Permian glacio-tectonic events, marked by widespread glaciation. In the Indian subcontinent, this phase is represented by the Talchir Formation, characterized by diamictites, varved shales, and dropstones, reflecting deposition under cold, glacial to glacio-marine conditions (Casshyap & Tewari, 2009). Progressive climatic amelioration during the Early Permian led to the establishment of extensive fluvio-lacustrine environments, favouring luxuriant vegetation growth and peat accumulation, which ultimately resulted in the formation of thick coal seams within the Barakar Formation.

Tectonically, Gondwana coal basins are predominantly rift basins, formed due to extensional stresses associated with the initial fragmentation. Reactivation of Precambrian lineaments played a crucial role in basin localization, subsidence patterns, and sediment dispersal systems (Biswas, 1999). Episodic subsidence and fault-controlled basin architecture governed accommodation space creation and influenced coal seam

thickness, continuity, and quality. Syn-sedimentary tectonism also affected fluvial styles, sediment supply, and peat preservation potential (Mukhopadhyay et al., 2010).

The Sohagpur Coalfield is a significant Permian coal deposit located in Central India, serving as an integral part of the Son Valley–Rewa Gondwana basin system (Figure 2.1). Its Gondwana stratigraphy showcases a nearly complete Lower–Upper Permian coal-measure succession, which includes the Talchir, Barakar, Barren Measures, and Raniganj formations. These formations are locally capped by younger Mesozoic sequences and, in certain areas, by the Lameta Formation and Deccan Trap volcanics (Raja Rao, 1983; Milici et al., 2003; CMPDI, 2023).

The geological framework of the coalfield is significantly influenced by syn-sedimentary extension and subsequent tectonic reactivation, particularly along the E–W to ENE–WSW fault systems. One notable feature is the Bamhani–Chilpa fault, which separates the coalfield into a downthrown northern block and an upthrown southern block (Raja Rao, 1983; CMPDI, 2023; Dhanam et al., 2013). This chapter aims to outline the geological evolution, stratigraphy, distribution of coal seams, and structural framework of the Sohagpur Coalfield. This foundational understanding is vital for interpreting (i) coal petrochemistry, (ii) the paleoenvironments of peat accumulation, and (iii) the factors influencing coalbed methane (CBM) prospectivity, including deformation-driven permeability and burial/intrusion-related variations in rank (Mukhopadhyay et al., 2001; Dhanam et al., 2013; Mondal et al., 2021).

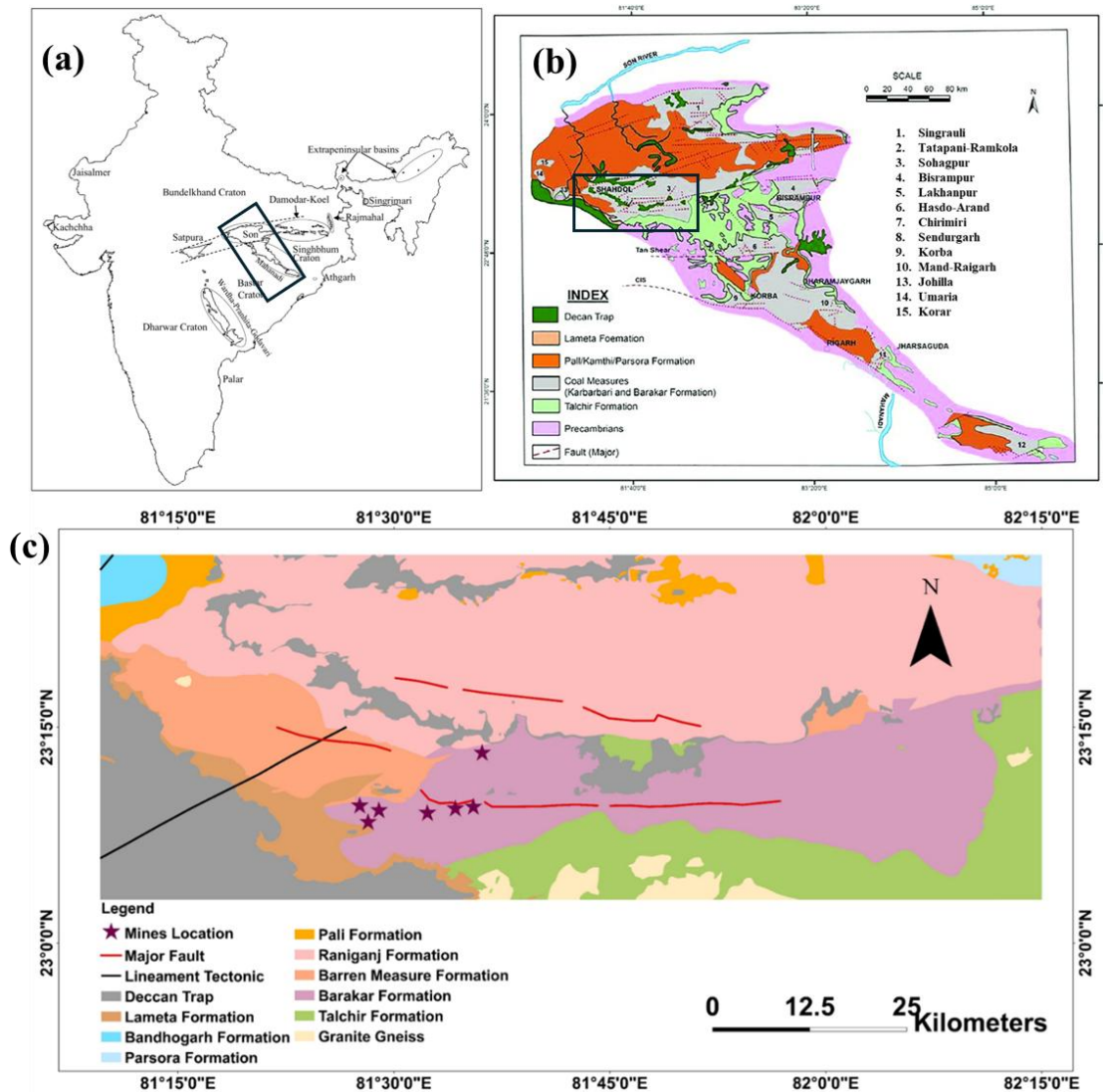


Figure 2.1 Location of the Son Mahanadi valley in the Indian Gondwana basins (a), Geology of Son valley basin (b) and location of Sohagpur coalfield within Son Valley Basin with major faults and lineaments (c).

2.2 Geological evolution of the Gondwana coal basins of India

The geology of the Gondwana basins of India has been extensively studied and described by several researchers (Fox, 1931; Navale and Saxena, 1989; Dutta, 2002). These basins are predominantly developed in the eastern and central regions of India (Figure 2.2). Nearly 99% of India's coal resources are confined within these Gondwana basins. The coal-bearing basins are generally named after prominent rivers such as the Damodar, Son, Mahanadi, and Godavari, or after linear hill ranges such as the Satpura and Rajmahal.

They typically occur in major river valleys, either as isolated units or interconnected through post-Permian strata (Mukhopadhyay et al., 2010).

Structurally, the Gondwana basins exhibit a graben or half-graben geometry and are distributed along four major linear belts:

1. Trans-Indian basin belt that includes ENE-WSW trending Satpura and Son Valley basin and E-W to WNW-ESE trending Damodar-Koel Valley Basins.
2. NNW-SSE trending Wardha-Pranhita-Godavari Valley Basin belt
3. NW-SE trending Mahanadi Valley basin belt that swerves to WNW-ESE direction in the southernmost Talcher coalfield
4. NNW-SSE trending Purnea-Rajmahal-Galsi basin belt.

Indian Gondwana basins are classic intracratonic, fault-bounded continental basins that developed predominantly under extensional tectonics along inherited Precambrian lineaments and shear zones. Sedimentation spans from the latest Carboniferous–Early Permian to the Early Cretaceous in many basins, although the coal-rich intervals are concentrated in the Permian (Veevers & Tewari, 1995; Acharyya, 2018; Mukhopadhyay, 2019).

2.2.1 Initiation: Late Paleozoic glaciation and Talchir sedimentation

The earliest Gondwana sedimentation in peninsular India begins with Talchir-type glaciogenic deposits (diamictites, varved shales, dropstone-bearing facies), representing the waning phases of the Late Paleozoic Ice Age and associated glacial–proglacial environments across Gondwana (Choudhuri et al., 2023; Tiwari, 2002).

2.2.2 Early Permian coal measures: Barakar peat accumulation under fluvial regimes

As glacial influence diminished, accommodation increased under continued extension and differential subsidence. Extensive fluvial systems (braided to meandering), floodplain mires, and backswamps created the most important coal-forming interval of the Lower Gondwana, commonly the Barakar Formation and equivalents (Raja Rao, 1983; Mukhopadhyay et al., 2001).

2.2.3 Mid-Permian reduction in peat preservation: Barren Measures

A widespread shift to more arenaceous, channel-dominated facies with reduced long-lived mire development produced the Barren Measures interval (Ironstone Shale/Barren Measures equivalents), reflecting changes in accommodation–sediment supply balance, hydrology, and/or base-level behaviour across several Gondwana basins (CMPDI, 2023).

2.2.4 Late Permian coal measures: Raniganj cyclicity and renewed coal formation

Renewed cyclic sedimentation with alternating channel, floodplain, and mire deposits characterizes the Raniganj Formation, where coal seams may be numerous but often thinner and less laterally persistent outside the Damodar Valley belt (CMPDI, 2023).

2.2.5 Post-Permian evolution: Triassic–Cretaceous sedimentation and Deccan volcanism

Gondwana sedimentation continues in many basins into the Triassic (e.g., Panchet/Pali equivalents) and younger sequences, but coal becomes scarce. Later, regional magmatism and Deccan flood basalt volcanism locally covered Gondwana successions, influencing burial, thermal maturity, and structural reactivation (Mukhopadhyay, 2019; Saxena et al., 2025).



Figure 2.2 Distribution of Gondwana basin of India (Mukhopadhyay et al., 2010)

The deposition of Gondwana sediments in India is thought to have initiated within glacially sculpted basement depressions of considerable dimensions. It has been hypothesized that these depressions may have originated from a single master basin, the remnants of which are still preserved today, fragmented due to later tectonic faulting (Mukhopadhyay et al., 2010). The presence of intra-basin faults suggests significant subsidence events, triggered by repeated fault activity, which in turn provided the necessary accommodation space for thick successions of sedimentary deposits. Furthermore, syn-sedimentary subsidence driven by these fault movements played a

critical role in the repeated accumulation of sediments (Chakraborty and Ghosh, 2008). Tectono-sedimentary studies provide crucial insights into the genesis and evolution of these basins. The Gondwana basins were primarily developed along ancient, reactivated shear zones within Proterozoic orogenic belts, which acted as structural controls. The Lower Gondwana formations, notably the Talchir and Barakar Formations, are widely interpreted as being deposited in early sag basins, reflecting tectonic quiescence and post-glacial sedimentation (Krook et al., 1986). In contrast, the Upper Gondwana formations were deposited under syn-rift conditions, associated with the progressive development of rift basins. The intra-cratonic nature of these Gondwana basins has been attributed to the reactivation of palaeo-sutures and the development of graben systems, which facilitated accommodation space for thick sedimentary packages (Casshyap and Tewari, 2009). The principal riftogenic Gondwana continental basins developed during the Permian to Jurassic, including the Narmada–Son–Damodar, Pranhita–Godavari, and Mahanadi basins. These basins exhibit a distinct tectonic configuration, converging towards the Satpura region in central India, which served as a tectonic hinge and junction of multiple rift systems.

A broad stratigraphic and structural correlation exists among these Gondwana basins, highlighting their common tectonic origin and depositional history. This correlation, depicted in Figure 2.3, illustrates the tectono-sedimentary linkage between the major Gondwana basins of India.

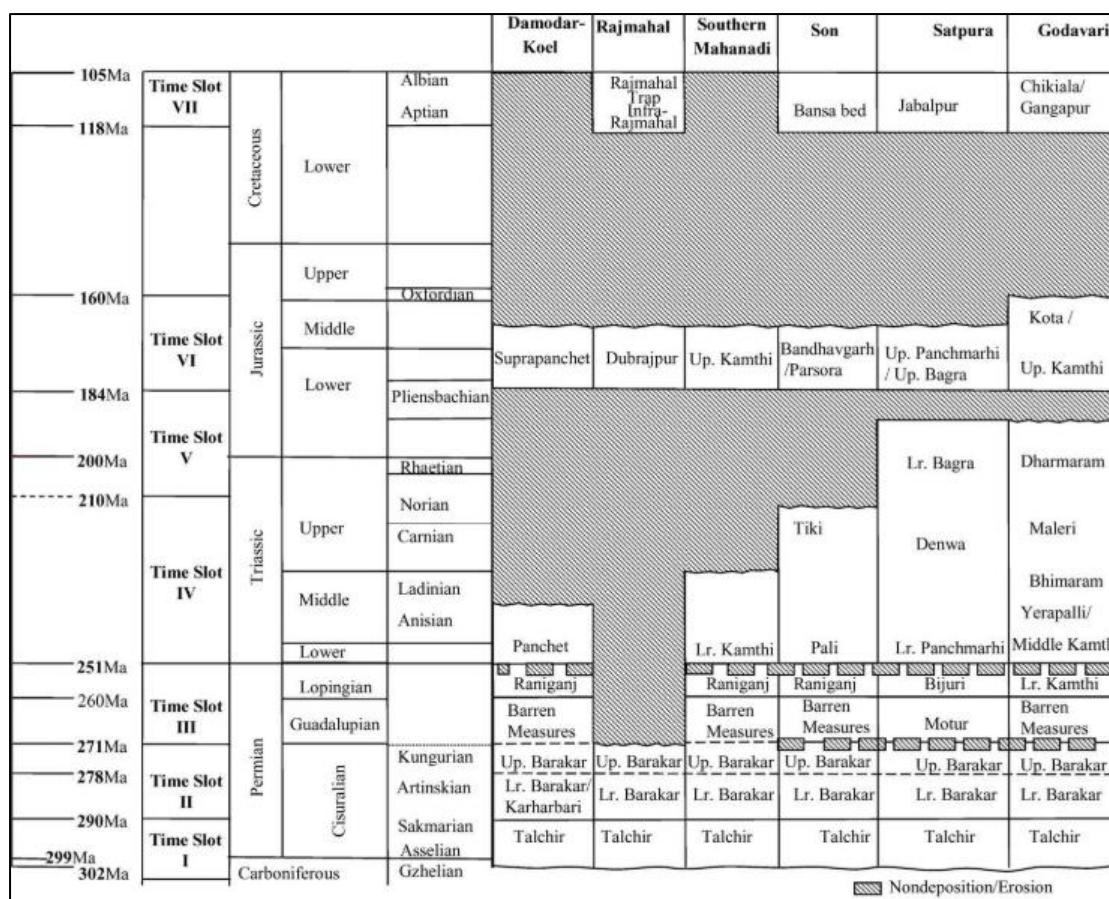


Figure 2.3 Correlation between different Gondwana basins (Mukhopadhyay et al., 2010).

2.3 Regional Geological framework of the Son Valley basin

The Son Valley Basin lies within the Proterozoic mobile belt known as the Central Indian Tectonic Zone (CITZ). This tectonic zone consists of two roughly east–west trending structural belts - the Son-Narmada mega lineament in the north and the Sausar mobile belt in the south. To the south of the CITZ lie the Singhbhum and Bastar cratons, while the Bundelkhand craton forms its northern boundary. Geologically, the CITZ in this region is bounded by the northern and southern Son-Narmada mega lineaments in the north, the Deccan Trap-covered areas in the southwest, and exposures of Precambrian rocks in the east (Figure 2.4). Towards the northwest, Gondwana sediments appear to merge into the Satpura Basin, while to the south, they extend into the Mahanadi graben. The Satpura-Son Gondwana Basin belt is bordered to the north by the Son-Narmada

South Fault (SNSF), with further basin development to the south controlled by several other major faults within the zone.

The Son Valley Basin (often treated within the Son–Mahanadi valley Gondwana basin system, including the Rewa Gondwana basin) is a major fault-bounded Gondwana basin tract of Central India, structurally influenced by regional lineaments such as the Son–Narmada system and adjacent Proterozoic tectonic fabrics (Mukhopadhyay & Bhattacharyya, 2018; Mukhopadhyay, 2019). Within this basin system, the Rewa Gondwana basin hosts multiple coalfields/sub-basins, with Sohagpur forming the central segment. Basin geometry, sediment thickness patterns, and coal seam architecture reflect syn-sedimentary faulting and intrabasinal differential subsidence (CMPDI, 2023; Dhanam et al., 2013)

The Chhotanagpur Granite Gneiss Belt, which hosts the Damodar Valley Gondwana basins, follows the same structural trend as the Sausar mobile belt. Most of the major tectonic discontinuities are confined within the CITZ, whose northern and southern limits are marked by the ENE–WSW trending Son-Narmada North Fault and the Central Indian Shear Zone, respectively. The northern boundary of the Son Valley Basin (SVB) is cut by a series of ENE–WSW and E–W trending faults parallel to the SNSF, forming the Malwa Ridge. From east to west, successive younger rock layers are truncated by different fault systems. The eastern and southern margins of the basin mainly expose normal stratigraphic contacts, while the western margin is buried beneath younger rock formations. The coal-bearing Permian strata are mostly found along the basin’s periphery. Overlying these are thick Mesozoic sequences that cover large parts of the basin’s western and central areas. The Manendragarh–Pratappur basement ridge, bounded by ENE–WSW trending faults, separates the Son Valley Basin from the Hasdo–Arand Basin to the south.

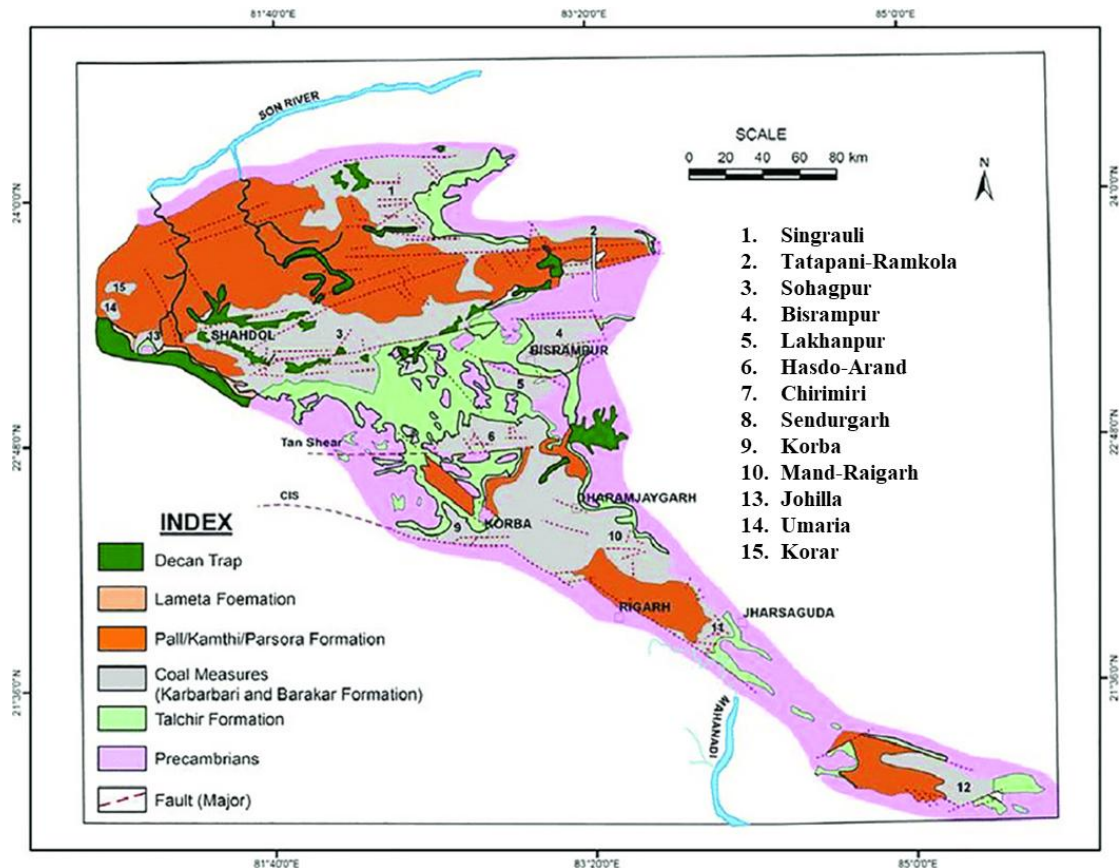


Figure 2.4 Geological map of Son-Mahanadi Valley basin (Mukhopadhyay & Bhattacharya 2018).

The Son Valley Basin (SVB) is asymmetrical in both its longitudinal and transverse profiles. It is a composite basin comprising several distinct depocenters (or sub-basins) of varying sizes. The basin-fill strata exhibit a gentle dip of less than 5° , and they are dissected by multiple faults that follow the structural trends of the underlying basement rocks. A prominent set of ENE–WSW trending faults runs through the middle of the SVB, effectively dividing it into northern and southern sectors (Raja Rao, 1983; Agarwal et al., 1993). Based on this structural divide, the basin is often referred to as the North Rewa and South Rewa basins.

The northern portion is represented by the Singrauli Basin, which includes the Moher Sub-basin in the east and the Main Sub-basin in the west. These are separated by a fault-controlled NW–SE trending paleoridge. The southern part of the SVB is also subdivided into several sub-basins, with major coal-bearing and non-coal-bearing sequences broadly

outlining the main structural units along the basin margins. Among the well-known sub-basins are Tatapani–Ramkola in the east and Umaria in the west. Along the southern margin of the SVB lie the Jhilimili, Sonhat, Sohagpur, and Johilla Sub-basins, collectively forming the Sohagpur Basin. Several shallow synclinal structures occur in the southern part of the basin: (a) a NE–SW trending syncline in the Umaria Sub-basin to the west; (b) synclines near Ramnagar–Bijuri and Amanand areas in the eastern Sohagpur Basin; (c) an E–W trending syncline in the Tatapani–Ramkola Basin; and (d) a broad basin-like structure with centripetal dips in the Bisrampur Sub-basin. These features are attributed either to differential fault displacement (unequal throws of paired faults) or to localized compressional forces within fault-bounded blocks. In the Chirimiri Sub-basin, a broad anticlinal–synclinal roll is a characteristic structural feature, which is likely a response to irregularities in the underlying basement topography (Raja Rao, 1983).

2.4 Regional Geological framework of the Sohagpur coalfield

Sohagpur Coalfield is located in the Sohagpur sub-basin, a part of the west-central part of the Son-Valley basin belt. The Late Permian Raniganj strata span a large portion of the Sohagpur Subbasin, while the rectilinear Barakar Formation outcrops on the fault's upthrown side and truncated wedges of the Barren Measures (Early to Late Permian) occur on both sides of the Bamhani-Chilpa Fault. In the northern end of the subbasin, the Triassic Pali Formation overlaps the Raniganj Formation. At the northwest extremity of the subbasin, the Parsora Formation is visible. The Pali Formation has been covered beneath the Parsora layers (Late Triassic to Jurassic), which exhibit modest angular unconformity in certain areas and overlap with the Barren Measures and the Raniganj. The Talchir Formation, an Early Permian formation, is primarily found in the subbasin's eastern and southern edges. The Gondwana strata are overlain by Late Cretaceous Lameta

beds and Deccan Traps in the southwest. The Sohagpur Subbasin's general structure is that of a monocline that has been divided and altered by intra-basinal extensional faults. The strata generally dip from 3 to 5 degrees north to north-west; occasionally, strata near faults steepen to a maximum of 30 degrees (Mukhopadhyay, 2019).

2.4.1 Basement and basin margins

The Gondwana sediments of the Son Valley–Rewa basin rest unconformably over Precambrian crystalline/metamorphic basement and Proterozoic successions exposed around basin margins. These older terranes provide provenance for Gondwana sandstones and control fault localization through reactivation of basement discontinuities (Acharyya, 2018; Mukhopadhyay & Bhattacharyya, 2018).

2.4.2 Basin architecture and lineament control

The regional tectonic grain is dominated by E–W to ENE–WSW and subordinate NE–SW/NW–SE fault sets. The E–W faults are particularly significant in controlling intrabasinal compartmentalization, depocenter migration, and coal seam continuity (CMPDI, 2023).

2.5 Stratigraphy of the Sohagpur coalfield

The Sohagpur Coalfield, located in the northeastern part of Madhya Pradesh, preserves a well-developed Gondwana stratigraphic succession resting unconformably over the Precambrian crystalline basement. The stratigraphic sequence records multiple phases of sedimentation, tectonic activity, and volcanism ranging in age from the Precambrian to the Early Eocene. The basement is constituted by the Surguja Crystalline Complex, comprising granite and gneiss of Precambrian age. This basement is separated from the overlying Gondwana sediments by a regional unconformity, indicating a prolonged period of erosion prior to Gondwana basin development. The Gondwana sedimentation

commenced with the deposition of the Talchir Formation (Early Permian), which is characterized by pebbly sandstones with an argillaceous matrix, along with shale and claystone. These litho-units represent deposition under glacial to glacio-fluvial conditions during the initial phase of Gondwana basin evolution. Conformably overlying the Talchir Formation is the Barakar Formation (Early Permian), consisting predominantly of medium- to coarse-grained sandstones alternating with siltstone, grey claystone, and shale, along with thick and laterally persistent coal seams. This formation represents sedimentation in fluvio-lacustrine environments under relatively warm and humid climatic conditions and constitutes the principal coal-bearing horizon of the Sohagpur Coalfield. The Barakar Formation is succeeded, after a local disconformity, by the Barren Measures (Late Permian). This unit is dominated by shale, siltstone, and claystone interbedded with arkosic sandstone and is marked by the virtual absence of workable coal seams, indicating unfavourable conditions for peat accumulation during this phase. Another local disconformity separates the Barren Measures from the overlying Raniganj Formation (Late Permian). The Raniganj Formation comprises coal seams, grey claystone, shale, and cross-bedded feldspathic sandstones, reflecting deposition in a humid fluvial regime with renewed coal-forming conditions. The Lower Gondwana succession is overlain by Upper Gondwana strata, beginning with the Pali Formation (Late Permian–Early Triassic). This formation consists of immature sandstones with variable clay matrix content, suggesting deposition under high-energy fluvial conditions and increased tectonic activity. The Parsora Formation (Late Triassic–Early Jurassic) conformably overlies the Pali Formation and is characterized by mature, well-sorted arenites interbedded with distinctive lavender-coloured clay beds, indicating sedimentation in relatively stable fluvial to lacustrine environments. The Gondwana succession is unconformably overlain by the Lameta Beds (Late Cretaceous), comprising

sandy limestone and calcareous sandstone deposited in fluvio-marine to shallow marine settings during the Late Cretaceous transgression. The entire sedimentary sequence is finally capped by the Deccan Trap volcanics (Late Cretaceous–Early Eocene), represented by basaltic lava flows and dolerite dykes, marking extensive volcanic activity associated with the breakup of Gondwana.

The generalised stratigraphic succession is presented in Table 2.1, and the geological map of Sohagpur coalfield is shown in Figure 2.5.

Table 2.1 Generalised stratigraphic succession of the entire Sohagpur coalfield (after Mondal et al. 2020).

Formation	Lithological details	Age
Deccan Trap	Basic flow and dolerite dykes	Early Eocene-Late cretaceous
Lameta Beds	Sandy limestone and Calcareous sandstone	Late Cretaceous
Parsora	Mature and well-sorted arenite mixed with lavender color clay beds.	Early Jurassic-Late Triassic
Pali	Varying amounts of clay matrix in immature sandstone.	Early Triassic-Late Permian
Raniganj	Coal, grey claystone and shale alternate with cross-bedded Feldspathic sandstone.	Late Permian
..... Local disconformity		
Barren Measures	Shale, siltstone, and claystone are mixed with Arkosic sandstone.	Late Permian
..... Local disconformity		
Barakar	Sandstone alternating with siltstone, grey claystone and shale, and thick coal seams.	Early Permian
Talchir	Pebbly sandstone with argillaceous matrix, shale, and claystone.	Early Permian
..... Unconformity		
Surguja crystalline complex	Granite and Gneiss	Precambrian

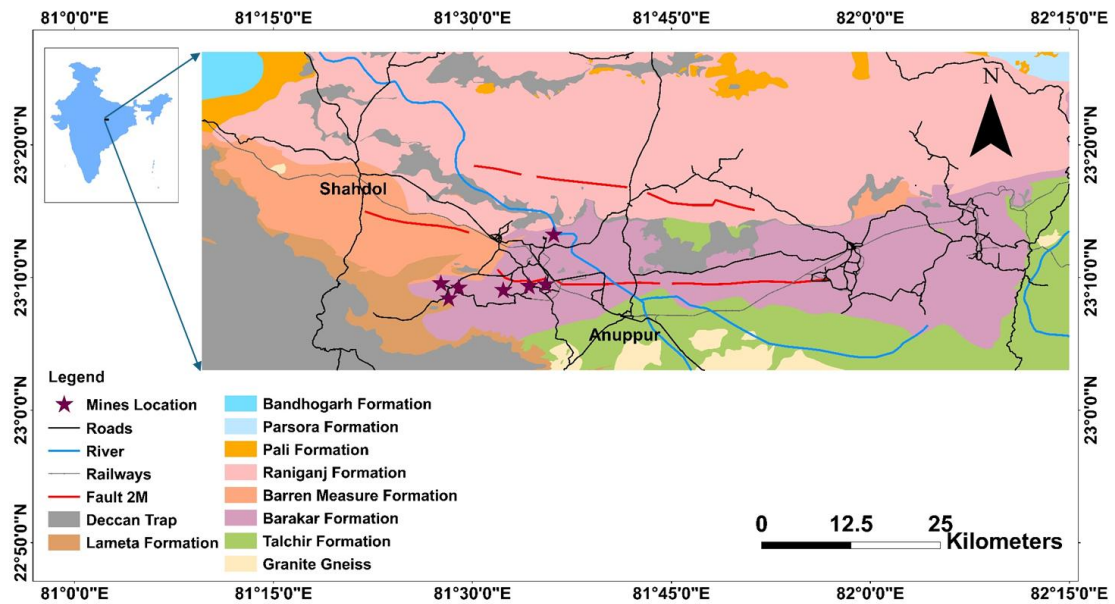


Figure 2.5 Geological map of Sohagpur coalfield.

2.5.1 Precambrian basement

The Precambrian basement rocks are mainly composed of Granite Gneisses and known as the Surguja crystalline complex. This basement is unconformably overlain by the Talchir formation (Dhanam et al., 2013; Mondal et al., 2021).

2.5.2 Talchir Formation

The Talchir Formation constitutes the basal Gondwana unit. It is characterized by glaciogenic-to-proglacial deposits commonly greenish shales, sandstones, and diamictites with scattered clasts reflecting deposition during the waning stages of Gondwana glaciation (Choudhuri et al., 2023; Tiwari, 2002).

Talchir formation of Upper Carboniferous to Lower Permian, having a thickness of about 120 meters and forms low-lying plains which include the Medium to coarse-grained pebbly sandstone with argillaceous matrix, angular pebbles of Quartz, rock fragments, claystone and shale.

Depositional Interpretation: The Talchir in this regional sector is interpreted as recording glacial to glaciofluvial/glaciolacustrine conditions, transitioning upward to more typical fluvial systems as climate ameliorated and ice influence waned (Choudhuri et al., 2023).

2.5.3 Barakar Formation

The Barakar Formation, Lower Permian age, has a rolling topography and comprises shale, sandstone and coal seams. This Formation hosts the principal economic coal measures in Sohagpur. Lithologically, it comprises alternating sandstones (often cross-bedded, gritty to pebbly), siltstone/shale intervals, carbonaceous shale/fire clay horizons, and multiple coal seams consistent with fluvial channel–floodplain and mire systems (Raja Rao, 1983).

The formation is separated into three sections, the central member being the thickest, and the whole formation is roughly 265 meters thick. The bottom part lacks coal seams and is composed of feldspathic garnetiferous sandstone, siltstone, and shale with a greyish-white colour. The middle member has thick workable coal seams in the lower part and cross-bedded garnet-bedded feldspathic sandstones. The top unit is composed of ferruginous sandstones, shales, and siltstones (Pareek, 1987).

Depositional Interpretation: The Barakar is widely interpreted as dominantly continental fluvial deposition with repetitive fining-upward cycles and peat accumulation in floodplain/backswamp settings; broader Gondwana-scale studies also discuss possible episodic marine influence in some basins, but Sohagpur coal measures are typically treated within a continental basin framework (Veevers & Tewari, 1995; Mukhopadhyay et al., 2001).

2.5.4 Barren Measures Formation

The Barren Measures Formation is separated through a local discontinuity and devoid of coal seams. The thickness of barren measures sedimentary deposits is approximately 250 meters and having Medium to coarse-grained arkosic, immature and poorly sorted sandstone interbedded with siltstone, shale and variegated claystone.

Weathering signature: Weathered exposures and residual soils over Barren Measures are commonly enriched in iron oxide, attributed to sideritic/chlorotic matrix components and secondary precipitation along joints and bedding planes (CMPDI, 2023).

2.5.5 Raniganj Formation

Raniganj Formation of the Late Permian is again separated by a local discontinuity similar to Barren measures and has an average thickness of 550 meters, along with impure sandstone, the Raniganj Formation has thin, unsustainable coal seams that are locally scattered throughout the region. The lamination, which is dominated by the tidally influenced zones, is encased in these sandstone beds.

Coal seams in the Raniganj of Sohagpur are generally thinner (often <1 m) and less laterally continuous than the major Barakar seams, reflecting channel–overbank alternations and potentially more frequent avulsion and higher clastic influx conditions (CMPDI, 2023).

2.5.6 Pali Formation

Over 250 meters thick, the Pali Formation (Triassic) sits above the Raniganj formation. The Lower Pali coalfield is composed of coarse-grained sandstones, chocolate and grey shales, with an arenaceous facies in the eastern half of the coalfield and an argillaceous facies in the western part. In the eastern portion of the coalfield, in the Bahera-band area,

carbonaceous shales have been found. Coal-bearing medium- to fine-grained sandstones, shales, and carbonaceous rocks make up the Middle Pali Formation.

2.5.7 Parsora Formation

The upper Triassic aged Parsora Formation, which is found in the northern region of the coalfield, is made up of shales and coarse-grained to pebbly ferruginous sandstones. The approximate thickness of the Parsora formation is 100 meters.

2.5.8 Lameta Beds

The Upper Cretaceous Lameta Beds, having a thickness of 25 meters, are composed of poorly consolidated greenish and reddish sandstones and shales with nodules of limestone at the top.

2.5.9 Deccan Trap

Deccan Trap of the Early Eocene to Late Cretaceous, having a thickness of 100 meters, includes the lithology of Dolerite dykes and basic flows.

2.6 Structural framework and deformation of the Sohagpur coalfield

The structural framework of the Sohagpur Coalfield is broadly that of an extensional basin with low regional dips but pronounced fault control on stratigraphic thickness, seam continuity, and depth-to-coal. The strata general strike WNW–ESE and dip gently (often a few degrees) to the north, though dips locally steepen near faults (Raja Rao, 1983; Milici et al., 2003).

High-resolution seismic imaging and exploration studies confirm the importance of syn-sedimentary subsidence and faulting as first-order controls on basin fill architecture in Sohagpur (Dhanam et al., 2013).

The present-day structural configuration of the Sohagpur Coalfield is the result of a prolonged and multi-phase tectonic evolution that governed basin formation, sedimentation, and post-depositional deformation. The coalfield developed as a part of the South Rewa Basin under an overall extensional tectonic regime during the Early Permian, which facilitated the accumulation of thick Gondwana sediments, particularly the coal-bearing Barakar Formation. Basement-controlled tectonics played a dominant role in shaping the basin architecture and coal distribution.

2.6.1 Fault systems

The fault system of the Sohagpur Coalfield is one of its most prominent structural elements. The coalfield is dissected by several east–west to ENE–WSW trending normal faults, among which the Bamhani–Chilpi Fault is the most significant.

The most prominent structural feature is the E–W/ENE–WSW fault system, of which the Bamhani–Chilpi (Bamhani–Chilpa) fault is the most important intrabasinal fault traversing the coalfield. It dips north and downthrows the northern block by >400 m at places, separating the coalfield into North(downthrown) and South (upthrown) sectors (CMPDI, 2023). In addition to the major E–W fault set, additional faults occur with NW–SE and NE–SW trends (lower frequency), likely related to broader regional lineament interactions and subsequent structural adjustments (CMPDI, 2023).

This major regional fault divides the coalfield into North Sohagpur and South Sohagpur sectors and exhibits a substantial vertical displacement, bringing Gondwana sediments into contact with older Precambrian rocks in places. The fault acted as a syn-sedimentary structure, controlling basin subsidence, sediment thickness, and facies variation. Several subsidiary faults/lineaments parallel and oblique to the main fault further compartmentalize the coalfield into smaller structural blocks, influencing seam

continuity and mine planning (Raja Rao, 1983). Major faults attributes are presented in Table 2.2, and the fault and lineament map is shown in Figure 2.6.

Local fault throws in blocks: Detailed block-level investigations record smaller faults with throws from ~0 to 70 m, demonstrating local compartmentalization of seams and depth variation even within individual exploration blocks (CMPDI,2023).

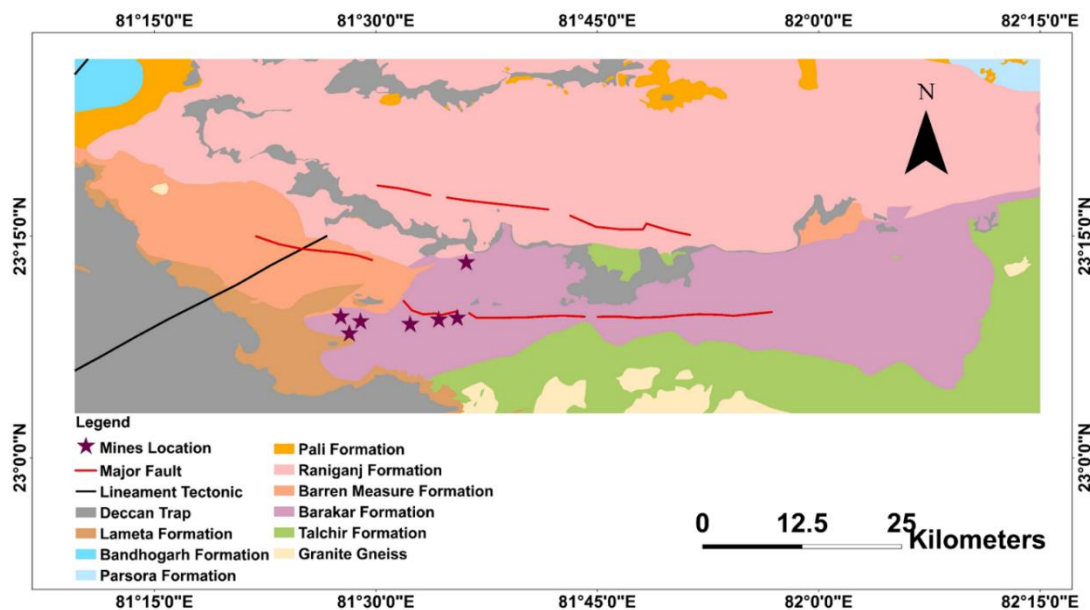


Figure 2.6 Major fault and lineament map of Sohagpur coalfield.

Table 2.2 Major faults system attributes.

Fault set	Typical trend	Structural role	Indicative throw	Coalfield-scale significance
Major intrabasinal fault	E–W /ENE–WSW	Basin segmentation (North downthrown vs. South upthrown)	>400 m(locally)	Controls depth-to-coal, preservation, and juxtaposition of formations (CMPDI,2023).
Secondary faults	E–W /ENE–WSW	Local offsets; seam discontinuities	0-70m (reported in blocks)	Compartmentalizes seams; affects mine planning and correlation (CMPDI,2023).
Cross faults	NW–SE, NE–SW	Local transfer structures	variable	May displace dykes/fault segments; local deformation patterns (CMPDI, 2023).

2.6.2 Folding and Jointing

While large-scale folding is not typically dominant, gentle warping and drag effects adjacent to major faults are reported, and jointing/cleating is pervasive within coal

measures. Joint sets often serve as pathways for fluid migration and may be preferentially mineralized or reactivated in later deformation phases. CMPDI notes visible drag on beds at places along the major fault, indicating localized strain and shear-related deformation superimposed on gentle regional dips (CMPDI, 2023).

Folding within the Sohagpur Coalfield is generally mild, reflecting the dominance of extensional rather than compressional tectonics. The Gondwana strata typically exhibit gentle homoclinal dips of 1° – 4° , mostly towards the north (Raja Rao, 1987; Agnihotri et al., 2016). However, localized warping, shallow synclines, and anticlines are observed near major fault zones, indicating minor compressional adjustments or reactivation of older basement lineaments during later tectonic phases. These folds are broad and open, with limited impact on coal rank but notable influence on seam depth and structural continuity. At the coal scale, cleat development (face and butt cleats) is strongly tied to coal rank, tectonic stress history, and proximity to faults/dykes; these relationships are critical for CBM permeability architecture (Dhanam et al., 2013; Mondal et al., 2021).

2.6.3 Tectonic Evolution

The tectonic evolution of Sohagpur can be generalized into five major events:

1. Basement-controlled rift initiation and early subsidence (Talchir).
2. Continued Permian extension with major accommodation development and peat-forming floodplain systems (Barakar).
3. Mid-Permian facies shift toward channelized arenaceous systems (Barren Measures).
4. Late Permian cyclic sedimentation with thinner coal horizons (Raniganj).

5. Post-Permian reactivation and igneous events, including dyke intrusions along fault planes and later burial/thermal overprint in some segments (Mukhopadhyay et al., 2001; Dhanam et al., 2013; CMPDI, 2023).

2.6.4 Correlation between regional tectonics and coal seam deformation

Regional tectonics influence coal seam deformation in Sohagpur through three principal mechanisms:

1. Syn-sedimentary faulting and differential subsidence: Fault-controlled depocenters produce lateral thickness variations in formations (notably Barakar and Barren Measures) and influence mine longevity and seam splitting/stacking (CMPDI, 2023; Dhanam et al., 2013).
2. Post-depositional fault reactivation: Later movement offsets seams, creates local steepening of dip near fault zones, and controls juxtaposition of formations (e.g., Barakar and Raniganj across major faults), complicating correlation and mining layouts (Raja Rao, 1983; CMPDI, 2023).
3. Dyke emplacement along structural planes: Intrusive bodies commonly exploit fault/joint networks, producing localized thermal alteration, fracture intensification and changes in coal properties (CMPDI, 2023).

2.6.5 Implication of deformation on coal properties

Deformation impacts coal properties relevant to petrochemistry and CBM potential by:

- Rank/thermal maturity variation: Differential burial (downthrown blocks) and igneous intrusion can raise rank locally and alter volatile matter, and reflectance tends (Mukhopadhyay, 2019; Mondal et al., 2021).
- Cleat and fracture permeability: Fault damage zones and joint networks enhance permeability pathways, whereas clay gouge, mineralization, or stress colure may

reduce effective permeability in places, making structure a key control on CBM productivity (Dhanam et al., 2013; Mondal et al., 2021).

- Ash yield and mineral matter distribution: Structural reworking and proximity to intrusive may influence mineralization (e.g., carbonates/iron oxides) and ash chemistry, relevant to utilization and environmental behaviour (Pareek, 1987).

2.7 Location and communication of the study area

The Sohagpur Coalfield is one of the most significant coalfields of central India, forming a part of the Son Valley Basin. It covers an estimated area of ~3000 km² (Mondal et al., 2020) and is geographically bounded between 23°05'–23°30'N latitude and 81°13'–82°12'E longitude. The coalfield lies in the western-central portion of Madhya Pradesh and plays an important role in the energy sector due to its strategic location and resource potential.

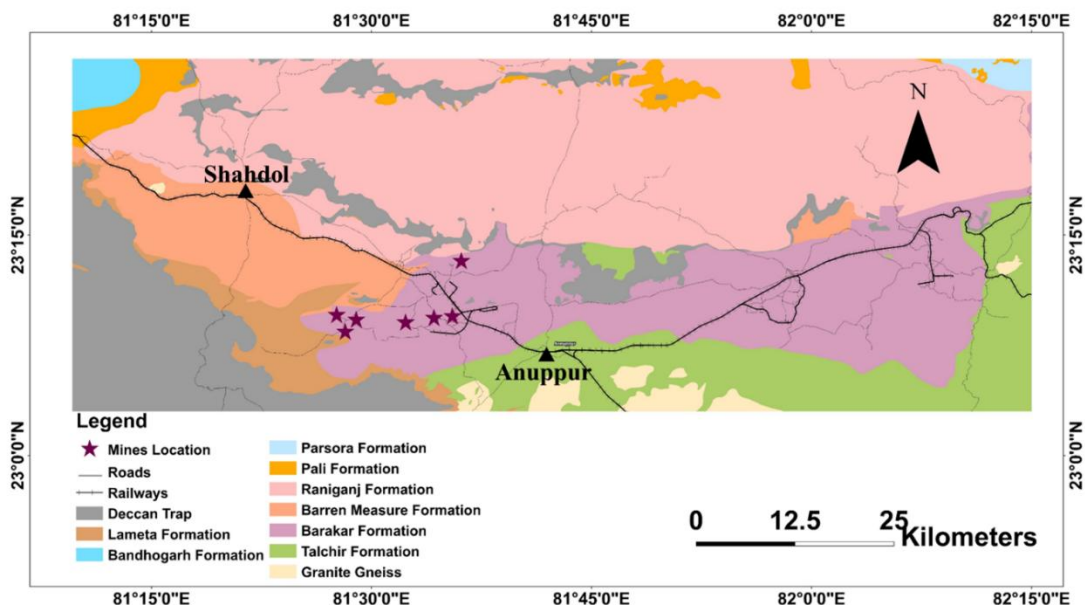


Figure 2.7 Communication map of the Sohagpur coalfield.

The area is well-connected by transportation networks, which greatly facilitates coal mining and allied industrial activities as shown in Figure 2.7. The Anuppur Junction, a major railway station falling under the Bilaspur Division of the Southeast Central Railway Zone, serves as the nearest railway hub. This junction connects the coalfield to

several industrial centres and power plants within central and eastern India. In addition, the coalfield is accessible via a network of state and national highways, linking it with nearby towns and cities. Among them, Burhar, Dhanpuri, and Amalai are the closest urban centres, providing logistical and workforce support to mining operations.

2.8 Physiography

The lithological contrasts of the different formations control the landform in the Sohagpur coalfield. The Talchir rocks have formed a low-lying plain with an average altitude of 450m to 500m above sea level. The area to the north rises to an elevation of over 1000m with successive escarpments (Raja Rao, 1983). The Barakar strata, with their undulatory to low dips, have given rise to a featureless rolling topography. However, the Barakar sandstone stands out prominently against the surrounding plains whenever they are capped by basic sills. East of Singara, one such prominent ridge is noted. The dolerite, a common feature of this coalfield, forms a rugged to hilly topography. In contrast to the featureless topography of the areas where Lower Gondwana strata occur, the Upper Gondwana rocks have prominent ridges. They constitute the prominent plateau to the north. This plateau joins with the Sonhat plateau to the east (Pareek, 1987; Agnihotri et al., 2016).

The Son River, with a north-westerly flow, is the main drainage channel of the region. Several streams originate in the high trappean region in the south and join the Son. These north-flowing streams include Nargara, Sarpa, Bagiha, Bakan, Suthna, Tipon, etc. The Kewai river originating in the Supra Barakar plateau of the Sonhat Coalfield, forms the main drainage in the eastern part of the coalfield. The easternmost part of the coalfield is also drained by the Jiria and Kulharia nalas, which ultimately discharge into the Hasdo, which flows close by (Raja Rao, 1983; CMPDI, 2023).

2.9 Topography and drainage

Son River is the main river that flows through this coalfield. Son River, also spelled Sone River, is a perennial river located in central India. It originates near Amarkantak Hill in Pendra (Gaurela-Pendra-Marwahi district), Chhattisgarh and finally merges with the Ganges River near Maner in Patna, Bihar (Raja Rao, 1983). The important tributaries of the Son River are Tipan, Chandas and Bakan, which flow in a north-west direction with dendritic pattern. The topography and drainage map of this coalfield is shown in Figure 2.8.

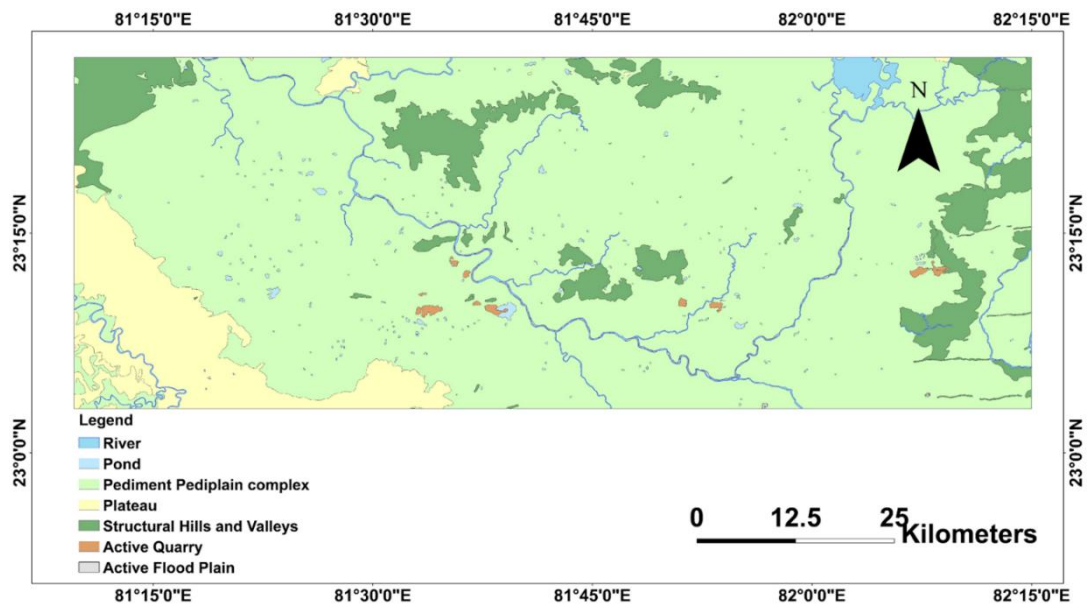


Figure 2.8 Topography and drainage map of Sohagpur coalfield.

2.10 Climate

The rainy season may range from June to October. June is the hottest month, and the temperature in January remains the lowest temperature. The Minimum temperature ranges from 7°C -10°C, while in summer maximum temperature shoots up to around 40°C - 46°C. The annual rainfall is approximately 110 cm (Raja Rao, 1983; CMPDI, 2023).

2.11 Vegetation

The area has sparse vegetal cover, and the major part is under cultivation. Thick vegetation is present in the vicinity of the Son River and on the Upper Gondwana plateau to the north. The forest areas have a large population of Sal, while the other trees are of Mahua, Palas, etc (Raja Rao, 1983).

2.12 Geological settings of Sohagpur coalfields

The Sohagpur basin is frequently described as a structurally simple but fault-dominated Gondwana basin segment, internally organized into multiple sub-basinal compartments. CMPDI identifies three well-defined sub-basin structures in the southern (Lower Sohagpur) sector: Jhagrakhand (east), Jamuna–Kotma (central), and Burhar–Amlai (west) (CMPDI, 2023).

A major intrabasinal E–W fault divides the coalfield into North Sohagpur(downthrown) where Raniganj and Barakar coal measures are inferred to occur under thicker cover, and South Sohagpur (upthrown), where Barakar coal measures are shallower and extensively mined (CMPDI, 2023).In the southwestern parts, the Lameta Formation and Deccan Traps may overlie Gondwana strata, and coal measure boundaries under trap cover remain less constrained without deep drilling and seismic control (CMPDI, 2023).

2.13 Comparative Geological Attributes of Coalfields in Son Valley

Within the broader Son Valley basin system, coalfields such as Sohagpur and Singrauli share the Gondwana stratigraphic motif but differ in structural style, thickness patterns, and coal seam continuity.

These coalfields, though developed within a common tectono-sedimentary framework, display notable variations in stratigraphy, coal seam characteristics, and quality, reflecting

differences in depositional environment and structural evolution. A comparative assessment of their geological attributes provides insights into the controls governing coal formation and distribution in the Son-Mahanadi Basin. Geologically, the Son Valley forms part of the Son-Mahanadi Gondwana Basin, which developed as a result of extensional tectonics during the Permian period. The coal-bearing sequences belong predominantly to the Lower Gondwana Supergroup, especially the Barakar Formation, which hosts the principal coal seams. These Gondwana sediments rest unconformably over Precambrian crystalline basement rocks and comprise cyclic alternations of sandstone, shale, and coal, indicative of fluvial to fluviodeltaic depositional settings (Raja Rao, 1983; Kishor et al., 2025c).

The Singrauli Coalfield is the largest and most extensively studied coalfield in the Son Valley. It exhibits a well-developed stratigraphic succession from the Talchir Formation at the base to the Raniganj Formation at the top (Raja Rao, 1983; Gopinathan et al., 2024). Coal seams are thick, laterally persistent, and mainly confined to the Barakar Formation. The exceptional thickness of certain seams suggests prolonged peat accumulation under stable subsiding conditions. The coal is predominantly non-coking with moderate to high ash content, making it suitable mainly for thermal power generation (Gopinathan et al., 2024). In contrast, the Sohagpur Coalfield displays greater structural and lithological variability. It is subdivided into several blocks separated by faults, notably the Bamhani–Chilpa fault, which has significantly influenced coal seam distribution and quality. While most seams occur within the Barakar Formation, variations in rank and coking properties are observed across structural domains. Notably, limited occurrences of coking to semi-coking coal in the northern part distinguish Sohagpur from other Son Valley coalfields (Mukhopadhyay et al., 2010). This heterogeneity reflects fluctuating depositional environments and differential tectonic subsidence.

2.13.1 Stratigraphy and seam architecture

- Sohagpur: Thick Barakar coal measures with multiple seams concentrated in the upper member; Raniganj may be thick but often contains thinner seams (CMPDI, 2023).
- Singrauli: Borehole-based block reports document Raniganj facies with carbonaceous/argillaceous richness in parts and variable thickness; seam development can be block-specific, reflecting local basin controls.

2.13.2 Structural controls

- Sohagpur is strongly compartmentalized by the Bamhani–Chilpi fault (>400 m throw locally), producing a clear north–south structural partitioning and deeper coal measures in the north (CMPDI, 2023).
- Son Valley basin syntheses emphasize broad fault patterns across Rewa basin (multiple named faults), indicating similar extensional segmentation across coalfields but with different dominant fault geometries and mining exposures (Mukhopadhyay & Bhattacharyya, 2018).

2.13.3 Implications for rank and CBM

Thermal and permeability conditions vary across Son Valley coalfields depending on burial, intrusion history, and fault damage-zone development; therefore, CBM prospectivity and coal utilization behaviour may differ even where stratigraphy appears similar (Mondal et al., 2021; Mukhopadhyay, 2019).

2.14 Significance of the geological setup to the present study

The geological setup of the Sohagpur Coalfield, Son Valley, Central India, is fundamental to the interpretation of this study, which deals with the paleoenvironments and CBM potential of this coalfield. The coalfield forms part of the Son–Mahanadi Gondwana

Basin, developed during the Permian as a result of extensional tectonics associated with the fragmentation of Gondwanaland. This tectono-sedimentary framework-controlled basin subsidence, sediment supply, and accommodation space, directly influencing peat accumulation and coal formation. Stratigraphically, the Sohagpur Coalfield is dominated by Lower Gondwana successions, with economically significant coal seams occurring within the Barakar Formation. The Barakar sediments represent deposition in fluvio-deltaic to swamp-dominated environments under fluctuating hydrological regimes. Such depositional conditions favoured repeated cycles of peat formation, burial, and preservation, which are reflected in the vertical and lateral variability of coal seams. The geological setting thus provides a critical context for understanding variations in coal rank, maceral assemblages, and elemental composition addressed in the present petrochemical study.

The basin architecture and paleogeography exerted strong control on the nature of organic matter and mineral matter input. Periodic clastic influx from surrounding uplands influenced ash yield and the distribution of major and trace elements in coal. These features are essential for reconstructing paleoenvironmental parameters such as redox conditions, water table fluctuations, and climatic regime during the Permian, which form a key objective of the present study.

Structurally, the coalfield is characterized by gentle folding and faulting associated with Gondwana tectonism. These structural elements influenced coal seam thickness, continuity, and burial depth, thereby affecting coalification and thermal maturity. Such geological controls are critical for assessing CBM potential, as methane generation, storage, and migration are strongly dependent on coal rank, permeability, and structural integrity of the seams.

2.15 Coal seam distribution and characteristics

Coal in Sohagpur occurs primarily within the Barakar Formation, especially its upper member, where multiple seams are regionally distributed and constitute the chief mining targets (Raja Rao, 1983; CMPDI, 2023; Milici et al., 2003).

The Sohagpur coalfield features a massive thickness of Gondwana sediments, and the coal seams are a part of these sediments as shown in Figure 2.9. There are currently 5 coal seams in mineable form. Table 2.3 shows the presence of coal seams and their respective coal mine.

2.15.1 Barakar Seams

CMPDI documentation indicates a multi-seam architecture, including regionally distributed seams (commonly referenced as Seams I–V) and local seams in some blocks. The upper member contains the principal economic beds, whereas the lower member contains no coal beds, according to the cited description (CMPDI, 2023).

2.15.2 Raniganj Seams

Raniganj coal seams are typically thinner and less continuous than those in Barakar, and the unit is often recognised more for its cyclic sedimentation and numerous carbonaceous horizons than for thick, laterally persistent mining seams in Sohagpur (CMPDI, 2023).

2.15.3 Quality and rank variability

Coal quality varies laterally and vertically due to differences in peat environment, clastic dilution, burial depth, and structural/igneous influences. Regional syntheses and basin studies emphasize that tectonics and sedimentary environment jointly controlled peat accumulation and coal measures development in Sohagpur (Mukhopadhyay et al., 2001; Pareek, 1987).

Table 2.3 Name and nature of coal mine and their respective coal seams in mineable form in the Sohagpur coalfield.

Name of Coal Mine	Nature of coal mine	Name of the respective coal seam
Amalai	Open cast mine	Burhar VI Top
Sharda	Open cast mine	Burhar IV
Dhanpuri	Open cast mine	Burhar VI Top
Khairaha	Underground mine	Burhar VI Bottom Burhar VII Top
Damini	Underground mine	Burhar V Burhar VI Bottom
Bangwar	Underground mine	Burhar VII Top
Rajendra	Underground mine	Burhar VI Bottom

Characteristics of the Coal seams of the Sohagpur coalfield are described as follows:

Burhar IV seam- Burhar IV seam is the seam having a thickness of approximately 1-1.5 meters and occurs currently in the mineable form of Sharda coal mine.

Burhar V seam- Burhar V seam is the seam that occurs in the Damini underground coal mine and has a thickness of approximately 2-3 meters.

Burhar VI Top seam- Burhar VI Top seam occurs in the Dhanpuri as well as Amalai open cast mine, the thickness of the coal seam varies between 4 to 9 meters.

Burhar VI Bottom seam- Burhar VI Bottom seam occurs in the Khairaha Underground mine as well Damini and Rajendra underground mine. The thickness of this coal seam approximately ranges from 1.2 to 4 meters.

Burhar VII Top seam- Burhar VII Top seam occurs in the Khairaha as well as Bangwar Underground coal mine. The thickness of the coal seam is approximately 3 meters.



Figure 2.9 Field photograph showing an Incline (passage connecting to the underground coal reserve) of an underground mine and open caste mine from where the samples have been collected.

2.16 Previous geological investigations

Geological understanding of Sohagpur has evolved through phased mapping, exploration drilling, coal petrography/chemistry studies and, more recently, geophysical studies.

1. Regional stratigraphic syntheses and coalfield compilations: The Gondwana coalfields framework, including Sohagpur and neighbouring coalfields, has been consolidated through Geological Survey of India compilations and coalfield volumes (Raja Rao, 1983).
2. Coal petrography and geochemistry: Detailed coal characterization in Sohagpur, including petrographic and chemical/trace-element composition, is documented by Pareek (1987), forming a key baseline for coal quality and depositional interpretations.
3. Tectonics–sedimentation linkage: Mukhopadhyay et al. (2001) explicitly integrate eustasy, climate, tectonics, and sedimentary environment in explaining

Permian coal measure formation in Sohagpur, providing a process-based framework for coal variability.

4. Collaborative resource studies: The GSI–USGS Sohagpur Coalfield Project (1995–2001) emphasizes coking coal potential, structural partitioning, and stratigraphic targeting in a resource-assessment context (Milici et al., 2003).
5. Modern geophysics and structural imaging: High-resolution seismic imaging demonstrates syn-sedimentary subsidence and faulting as key basin controls, strengthening structural interpretations used in CBM-oriented studies (Dhanam et al., 2013).
6. Recent applied basin studies (CBM/coal property focus): Integrated geochemical–geophysical investigations and newer publications further evaluate permeability, CBM prospectivity, and coal property controls in the basin (Mondal et al., 2021).

Fieldwork, Sampling and Analytical Methodology

Chapter: 3

3.1 Introduction

Field investigations, sample collection, and laboratory analyses are indispensable elements of the comprehensive petrochemical examination of coal, particularly when the objective encompasses paleoenvironmental reconstruction and the assessment of coal bed methane potential. Chapter 3 delineates the integrated fieldwork, sampling methodologies, and analytical techniques employed in the examination of Permian coal deposits within the Sohagpur coalfield, Son Valley, Central India. A systematic and reproducible methodology as essential for recording the spatial, serigraphic and compositional variability of coal seams and their associated lithofacies within the Gondwana succession.

The purpose of the fieldwork was to meticulously document the geological, stratigraphy and structural characteristics of coal-bearing horizons through detailed observations of both the surface and subsurface. We used standard procedures to get scientifically valid coal samples that were representative for petrographic, geochemical and other tests. It was very important to protect the samples from oxidation and contamination, which can alter the chemistry of coal and properties for CBM.

We use a full set of petrographic, proximate and ultimate, mineralogical and geochemical techniques to learn about the coal rank, maceral composition, mineral matter, depositional conditions and diagenetic influence. These datasets are what we use to figure out how peat forms, how the climate has changed over time, and how the basin has changed over time. They are also used to determine what affects the production, storage and generation of methane in the Permian coals of the Sohagpur Coalfield. This chapter established the

methodological framework that underpins the interpretation and discussion in the subsequent chapters of the thesis.

3.2 Fieldwork strategy and sampling design

The analytical strength of this thesis is rooted in a systematic field campaign designed into three major strategies:

1. Capture the spatial variability of the Sohagpur Coalfield
2. Obtain representative coal samples from active production sites
3. Ensure that the collected material is suitable for petrographic, geochemical, mineralogical, pore structure and adsorption analyses. The fieldwork focused on collecting fresh, minimally altered coal from mine faces and benches to minimize the effects of weathering, oxidation, moisture fluctuation and contamination from mining operations.

3.2.1 Mine selection rationale (all operating mines)

Sampling was conducted across all operating coal mines in the Sohagpur coalfield to ensure these four key points:

1. Maximum spatial coverage across the coalfield and its structurally defined domains/sub-basins.
2. Representative variability in seam character, lithotype, and apparent coal quality can be expressed across different mines.
3. Reduction of sampling bias, avoiding over-representation of any single mine of seam panel.
4. Comparability, by targeting active faces where stratigraphic context and operational exposure provide fresh, accessible coal surfaces.

Where multiple benches/seam sections are exposed at a given mine, sampling was designed to capture within-seam variability (e.g., bright vs dull bands, mineral partings and local change in cleat intensity).

3.2.2 Representative sampling within the exposure

The sampling strategy was designed to ensure representative and lithologically meaningful specimens, as outlined below:

- Hand specimen blocks were extracted to preserve banding and lithotype content.
- In banded seams, sampling attempted to include a representative proportion of bright and dull bands, unless a specific bench/band was targeted for comparative analysis.

3.2.3 Coal sampling for the working mines

In this study, the coal samples were collected from all the operational coal mines in the Sohagpur coalfield. Few coal mines have more than one coal seam; in those cases, coal samples were collected from all the coal seams for detailed study. The coal samples were taken from specific sections of the seams, representing the full thickness of coal present in those seams.

3.3 Method of coal sampling

The sampling is a process that includes the representative fraction of bulk material required for analyzing nature, composition and other properties of coal samples. Adequate sampling is an essential requirement for the interpretation and reliability of the coal samples (Stach et al., 1982).

According to Thomes (2012), sampling in coal is mainly of two types:

- 1) In situ sampling

2) Ex situ sampling

The In-situ sampling described the samples taken from the exposed coal seams from the underground or open-cast coal mines, while ex-situ sampling described that samples were collected from the coal transport containers or coal stockpiles.

For this current study, the coal samples were collected by in situ sampling, in which the pillar sampling method was followed with the guidelines of the Indian standard (IS:436, 1964). The coal samples were collected from all the operational coal seams in 7 coal mines (Sharda, Bangwar, Khairaha, Amalai, Rajendra, Damini, Dhanpuri). In these 7 coal mines, the coal samples were collected from Top to Bottom by pillar sampling techniques and kept in a zip-lock bag to avoid any moisture content and numbered respectively. Location of sample collection from mines and their respective seam profile is shown in Figure 3.1.

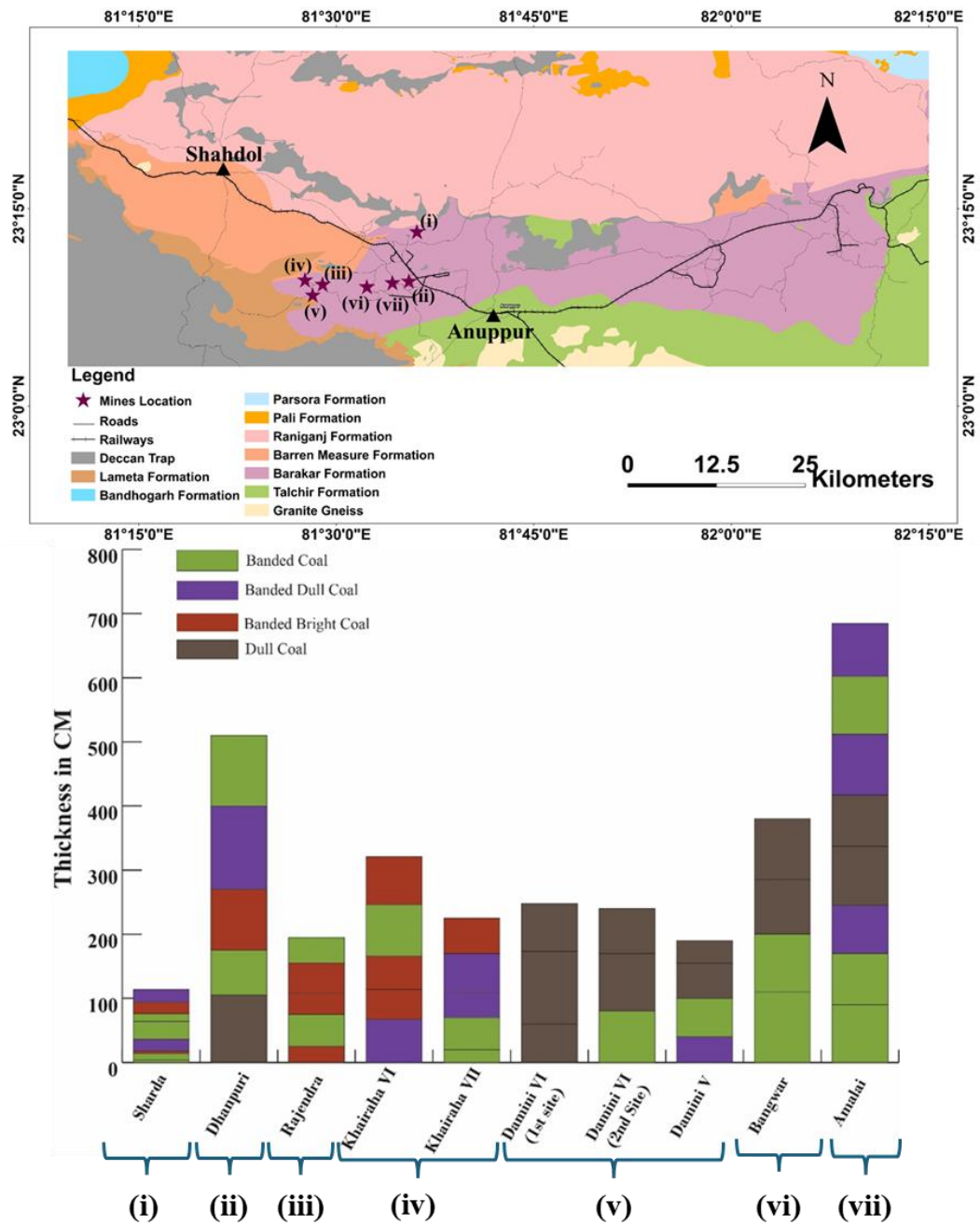


Figure 3.1 Location map of sampling site and seam profile of collected coal samples.

3.3.1 Sample naming scheme and metadata

A uniform sample naming scheme was adopted to encode essential provenance data and enable consistent dataset integration across analytical techniques. For each sample, a metadata sheet was maintained, including

- Mine name and code, geographic coordinates and local block/lease information.
- Seam number as per nomenclature and approximate depth.

- Field description which includes the lithotype, banding, mineral parting and visible carbonate/pyrite fracture.
- Date and time of the collection.

3.4 Megascopic characterization

Megascopic characterization was performed to establish a field-to-laboratory link between the visible coal fabric and subsequent microscopic and geochemical datasets. Hand specimen observation was especially important for documenting lithotype banding, mineral parting or any other evidence of deformation or intrusive influence on the sample scale.

The collected coal samples were brought to the laboratory, and the Megascopic characterization was performed following Diessel's method. The coal samples of Sohagpur are classified as the Banded Bright, Banded, Dull and Banded Dull coals. Samples having similar megascopic characterization with high thickness have been clubbed together for further sample preparation and analyses. The flowchart of various analyses performed in this study is shown in Figure 3.2.

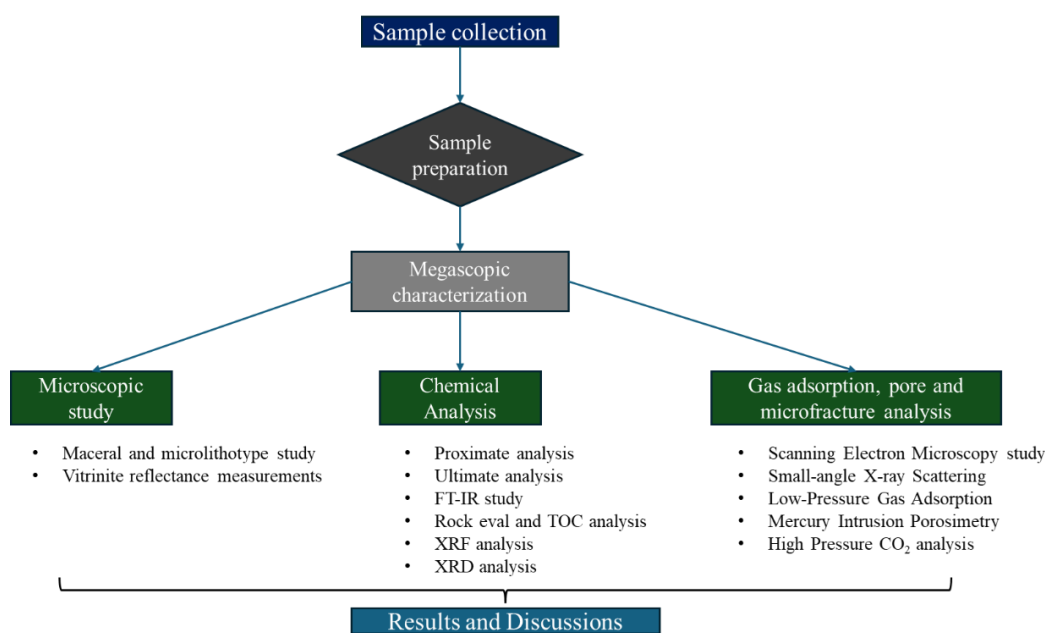


Figure 3.2 Flowchart of the various analyses performed in this study.

3.5 Sample preparation

Coal samples were brought to the laboratory and prepared for various sophisticated analytical tools according to their standard sample size requirements.

3.5.1 Sample preparation for the petrographic study

Collected coal samples from the field are crushed manually by using the mortar and pestles and sieved through a -18 mesh size and should not pass through the -60 mesh size are used for the petrographic study. The samples passed through the -60 mesh size are taken for further sample preparation and use in other sophisticated analytical tools.

Embedding- After the preparation of -18 mesh coal samples for microscopic study, we need to prepare coal mounts from these -18 mesh coal samples. The coal mount was prepared using the 5 g of coal sample mixed with the 5 g of Geologists powder with 10 ml of rapid repair liquid. Geologist powder was a low viscous epoxy used in the preparation of coal mount. This mixed liquid was further poured into the mold for the coal mount preparation without any external pressure. When the liquid settled down, after 4-5 hrs., this liquid became solid, and the sample was removed from the mold, and the further process of grinding started.

Grinding- After the preparation of coal mount (pellet), the coal pellet was ground on a polishing machine to produce a smooth, scratch-free surface for the measurement of vitrinite reflectance as well as qualitative and quantitative values of maceral and mineral matter. For the grinding process, the coal mount was ground on the different grit sizes of silicon carbide paper, starting from coarser particle sizes to finer, with a time duration of 4-5 minutes. During this process, the coal mounts were also cleaned each time with water when the smaller size of grit was used, so that the coarser particles would not come up with the finer grit and avoid any scratches.

Polishing- After the grinding on the various grit sizes of paper, the coal mounts were ready for the polishing. For the first stage of polishing of the coal mount, the blazer cloth was used with a mixture of distilled water and magnesium carbonate. The second stage of polishing was carried out on velvet cloth using alumina grade 3 (0.5–1 μm) to obtain a finely finished surface suitable for microscopic examination. The polishing was performed with uniform and gentle pressure to avoid the development of surface relief or unevenness. Adequate lubrication was maintained during the process to ensure smooth movement of the sample and to prevent overheating or surface damage. For this polishing the coal mounts were clean with a 3–4-minute interval, and the process of polishing takes up to 15 minutes to make the mount scratch-free and ready for the analysis.

3.5.2 Sample preparation for Geochemical analysis

For the Geochemical analysis, the coal samples were crushed into -72 mesh size using the mortar and pestle. The sample size, which passed through a 72 mesh and lies above 100 mesh used for the various Geochemical analyses.

For the Proximate and Ultimate analysis, the coal samples of -72 mesh size were air dried and then made ready for the analysis.

For the Fourier Transform Infrared analysis -72 mesh size was prepared.

3.5.3 Sample for Mineralogical study

For the mineralogical study, X-ray fluorescence and X-ray diffraction analysis were performed. The coal samples of - 100 mesh were used for this analysis. The samples were crushed using a mortar and pestle and sieved through a 100 mesh sieve. All the samples that passed through this sieve were categorized as the -100 mesh size sample and used for these analyses.

3.5.4 Sample for Pore and Microfracture study

Pore and Microfracture studies have been performed using Scanning Electron Microscope (SEM), and Low-Pressure gas adsorption (LPGA), Small angle X- Ray scattering (SAXS) and Mercury intrusion Porosimetry (MIP) studies. For the SEM and MIP study, a chip sample was used, while for the LPGA and SAXS analyses, -230 mesh powder sample was used.

For SEM analysis, one side of the coal sample surface was polished using sandpaper so that the sample would easily fit in the sample chamber. Before the SEM analysis, samples were dried in the oven to remove the moisture.

3.6 Methods of study

3.6.1 Macroscopic study

The macroscopic study is conducted by analyzing several lithotypes of coal determined under the hand specimen. Based on the colour, lustre, texture, and type of stratification, the humic coal has four types of lithotype known as vitrain, clarain, durain and fusain. Vitrain and clarain are known as the bright bands, while the durain and fusain are known as the dull bands. The macroscopic scheme of the humic coals has been proposed by Diessel (1965). The pillar samples collected from the Sohagpur coalfield were identified based on the scheme proposed by Diessel, and samples having similar megascopic characteristics were kept in a single band. Based on these properties, the seam profile was constructed, showing the thickness and lithotype present in coal seams.

3.6.2 Microscopic study

3.6.2.1 Maceral and microlithotype study

At the microscopic level, coal contains several organic and inorganic constituents. Organic constituents are known as the maceral, while inorganic ones are known as the

mineral matter. The association of macerals with macerals or mineral matter (<5%) is known as the microlithotype, while if the maceral and mineral matter (5-60%) are associated, known as the carbominerite. The identification of the maceral was done following the standard procedure and recommendation of ICCP (ICCP, 2001, 1998; ISO 7404-3, 2004; ISO 7404-4, 2017; Pickel et al., 2017). Microscopic analysis was done on the petrological microscope with fluorescent attachment for liptinite macerals in the immersion oil medium. The refractive index of immersion oil is 1.51, which protects the incident rays from diffraction. The macerals present in coal are categorized into 3 main groups known as Vitrinite, Liptinite and Inertinite, while mineral matter is also categorized into three groups known as Argillaceous, Carbonate and Pyrite.

The quantitative assessment of the macerals and minerals under the petrological microscope was done manually. The analysis was performed on the Leica DM2700P microscope and Leica Application Suite (version 4.6) software, compatible with capturing the photos. For the point count, a uniform distance of 0.4mm was maintained during the whole process. The line-to-line and point-to-point count was performed to complete the coal mount. The crosswire present in the eyepiece is used as the focus point for the maceral and mineral matter count. A fluorescent attached to the microscope was used during the count of the liptinite group of macerals. This fluorescent system consists of a blue light extinction which fluoresces the liptinite group of macerals and makes them easily countable (Teichmuller and Wolf, 1977).

The microlithotype analysis was carried out following the recommendations of the ICCP (International Committee for Coal and Organic Petrology; 1963, 1975, 1998, 2001; Pickel et al., 2017), as well as the procedures outlined by Stach et al. (1982) and Taylor et al. (1998).

Microlithotypes were identified based on the occurrence of macerals or maceral groups within an area of at least $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$, constituting 5% or more of the surface area. Accordingly, a microlithotype may consist of a single maceral or maceral group provided it meets these dimensional and proportional criteria. Microlithotypes may contain up to 20% by volume of mineral matter (including argillaceous, carbonate, or siliceous minerals) and up to 5% by volume of sulphide minerals. When the mineral matter content exceeds these limits, the lithotype is classified as minerite or carbominerite, depending on the relative proportions of coal and mineral matter. A 20-point graticule (Kötter's graticule) was fitted into the ocular of the petrological microscope used for the analysis, with each square representing 5% of the observed area. Qualitative microlithotype analysis was conducted simultaneously with maceral analysis using the same microscope, maintaining a line-to-line and point-to-point spacing of $400\text{ }\mu\text{m}$. For quantitative determination, a manual point counter was employed to record the microlithotype proportions systematically. Microlithotypes were identified to describe the maceral associated at the microscopic scale, and these distributions provide insights into:

- Mire conditions (water table fluctuations, oxidation intensity),
- Organic matter input and preservation
- Mechanical behaviour relevant to fracture development.

Fluorescence microscopy- The coal samples were also examined under fluorescent microscopy for the identification of the liptinite group of macerals. For the same microscope, attached with a fluorescence photometer was used. The fluorescence system consisted of a blue light excitation filter, a dichroic mirror and a suppression filter. A similar pattern of maceral count was done under the fluorescent light. Fluorescence in coal macerals occurs due to the presence of phytopolymer-derived aromatic and phenolic compounds, which are particularly abundant in the macerals of the liptinite group.

3.6.2.2 Vitrinite Reflectance measurements

The vitrinite reflectance measurements ($R_o\%$) of coal samples have been done under the sample reflected light microscope following the ISO standard (ISO 113581, 2015). For this, the scratch-free collotelinite grain was identified under the monochromatic light of 564 nm. Before the analysis started, the system was calibrated with the 3 standards having the 3 different reflectance values- Spine (0.420), Yttrium-Aluminium-Garnet (0.902) and Gadolinium-Gallium-Garnet (1.715). For this analysis, at least 100 points were taken on each coal mount covering the whole area.

3.6.3 Chemical analysis

3.6.3.1 Proximate analysis

The proximate analysis of coal samples has been done for the determination of Moisture (M), Volatile matter (VM), Fixed Carbon (FC) and ash yield (A). The analysis was done on the Leco TGA 801 proximate analyser present at the Geology and Geochemistry Lab, RGIPT. 1 g of powdered coal samples was required for this analysis. An analysis has been done following the Indian standard (IS:1350, 1984). This instrument automatically analyses the value of Moisture, Volatile Matter, Ash and Fixed Carbon. In this, the Nitrogen, Oxygen and Zero air gas was required for the combustion of coal samples. The sum of given values is always raised to the 100.

3.6.3.2 Ultimate analysis

The ultimate analysis has been done on the Elementar, UNICUBE analyser present at the Centra Instrument Facilities (CIF), RGIPT. For this the 3-5 mg of coal samples is required following the standard (ASTM D 3176-89, 2013). This analysis provides the presence of Carbon, Hydrogen, Nitrogen and Sulphur present in coal samples. According to this investigation, combustion occurs in a catalytic tube at a high temperature and in an oxygenated CO_2 atmosphere. While the combustion gases are being freed from the

mixing of external gases, a non-reactive gas, like helium, serves as a cleansing and carrier gas. Using a particular adsorption column, the components of carbon, hydrogen, nitrogen, and sulfur were separated from one another, and the results were ascertained using a thermal conductive detector. The total amount of carbon, hydrogen, nitrogen, and sulfur was subtracted from 100 to find the amount of oxygen.

3.6.3.3 Fourier transform infrared (FTIR) spectroscopy

FT-IR is a powerful tool for the identification of organic and inorganic functional groups present in coal samples (Chen et al., 2015; Painter et al., 1985, 1981). The samples analysis was done on Thermo Electron Scientific Instruments LLC, Nicolet iS20, present at CIF, RGIPT. For this analysis, coal samples were finely ground in an agate mortar. The samples were then mixed with the KBr in a 1:99 ratio and pressed under high pressure to achieve a transparent tablet. The KBr was mixed with coal due to its transparency in the Infrared wavelength. For this analysis, the data were recorded in Transmittance mode, with 20 scans taken with a spectral resolution of 4 cm^{-1} within the range of 400 to 4000 cm^{-1} .

3.6.3.4 Rock eval and TOC analysis

The Rock eval pyrolysis analysis of collected samples was conducted at the Department of Geology, Malaya University, Kuala Lumpur, Malaysia, using Hawk Pyrolyzer (Wildcat Technology). Coal samples were powdered to -72 mesh and analyzed with 5-8 mg. The pyrolysis temperature ranged from $50\text{ }^{\circ}\text{C}$ to a maximum of $850\text{ }^{\circ}\text{C}$. A dual infrared detector (for CO and CO_2) and flame ionization detector (FID, for hydrocarbons) were fitted to the Hawk Pyrolyzer for the quantification and reproducibility of data. Helium gas was used as a carrier gas, with hydrogen and air as FID fuel. Hydrocarbon peaks (S1 and S2 in mg HC/g rock) and T_{max} ($^{\circ}\text{C}$) were observed at $50\text{-}300\text{ }^{\circ}\text{C}$ and $300\text{-}600\text{ }^{\circ}\text{C}$, with the remaining CO_2 peak (S3 in mg CO_2 /g rock) observed at $300\text{-}400\text{ }^{\circ}\text{C}$.

Total organic carbon (TOC in wt.%) was determined via pyrolysis and oxidation parameters. Further hydrogen index ($HI = S_2/TOC \times 100$; mg HC/g TOC), oxygen index ($OI = S_3/TOC \times 100$; mg CO₂/g TOC), generation potential ($GP = S_1 + S_2$), and production index ($PI = S_1/S_1 + S_2$) were calculated from the pyrolysis data.

3.6.3.5 X-ray fluorescence (XRF) analysis

XRF analysis was performed on PANalytical, EPSILON 3X, present at CIF, RGIPT. For this, the coal samples of -100 mesh size are pressed under the weight of 25 tons to prepare a pallet for the measurement. Helium gas is used in this analysis as a carrier gas. The instrument works on the principle that an incoming X-ray strikes an electron from one of the orbitals next to the sample atom's nucleus, creating a hole in the orbit and leaving the atom in an unstable condition. An electron from an outer orbital's higher energy states falls into the hole, emitting extra energy in the form of a fluorescent X-ray, to maintain equilibrium. The characteristic of every given element that allows for the analysis of individual elements is the fluorescence X-ray that is released.

3.6.3.6 X-ray diffraction (XRD) analysis

The XRD analysis has been done on the Panalytical EMPYREAN-QTY1 present at CIF, RGIPT. XRD is a rapid and powerful tool for the identification of mineral phases present in coal samples. The XRD analysis has been done on the -100 mesh powdered coal samples.

XRD works on the principle of constructive interference between the monochromatic X-ray and the samples. A cathode-ray tube generates X-rays, which are then filtered to produce monochromatic radiation. The focused monochromatic radiation is directed at the sample. The interaction of incoming X-rays with the sample results in diffracted rays that correspond to a specific lattice pattern.

Bragg's Law ($n\lambda = 2d \sin \theta$) connects the wavelength of electromagnetic radiation to the diffraction angle and lattice space in a crystal sample. The diffracted X-rays are then detected and counted. Changing the 2θ angles revealed all potential lattice diffraction paths. The conversion of diffraction peaks to d-spacing enables the identification of the material with a distinct set of d-spacings. Standard reference patterns are useful in comparison to the d spacing.

3.6.4 Gas adsorption, pore and microfracture study

3.6.4.1 Scanning Electron Microscopy (SEM)

The pore and surface morphological identification was done on the JEOL JSM-7900F field emission scanning electron microscope (FE-SEM) available at CIF, RGIPT. For this analysis, the coal samples were prepared as a chip of ~2mm thickness. One side of the samples was polished with sandpaper for a smooth surface so that the samples could be placed in a sample holder for better analysis. Before the analyses started, the samples were dried in the oven to remove the moisture present in the coal samples so that pores and microfractures could be easily identified in this analysis. Before placing the samples in the sample holder, the gold coating was done on the sample's surface for the conductivity enhancement during the sample's analysis for better resolution and imaging.

3.6.4.2 Small Angle X-ray Scattering (SAXS)

SAXS is a non-destructive analysis for the characterisation of pores in coal samples with a wide range of length scales. This method operated based on the X-ray scattering of minerals, which possess a unique scattering length density (SLD). SAXS analysis was done on XENOCSS, Xueess 3.0 HR available at CIF, RGIPT. For this analysis, coal samples of $< 60 \mu\text{m}$ were prepared. The samples were packed with the Kapton tape and mounted over the sample holder with a detector distance of $\sim 1.5\text{m}$. The measurement was done 30 W Cu X-ray source paired with a Pilatus 300K 1 M hybrid pixel detector with single

photon counting capability. The raw data were recorded in Intensity $I(Q)$ as a function of Q .

3.6.4.3 Low-Pressure Gas Adsorption (LPGA)

LPGA analysis was done on a single-station Quantachrome Autosorb iQ physisorption instrument present at the Indian Institute of Technology, Bombay (IIT-Bombay). The samples of $< 60\mu\text{m}$ were required for this analysis. Before the analysis started, the samples were degassed at 110°C for at least 12h at a pressure of 10^{-4} torr for the removal of moisture content present in the coal samples. In this analysis, two gases were used. CO_2 gas adsorption at 273 K with a relative pressure range of 0.0003 to 0.03 was used for the Micropore analysis, while N_2 at 77 K with a relative pressure range of 0.1 to 1.00 for mesopore and some extent up to macropore analysis. The condensation pressure of CO_2 and N_2 is 261620 torr and 760 torr, respectively.

3.6.4.4 Mercury Intrusion Porosimetry (MIP)

MIP worked on the principle of the fluid-invasive method to determine the pores present in samples. The analysis was done on the Mercury Intrusion-Extrusion Pore-Size Analyzer (PoreMaster PM60) manufactured by Anton-Paar, present at IIT Bombay. Chip size samples of 0.5-1 cc were used in this analysis. The instrument works when mercury intrudes into the pores with increasing pressure up to 60,000 PSI to characterise the Pore size, Pore volume and Surface area. A higher intrusion pressure forces mercury to intrude into smaller pores. Pure mercury has a surface tension (γ) of 480.00 mN/m and a contact angle (θ) of 140° . Before the analysis started, the samples were kept in an oven at 100°C for at least 6 hrs to remove any moisture present on the pores of coal.

3.6.4.5 High pressure CO_2 adsorption

High-pressure CO_2 adsorption experiments were carried out using a BELSORP-HP volumetric adsorption analyzer at the Indian Institute of Technology (IIT) Bombay. The

instrument is capable of measuring gas adsorption isotherms at high pressures and elevated temperatures, providing reliable data for the evaluation of gas storage. For the analysis, the samples were ground and sieved to a particle size of -230 mesh to ensure uniformity and optimal packing in the sample cell. Before the adsorption experiments, approximately 0.5-1.0 g of the sample was accurately weighed and degassed under high vacuum at 110 °C for 12 hours. This pretreatment step was essential to eliminate any residual moisture or volatile contaminants that might interfere with gas adsorption. Adsorption isotherms were recorded at a constant temperature of 50 °C, maintained using a built-in temperature control system. The pressure was gradually increased, and adsorption data were collected up to a maximum pressure of 50 bar (5000kPa). These temperature and pressure conditions is realistic conditions for reservoirs storing the CO₂ as well as used for enhanced coal bed methane recovery. CBM reservoirs generally experience pressures between 3 and 10 MPa, depending on burial depth, hydrological conditions, and basin characteristics. Conducting adsorption measurements up to 5 MPa captures the pressure range over which the majority of methane and carbon dioxide adsorption occurs and encompasses the conditions relevant to primary CBM production, ECBM operations, and geological CO₂ storage in coal seams.

4.1 Introduction

Coal is a heterogeneous sedimentary rock whose composition, texture, and internal structure exert strongly on its physical and chemical behaviour. A comprehensive understanding of coal characteristics is therefore essential for interpreting its origin, evaluating its quality, and assessing its suitability for various geological and industrial applications. This chapter presents an integrated study of coal petrography, geochemical characteristics, and pore and microfracture systems to establish a detailed characterization of the coal samples investigated in this thesis.

Coal petrography forms the foundation of this chapter, providing insights into the maceral composition, mineral matter distribution, microlithotype, and carbominerite. Petrographic analysis is crucial for understanding the depositional environment, diagenetic evolution, and maturity of coal, as well as for interpreting variations in its chemical and physical properties. Geochemical analysis is employed to quantify the elemental and compositional attributes of the coal, including organic matter composition and mineralogical influences. These analyses complement petrographic observations by elucidating the chemical processes governing coal formation and alteration. Together, petrographic and geochemical data provide a robust basis for evaluating coal quality, reactivity, and potential utilization.

In addition, this chapter investigates the pore structure and microfracture development within the coal matrix. Pores and microfractures play a critical role in controlling fluid storage, permeability, and gas transport behaviour. Their distribution, morphology, and connectivity are examined to understand better the internal architecture of the coal and its implications for fluid flow and mechanical behaviour.

4.2 Coal Petrography

The world's energy needs are growing daily, and fossil fuels cannot keep up with the demand. Coal is typically used in the chemical, steel, combustion, and thermal power-generating sectors. Their usefulness is unexpected because technological advancements have led to overuse of coal as a raw material. In such instances, the organic petrographic analysis provides valuable information on the coal's properties, qualities and suitability for a range of uses, as well as a deeper insights into its characteristics. Swamp's scientific behaviour is determined by the biological and physicochemical processes that turn plant waste into coal. These regulating mechanisms can be traced by the petrography of coal. According to Suárez-Ruiz et al. (2012), the field of organic petrology, which developed from coal petrology, can also be utilized for multidisciplinary research, basin analysis, and the exploration of fossil fuel resources. Because of its complex nature and organic origin, coal differs from other rocks in the earth's crust, making petrographic analysis of this material difficult and complex. One of the key facets of coal petrology is coal petrography, which focuses on identifying the macroscopic and microscopic components of coal to determine its intrinsic qualities. Coal can be classified macroscopically as either non-banded/sapropelic coal or banded/humic coal. The lithotypes (macroscopically identifiable bands) in coal, such as vitrain, clarain, durain, and fusain, are the primary focus of macroscopic petrography. Micro petrography, on the other hand, examines the microcomponents of coals, known as fine-sized minerals of inorganic origin and macerals of organic origin. Coal is composed of various visually distinct entities derived from both organic and inorganic natural materials at the microscopic level. The inorganic fraction is represented by the mineral found in coal, whereas the organic fraction is made up of the coalified residues of plant matter. Macerals are the organic components of coals, whereas mineral matter is the inorganic component.

4.2.1 History of coal microscopy

The investigation of coal in a thin section marked the beginning of the microscopic research of coal in the nineteenth century (Witham 1831). The first written description of the coal's cell structure was given by Hutton in 1833. When spores were discovered in coal in 1870, it became evident that terrestrial plants had served as coal's forerunner. One of the significant turning points with thin-section research of coal was the origin of coal by White and Thiessen in the form of a treatise (White & Thiessen, 1913). After Thiessen's microscopic investigation, coal under transmitted light gained popularity in the United States and Europe. Seyler, Stach, Mackowsky, and Teichmüller made more contributions in this area. When studying coal under a microscope, Prof. E. Stach introduced the oil immersion objectives in 1925 to determine the macerals of prepared coal blocks. The Berek photometer was used by Hoffmann and Jenkner (1932) to quantitatively measure the amount of light reflected from vitrinite surfaces. This technique advanced the concept of coal rank with varying reflectance values and was groundbreaking in the field of coal microscopy. The fluorescence microscopy technique was developed to help identify the microscopic components rich in hydrogen and to provide parameters for determining the maturity of low-rank coal (Schochardt 1936; Teichmüller & Wolf 1977).

The International Committee for Coal and Organic Petrology was established in 1951 with the goals of ensuring the ongoing international exchange of scientific knowledge pertaining either directly or indirectly to organic petrology and creating and disseminating definitive descriptions and methods in the fields of coal/organic petrology and petrography that are accepted and recognized worldwide. The International Handbook of Coal Petrography, together with its updates and additions, has been published by the committee, which has also established formal coal petrographic

nomenclatures (International Committee for Coal and Organic Petrology 1963, 1975, 1998, 2001). The terminology used in the book served as the foundation for various coal scientific standards used by various international organizations, including ISO, ASTM, BIS, and others. The ICCP System 1994 (International Committee for Coal and Organic Petrology 1998, 2001; Sýkorová et al. 2005; Pickel et al. 2017) adopted the new global definitions and nomenclature for the microscopic constituents of coal.

One of the pioneers in modern coal petrology is Professor Erich Stach of Krefeld, Germany. He used the analysis of polished sections and oil immersion to highlight the variability of coal in his 1935 original book *Lehrbuch der Kohlenpetrographie*. E. Stach, M.Th. Mackowsky, M. Teichmüller and R. Teichmüller wrote the revised version, which was published in English in 1975. Like the original textbook, it was heavily illustrated with top-notch photomicrographs and figures. The book addressed almost every facet of coal petrology and undoubtedly addressed a significant void in the basic scientific literature. A significant milestone in this field was also reached in 1982 with the publication of the third updated and expanded version, written by E. Stach, M.Th. Mackowsky, M. Teichmüller, G. H. Taylor, D. Chandra, and R. Teichmüller, translated by D. G. Murchison, G. H. Taylor, and F. Zierke (Stach et al. 1982). In 1998, G.H. Taylor, M. Teichmüller, A. Davis, C.F.K. Diessel, R. Littke, and P. Robert produced a new handbook called “Organic Petrology,” which included certain updated sections of Stach’s *Textbook of Coal Petrology* (Taylor et al. 1998).

4.2.2 History of coal petrography in India

The microscopic components of Indian coal were first reported by Lomax (1911). Fox (1926) reported on the systematic petrography of Indian coals from the Raniganj coalfield. Banerjee (1932) used petrographic analysis to report the presence of woody tissue in Gondwana coals. Chatterjee (1940) provided the microstructural features of fusain from

Gondwana coals. Ganju (1955) used widely accepted terminology to present a comprehensive petrographic analysis of Indian coals. The petrographic studies of Indian coals gathered speed after 1950, and early researchers made significant contributions (Lahiri 1951; Lahiri and Basu 1952; Iyengar and Lahiri 1957; Chandra 1958, 1966; Mazumdar et al. 1959, 1962; Pareek 1966, 1981; Ghosh 1964, 1969, 1971; Lahiri et al. 1968; Navale 1971, 1979; Lele and Chandra 1975; Navale and Misra 1980; Pareek and Bardhan 1985; Chandra and Chandra 1988; Chandra and Chakrabarti 1989; Misra et al. 1990; Rajarathnam et al. 1996). Chandra began studying the vitrinite reflectance of Indian coals in 1965. Following the 1960s and 1970s, several workers strengthened the field of coal petrology and introduced techniques in India.

In response to increasing research demands, systematic investigations were undertaken across several major coalfields of India. These studies primarily focused on the palynology, petrography, and associated lithologies of coal-bearing sequences, employing standard petrographic techniques. Extensive research has been carried out in the coalfields of the Damodar River basin, including the Jharia coalfield (Pareek 1964, 1966; Verma et al. 1979; Mishra et al. 1990; Mishra and Cook 1992; Singh et al. 2007, 2008; Mishra and Pandey 2011; Paul and Chatterjee 2011; Chatterjee and Paul 2013; Sen and Banerjee 2015), East and West Bokaro coalfields (Navale and Saxena 1989; Singh and Banerjee 2006; Mahesh et al. 2015; Tewari and Khan 2015; Bhowmick et al. 2017; Mendhe et al. 2017), North and South Karanpura coalfields (Venkatachala and Kar 1968; Mukherjee and Arabinda 1969; Pareek 1986; Chakrabarti 1991; Singh 2000; Ali et al. 2017; Mendhe et al. 2017), and the Raniganj coalfield (Ganju and Pant 1963; Navale and Saxena 1989; Hazra et al. 2015; Sen et al. 2016b; Acharyya 2019).

Significant petrographic contributions have also been made for several other Indian coalfields, including the Rajmahal coalfield (Singh and Singh 1995, 1998, 2011; Singh

2004), PENCH–KANHAN coalfield (Pareek et al. 1964; Pareek 1969a; Singh and Shukla 2004; Srivastava and Agnihotri 2013), Pathakhera (Nandgaonkar 1977), Mohpani (Chakraborty et al. 2003), Sohagpur (Pareek 1987; Chakrabarti 1991; Rathore et al., 2025), Singrauli (Pareek 1969b, 1970; Singh et al. 1987, 2014b; Singh and Navale 1989; Misra and Singh 1993; Gopinathan et al., 2024), Chirimiri (Pattanaik et al. 2011), Lakhanpur (Kumar and Patel 2008), Korba (Singh and Singh 1991; Singh and Dwivedi 1994; Varma et al. 2013; Singh et al. 2016a), Wardha Valley (Pareek and Pande 1970), Talcher coalfield (Pareek 1963, 1986; Navale and Tiwari 1966; Navale and Srivastava 1969; Cheepurupalli et al. 2015; Singh 2016a, b), and the Ib River valley coalfield (Pareek 1986; Singh et al. 2013c; Chakravarty et al. 2015).

Coalfields of northeastern India have also been extensively evaluated using petrographic approaches (e.g., Ahmad 1971; Ahmed and Bharali 1984; Singh et al. 1992, 2013d, 2015a; Mishra 1992; Misra 1992; Ahmed 1996; Mishra and Ghosh 1996; Singh and Singh 2000, 2001, 2003, 2005, 2013; Phukan 2002; Nath 2005; Saikia 2009; Nayak et al. 2009; Dutta et al. 2011; Sharma et al. 2014; Singh 2015, 2018).

In addition, several studies have specifically addressed the characteristics and behaviour of low-rank coals (e.g., Misra and Singh 1994; Singh 2002, 2012; Singh et al. 2013a, 2016b, 2016d, 2017c, d; Paul et al. 2015; Singh and Kumar 2017, 2018, 2020;21 Kumar et al. 2025a).

4.2.3 Recent advances in coal petrography

Coal petrology has witnessed significant methodological evolution over the past decade, moving from conventional qualitative techniques to highly automated, quantitative, and computer-assisted approaches. Early coal petrographic analysis relied heavily on manual point-counting and visual interpretation under the microscope, which, although effective,

was time-consuming and prone to operator bias. A major step toward automation was introduced by Iwaszenko and Róg (2021), who applied deep learning, specifically U-Net convolutional neural networks, to segment macerals in reflected-light coal images. Their study demonstrated high accuracy in identifying vitrinite and inertinite macerals and highlighted the potential of artificial intelligence to reduce subjectivity in maceral identification. This work was foundational in establishing that machine learning could serve not only as an auxiliary tool but also as a core analytical method in modern coal petrography, offering reproducible results with minimal human intervention.

Building upon this foundation, Santos et al. (2022) developed a more specialized deep-learning-based system for collotelinite segmentation and automated determination of vitrinite reflectance. Vitrinite reflectance is a key parameter in coal rank assessment and thermal maturity estimation, and its accurate determination has traditionally required careful visual measurement under controlled conditions. The system proposed by Santos and colleagues integrated machine learning with petrographic imaging to reduce operator bias, improve consistency, and significantly accelerate analysis. Their results showed that the automated measurements correlated strongly with conventional expert determinations, suggesting that artificial intelligence could reliably replace or complement manual methods in routine coal petrology and quality assessment.

While these studies primarily focused on image-based analysis of maceral composition, Zhou and Sanei (2025) addressed challenges associated with the quantification of dispersed organic matter (DOM) in coal and organic-rich sedimentary rocks. Traditional point-counting methods for DOM are often laborious and prone to inconsistencies between observers. To overcome this, Zhou and Sanei introduced a standardized grid-based point-counting method that considerably improved the speed and accuracy of maceral quantification. Their approach demonstrated strong correlations between

maceral volume percentages and total organic carbon (TOC), enabling more precise assessments of organic matter distribution and composition in coals and sediments. This advancement represents a significant step toward harmonizing quantitative methods in coal and source rock petrography, providing reproducible data essential for both geological and industrial applications.

Expanding the application of modern analytical tools beyond coal, Brassell (2025) utilized machine-learning-assisted image analysis to quantify maceral composition in organic-rich source rocks, including the Devonian New Albany Shale and Marcellus Shale. This work highlighted the capability of automated systems to detect and quantify minor maceral types such as alginite and pyrobitumen, which are critical indicators of kerogen type, thermal maturity, and hydrocarbon generation potential. Brassell's findings underscore the broader relevance of digital and machine-learning methods for assessing organic matter evolution and maturity trends across both coals and related source rocks.

4.2.4 Present work

The earlier researchers work in this coalfield was based on sporadic sampling; researchers did not conduct extensive petrographic analysis or employ sophisticated petrographic equipment (Pareek, 1987). The current study has been designed to address the information gaps, and an effort has been made to use modern techniques to conduct a regional petrographic examination of the coal deposits of the Sohagpur coalfield. In this regard, numerous coal samples have been collected from the exposed faces of the Sohagpur coalfield as well as from all the operating faces of open-pit and underground coal mines.

4.3 Megascopically recognizable constituents

Coal is made up of layers of decomposed plant matter. Nature's physical, biochemical, and dynamo chemical processes cause the breakdown of the plant litter. Eventually, these mechanisms transform plant matter into megascopically separate bands with different chemical compositions. It is possible to further clarify these megascopically identifiable elements into smaller microscopic units known as "Maceral." Sapropelic and Humic are the two main genetic groupings into which coal is divided. The Sapropelic coals are uniform and band-free at the megascopic level. They break with a conchoidal fracture and have a dull or somewhat oily sheen. The two lithotypes of sapropelic coals- Cannel and Boghead, can be distinguished based on the kind of biological facies. Boghead coals have a lot of algae, while cannel coals are rich in spores and pollen. Boghead coals are slightly brown and leave a brown stripe, while cannel coals are often black with a black streak. Figure 4.1 shows the different megascopic bands identified in a hand specimen of coal.

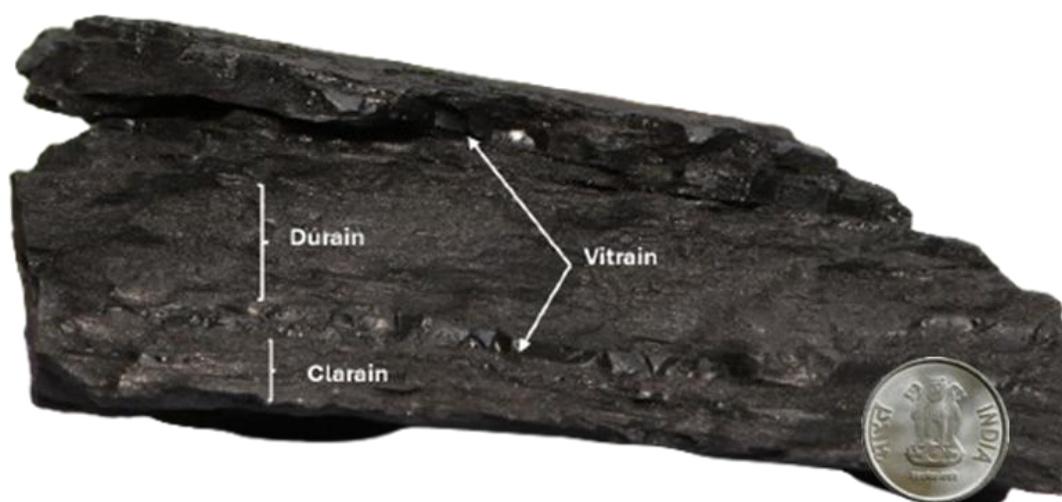


Figure 4.1 Different megascopic bands are present in banded humic coal as per Diessel's classification scheme.

In nature, humic coal is typically banded. These bands, which vary in physical characteristics, chemical composition, and maceral composition, reflect changes in facies

over the course of coal's history. The idea of identifying the megascopic coal lithotype using the lithotype nomenclature was considered and developed by several workers (Stopes 1919; Thiessen and Sprunk 1935; Schopf 1960; Diessel 1965; Hower et al. 1990; Standards of Australia 1993; Larkin and Green 2012; Rusnak 2017). Vitrain, durain, clarain, and fusain are the four basic banded elements of coal that were initially identified and described by Stopes (1919). These bands were later collectively referred to as "lithotype". A band must be at least 3 to 10 mm thick to be classified as a lithotype.

Vitrain- The brightest of the banded elements with vitreous lustre is called vitrain. Vitrain bands feature a dazzling lustre and are black in colour. Because of the fine fissures material's brittle nature, it breaks into cubes when mined. The layer's minimum thickness is 3 mm.

Clarain- Clarain bands are made up of alternating layers of dull and bright lustre, giving them a bright to semi-bright look. Individual laminae remain less than 3 mm thick. Clarain does not have a conchoidal fracture, but it does have a silky lustre.

Durain- Durain bands have the dullest appearance and are either black or grey in colour. Black durain, have a somewhat oily sheen and irregular fractures. It is the hardest band, less common than vitrain and clarain, and tends to shatter into large, blocky pieces. Sometimes, because of its dreary appearance, it resembles carbonaceous shale.

Fusain- Fusain is similar to wood charcoal. It is black, has a smooth shine, and is generally soft and fibrous. It accounts for only a small portion of the total coal seam and appears as lenses oriented parallel to the seam. Fusite that has been impregnated with mineral substance can make fusain hard.

4.4 Macroscopic study of Sohagpur coals

Based on the above macroscopic characterization, Diessel (1965) proposed classification schemes for macroscopic characterization, describing the lithotype based on the Vitrain, Clarain, Durain, and Fusain bands. Table 4.1 shows the classification proposed by Diessel (1965).

Table 4.1 Lithotype classification proposed by Diessel (1965).

Lithotype	Symbol	Description
Bright coal	B	Vitreous to sub-vitreous lustre; even to conchoidal fracture; brittle; may contain up to 10% dull coal in bands less than 5mm thick
Banded bright coal	Bb	Mainly bright coal containing thin (less than 5 mm) dull coal bands ranging in proportion between 10 and 40%; even fracture
Banded coal	BD	Contains bright and dull coal bands (all less than 5 mm), the ranging proportion between 40 and 60% each
Banded dull coal	Db	Mainly dull coal containing thin (less than 5 mm) bright bands ranging in proportion between 10 and 40%; uneven fracture
Dull coal	D	Matt lustre and uneven fracture; may contain 10% of bright coal bands less than 5mm thick

Bright Coal- The bright coal band exhibits vitreous to sub-vitreous lustre and contains less than 10% dull component. These bands are brittle in nature. In Sohagpur coals, the Bright coal is absent during macroscopic seam profile construction.

Banded Bright Coal- The bands have more than 60%, but less than 90% bright components, and are identified as Banded bright coal. These bands exhibit even fracture. Sohagpur coals have a moderate occurrence of banded bright coal. The Bright band is only noticed in coal seams from Sharda, Dhanpuri, Khairaha, and Rajendra coal mines

Banded Coal- Banded coal contains bright and dull coal bands (all less than 5 mm) ranging in proportion between 40% and 60% each. Banded Coal is dominant in Sohagpur coals and found in all coal seams/mines except the Burhar Seam VI of the Damini coal mine.

Banded Dull Coal- Banded dull coal is comparatively dull in appearance due to being rich in dull components varying between 60% and 90%. Banded Dull Coal is the second

most dominant band found in the Sohagpur coals. This band is present in Sharda, Dhanpuri, Khairaha VII, and Damini V.

Dull Coal- Dull coal is recognized by its dull appearance. It may only contain less than 10% bright component. The dull band is most prominent and covers almost the whole thickness of Damini Seam VI.

4.4.1 Macroscopic Seam Profiles of Sohagpur Coalfield

Based on Diessel's classification, it was observed that coal samples fall in the Banded, Banded Dull, Banded Bright, and Dull coal categories for coals from the Sohagpur coalfield.

Coal seam from Sharda coal mine has Banded, Banded Dull, and Banded bright coal. Dhanpuri has the Dull, Banded, Banded Bright, Banded Dull, and Banded. Rajendra has the Banded Bright and the Banded only. In the Khairaha coal mine, coal seams VI and VII have the Banded Dull, Banded Bright and Banded. Damini coal mine, seam VI present at two places that show coals belonging to the Dull to Banded coal, while seam V shows Banded, Banded Dull, and Banded bright in nature. Bangwar coal mine showing Dull to Banded in nature. Amalai mine has the Banded, Banded Dull, and Dull coals. Based on this characterization, a combined macropetrographic seam profile has been prepared as shown in Figure 4.2.

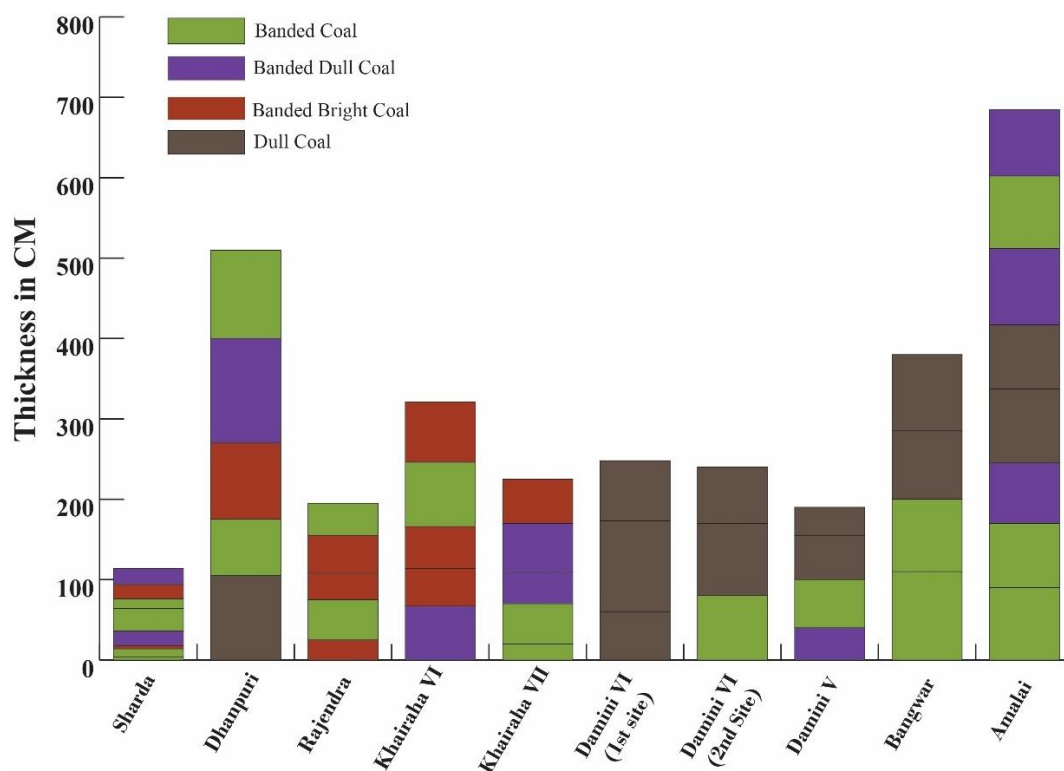


Figure 4.2 Macropetrographic seam profile of Sohagpur coal seams.

4.4.2 Seam Characteristics of Sohagpur Coalfield

Table 4.2 summarizes the percentage distribution of coal lithotypes: Banded, Banded Dull, Banded Bright, and Dull across different seams/mines, providing valuable insight into the variability of coal characteristics within the study area. A pronounced inter-seam heterogeneity is evident, reflecting differences in peat-forming environments, organic matter composition, and subsequent coalification processes. In most seams, banded coal constitutes a major proportion, indicating alternating layers of bright and dull macerals and suggesting relatively stable depositional conditions.

The coal seam from the Sharda mine is dominated by banded coal (47.37%), followed by banded dull (33.33%) and banded bright (19.30%), with no dull coal, suggesting favourable conditions for preservation of brighter organic constituents. The Dhanpuri mine exhibits a more heterogeneous composition, with banded coal (35.29%) forming the largest share, while appreciable amounts of banded dull (25.49%), banded bright (18.63%), and dull coal (20.59%) indicate fluctuating depositional environments and

variable organic input. Rajendra mine, in contrast, is characterized exclusively by banded and banded bright coal, with banded bright forming the dominant component (53.85%). This dominance of brighter lithotypes suggests a higher proportion of vitrinite-rich material and comparatively better coal quality. A similar trend is observed in Khairaha VI, where banded bright coal accounts for 54.21%, indicating enhanced preservation of vitrinite macerals. In contrast, Khairaha VII shows a contrasting dominance of banded dull coal (44.44%), suggesting increased inert macerals or mineral matter influx. The Damini seams display marked site-specific variation. Damini VI (1st site) is composed entirely of dull coal (100%), pointing toward strong oxidation, reworking, or dominance of inertinite-rich material during peat accumulation. Damini VI (2nd site) is also dull coal-rich (66.67%), though it retains a significant proportion of banded coal (33.33%). Damini V presents a mixed assemblage, with nearly half of the coal being dull (47.37%), accompanied by banded (31.58%) and banded dull (21.05%) varieties, reflecting transitional depositional conditions. Bangwar seam shows a high proportion of banded coal (52.63%) with an almost equal contribution from dull coal (47.37%), indicating alternating phases of favourable and unfavourable conditions for bright coal formation. Amalai seam exhibits a relatively balanced distribution of banded (37.96%) and banded dull coal (36.93%), with a moderate proportion of dull coal (25.11%), suggesting intermediate coal quality.

Table 4.2 Macropetrographic seam characteristics of Coal seams from Sohagpur coalfield.

Seam/Mine Name	Banded		Banded Dull		Banded Bright		Dull	
	CM	%	CM	%	CM	%	CM	%
Sharda	54.00	47.37	38.00	33.33	22.00	33.33	0.00	0.00
Dhanpuri	180.00	35.29	130.00	25.49	95.00	25.49	105.00	20.59
Rajendra	90.00	46.15	0.00	0.00	105.00	0.00	0.00	0.00
Khairaha VI	80.00	24.92	67.00	20.87	174.00	20.87	0.00	0.00
Khairaha VII	70.00	31.11	100.00	44.44	55.00	44.44	0.00	0.00
Damini VI 1 st site	0.00	0.00	0.00	0.00	0.00	0.00	248.00	100.00
Damini VI 2 nd Site	80.00	33.33	0.00	0.00	0.00	0.00	160.00	66.67
Damini V	60.00	31.58	40.00	21.05	0.00	21.05	90.00	47.37

Seam/Mine Name	Banded		Banded Dull		Banded Bright		Dull	
	CM	%	CM	%	CM	%	CM	%
Bangwar	200.00	52.63	0.00	0.00	0.00	0.00	180.00	47.37
Amalai	260.00	37.96	253.00	36.93	0.00	36.93	172.00	25.11

4.5 Microscopically recognizable constituents of Sohagpur coalfield

The coal is heterogeneous because it is formed from a variety of plants and tissues, with varied degrees of syngenetic and epigenetic changes. The heterogeneity of coal can be seen with the naked eye, but a microscopic examination of coal can show its contents in detail. Coal, like minerals in rocks, is made up of microscopic organic entities known as macerals. In addition to macerals, coals contain varying amounts of inorganic matter known as mineral matter. To eliminate uncertainty in the microscopic study of coal worldwide, the International Committee for Coal and Organic Petrology (ICCP) established standards and norms and characterized the microscopic components present in coal. The current naming scheme is known as the “ICCP system 1994”. At its 46th meeting in Oviedo (Spain), the International Committee for Coal and Organic Petrology (ICCP) approved a new set of definitions for the vitrinite group of macerals that differ significantly from the Stopes Heerlen System (Stopes 1935) included in the 1963 edition of the International Handbook of Coal Petrology (International Committee for Coal and Organic Petrology 1963). The new ICCP System 1994 defines the maceral group based on reflectance, the maceral subgroup based on the degree of destruction, and macerals are generally classified based on their morphology and/or degree of gelification (International Committee for Coal and Organic Petrology, 1998). The International Committee for Coal and Organic Petrology (ICCP) classified huminite (Sýkorová et al. 2005), inertinite (ICCP 2001), and liptinite (Pickel et al. 2017) using the ICCP system from 1994. Aside from identifying maceral and mineral matter, the ingredients are also classified into a combination of two or more macerals known as a microlithotype, and

into maceral-mineral relationships known as carbominerite. All microlithotypes have the suffix “ite” to distinguish them from macerals, which have the suffix “inite”.

4.5.1 Maceral

Macerals are the organic entities that are recognizable through a microscope. Stopes (1935) first used the word maceral for the isolated coal constituents from the maceration process, i.e., selective oxidation treatment. Sohagpur coals have the macerals of all groups: vitrinite, inertinite, and liptinite. The organic entities ‘macerals’ are classified according to their shape, hardness, colour, relief, internal structure, and reflectivity. The macerals of one group are similar in their chemical properties and scientific behaviour, but they differ greatly from those of other groups. Vitrinites are generated by the coalification of humic compounds such as lignin and cellulose derived from plant cell walls. Liptinites are made from particularly hydrogen-rich plant remnants such as sporopollenin, waxes, resins, and fats, whereas alteration of the original plant materials forms the inertinite. In a given rank of coal, vitrinites are relatively rich in oxygen, liptinites in hydrogen, and inertinites in carbon (Ward and Suárez-Ruiz 2008). Table 4.3 provides a comparison of the key characteristics of group macerals.

Table 4.3 Comparison of key characteristics of group macerals (Osborne, 2013).

Characteristics	Vitrinite	Liptinite	Inertinite
Abundance	Major	Minor	Major (during fire in mire or especially in Southern hemisphere coals) Dull and dusty
Appearance in hand specimen	Bright, vitreous, or glassy	Resinous	
Appearance under reflected light	Low to moderate and consistent reflectance	Relatively low in reflectance	Moderate to high and variable reflectance
Chemistry	Intermediate hydrogen content and volatile matter	Higher hydrogen content and volatile matter, more aliphatic	Lower hydrogen content and volatile matter, high carbon content
Reactivity during carbonisation	Reactive, principal reactive component of coking coals	Highly reactive	Inert

4.5.1.1 Vitrinite group

Stopes (1935) introduced the term Vitrinite, which derives from the Latin word vitrum, meaning glass. According to the new ICCP System 1994, the vitrinite group of macerals is classified as those with a grey colour and a reflectance between inertinite and liptinite. Because of geochemical gelification, open-textured, distinct huminite macerals combine to form more or less homogeneous vitrinite. Tables 4.4 and 4.5 present a correlation of the huminite macerals of brown coals and lignites (ICCP 1971, 1975) with macerals of bituminous coal (ICCP 1971, 1975) and vitrinite classification by the ICCP system 1994 (ICCP 1998). Hydrolysable plant materials such as disaccharides, starch, cellulose, hemicellulose, pentosans, pectins, and proteins break down during peatification and coalification to produce gaseous and liquid products such as carbon dioxide, ammonia, methane, and water, while the remaining humic materials contribute to the formation of coal. The preservation potential of lignin-rich wood is superior to that of cellulose-rich herbaceous plant tissues.

Table 4.4 Correlation of the huminite macerals of brown coals and lignite (ICCP 1971, 1975) and (Sýkorová et al. 2005).

Brown coal-lignite (ICCP 1971,75)				
Maceral Group	Maceral Subgroup	Maceral	Maceral type	
Huminite	Humotelinite	Texinite	Levigelite Porigelinite Phlobaphinite Pseudiphlobaphinite	
		Ulminite		
	Humocollinite	Gelinite		
		Corpohuminite		
	Humodetrinite	Attrinite Densinite		
transformation through maturation				
Maceral group	Maceral subgroup	Brown coal-lignite Maceral	Maceral type	Maceral variety
Huminite	Telohuminite	Textinite		A (dark)
		Ulminite		B (Light)
	Gelohuminite	Gelinite	Levigelite Porigelinite	A (dark)
				B (light)

Maceral group	Maceral subgroup	Brown coal-lignite Maceral	Maceral type	Maceral variety
		Corpohuminite	Phlobaphinite Pseudophlobaphinite	
	Detrohuminitite	Attrinite Densinite		
transformation through maturation				

Table 4.5 Correlation of the macerals of bituminous coals (ICCP 1971, 1975) and Vitrinite-94 (ICCP 1998).

Bituminous coal (ICCP 1971, 75)			Bituminous coal (ICCP 1994)		
Maceral type	Maceral	Maceral group	Maceral	Maceral Subgroup	Maceral
Telinite 1		Vitrinite	Telinite	Telovitrinite	Vitrinite
Telinite 2	Telinite		Collotelinite		
Telocollinite	Collinite		Corpogelinite	Gelovitrinite	
Gelocollinite			Gelinite		
Desmocollinite					
Corpocollinite			Vitrodetrinite	Detrovitrinite	
	Vitrodetrinite		Collodetrinite		
transformation through gelification					

4.5.1.1.1 Telovitrinite

The Latin words tela, which means tissue, and vitrum, which means glass, are the roots of the word telovitrinite. In 1994, the ICCP introduced the term. Telovitrinite is a subgroup within the vitrinite maceral group. It comprises vitrinites that retain their original botanical cell structure and are therefore typically identifiable in reflected white light due to their preserved cellular features. Telinite and collotelinite are the macerals that make up telovitrinite. These macerals predominance suggests that cell tissue is well preserved in wet, forested peatlands or forested wet raised bogs, which may have low pH levels.

Telinite

Telinite is made up of intact plant tissue with easily visible cell wall. Jongmans and Koopmans (1933) introduced the word “telinite” to describe vitrinite with apparent cell structure. The woody portions, leaves, and roots of plants are the source of telinite. Low-

rank coal frequently contains it. Its cell lumens vary in size, shape, and openness, which are mostly determined by the original plant material, section orientation, and deformation history. The cell lumens of telinite can be completely or partially filled with colloidal masses, resins, or minerals.

In Sohagpur coals, the concentration of telinite is less than 1%. The cell lumens are found to be filled with gelinite as shown in Figure 4.3a.

Collotelinite

Collotelinite is a homogeneous, nearly structureless maceral of vitrinite that develops through geochemical gelification, also known as vitrinitization. The rank of coal or organic sediment is ascertained using its reflectance value. In 1994, ICCP introduced the word “collotelinite” to describe a vitrinite maceral that had any botanical structure. It also derives from the roots, leaves, and woody portions of the plants. The infilling of colloidal humic gel in the cell lumens to telinite gives the collotelinite bands their uniform appearance. The reflectance of coals is only measured on the collotelinite maceral because it is considered as more reactive maceral. It participates actively in technical processes like liquefaction and coal carbonization.

In the coals from Sohagpur coalfield, collotelinite is found in patches as well, containing numerous desiccation cracks as shown in Figure 4.3, b. It is the dominant maceral of the vitrinite maceral group.

4.5.1.1.2 Detrovitrinite

The term detrovitrinite is derived from the Latin concepts detritus (abrasion) and vitrum (glass). The term was initially used by ICCP in 1994 to describe vitrinite particles. It shows that macerals from this subgroup are composed of finely fragmented vitrinitised

vegetative relics that appear solitary or cemented by amorphous vitrinitic materials. This subgroup includes the macerals collodetrinite and vitrodetrinite.

Collodetrinite

This maceral appears to be a mottled vitrinitic groundmass composed of vitrinite particles smaller than 10 μm . Collodetrinite lacks textural continuity and appears as uneven patches, with less pronounced layering perpendicular to the bedding. Collodetrinite contains a high concentration of volatile matter, which degasses and contributes to industrial processes such as carbonization and liquefaction.

In Sohagpur coals, the Collodetrinite maceral is present (Figure 4.3c), showing all bands at approximately 1%.

Vitrodetrinite

In 1970, the ICCP introduced the term vitrodetrinite to describe macerals that appear as separate vitrinite fragments of small size. It has spherical grains measuring less than 10 μm and thread-like measuring 10 μm in the minimum dimension. When surrounded by non-vitrinitic materials, the maceral distinguishes itself. Vitrodetrinite gels either before transit and deposition or after sedimentation. Vitrodetrinite is formed by the significant comminution of parenchymatous and woody tissues composed of cellulose and lignin in stems, roots, and leaves.

Vitrodetrinite is the second most abundant maceral of the vitrinite group after the collotelinite. The presence of this maceral in Sohagpur coals indicate great chemical decay or mechanical attrition of the peat (Figure 4.3, e).

4.5.1.1.3 Gelovitrinite

The term gelovitrinite derives from the Latin terms gelu and vitrum, which imply frost or stiffening and glass, respectively. The ICCP introduced this word in 1994. These macerals are formed by the gelification of humic solution obtained from plant cell breakdown as colloidal gels within voids or cavities, and they are not associated with any specific plant tissue. The macerals in the gelovitrinite subgroup include gelinite and corpogelinite.

Gelinite

In 1994, the name “gelinite” was accepted by the ICCP. Collinite and gelocollinite are which was previously used in the literature. Gelinite is a secondary maceral composed of structureless, homogenous infillings in cracks and voids that occur either as matrix embedding mylonitized coal particles or in cell cavities of funginite, fusinite, and semifusinite. It has the lowest relief and generally somewhat higher reflectivity than other vitrinites. During early diagenesis, humic colloids developed and precipitated as a colloidal gel.

Coal from the Sohagpur coalfield has a negligible amount of Gelinite presence (Figure 4.3g), it shows rarely in 2-3 samples.

Corpogelinite

The name corpogelinite is derived from two Latin terms: corpus (body) and gelu (stiffness). In 1994, the ICCP accepted the name ‘corpogelinite’. It has a homogeneous, structureless, and distinct body that is filled with humic cells. It may appear isolated, surrounded by fragmented bodies resulting from the degradation of the enclosing plant tissue, or it may be found in its original location, embedded within telovitrinite. Corpogelinite can be as large as 300 microns (Soos 1963). Its reflectance is higher than

that of other vitrinite macerals, which could be attributed to tannin oxidation (Stach et al. 1982). It has a smooth outline and can take the shape of a sphere, an oval, or an extended, shape depending on its position. Corpogelinite is primarily formed through the secretion of cell walls or tannin. Secondly, gel precipitated from humic solutions during the early stages of coalification. Corpogelinite was formerly referred to as phlobaphinite (Soos, 1963) and, in the case of brown coals, termed as corpocollinite.

Coal from the Sohagpur coalfield has a negligible amount of Gelinite (Figure 4.3d), which is rarely observed in a few samples.

Dark Vitrinite

In 1994, the ICCP defined the term “dark vitrinite” to describe vitrinite in steam coal that has low reflectance and high fluorescence when compared to typical vitrinite. The accompanying lipid components are responsible for their decreased reflectance. It is commonly found in sapropelic coal (cannel and boghead) and a few hydrogen-rich humic coals. Under white incident light, it appears dark grey, and when exposed to UV light, it fluoresces orange to dark brown. The fluorescence of dark vitrinite could be primary or secondary in origin. First, it creates fluorescence as a result of the incorporation of biopolymers into vitrinite, which diminishes from the peat formation stage to the subbituminous stage and is absorbed at 0.55 mean vitrinite reflectance. At a mean vitrinite reflectance of 0.8%, the secondary vitrinite fluorescence reaches its highest point. This stage also marks the second coalification jump, in which a lipid component in coal is adsorbed onto the vitrinite macerals (Teichmüller & Teichmüller 1982). Because of its high lipid and hydrogen content, black vitrinite actively participates in coal liquefaction. Very small amounts of Dark vitrinite maceral are found in a few seams of Sohagpur coals (Figure 4.3f).

Pseudovitrinite

Pseudovitrinite is also generated from parenchymatous or woody tissues of barks, roots, stems, and leaves that contain cellulose and lignin and are found in herbaceous and arborescent plants. It is distinguished by a higher reflectance than other vitrinite macerals (about 0.05% higher) in the same coal (Mastalerz et al. 2005). However, the decrease in reflectance differs by rank. It describes a transitional stage between vitrinite and inertinite, with chemical and optical qualities that fall somewhere between the two.

In the coals of the Sohagpur coalfield, Pseudovitrinite maceral is found commonly between the transition of Collotelinite to Semifusinite maceral, as shown in Figure 4.3h.

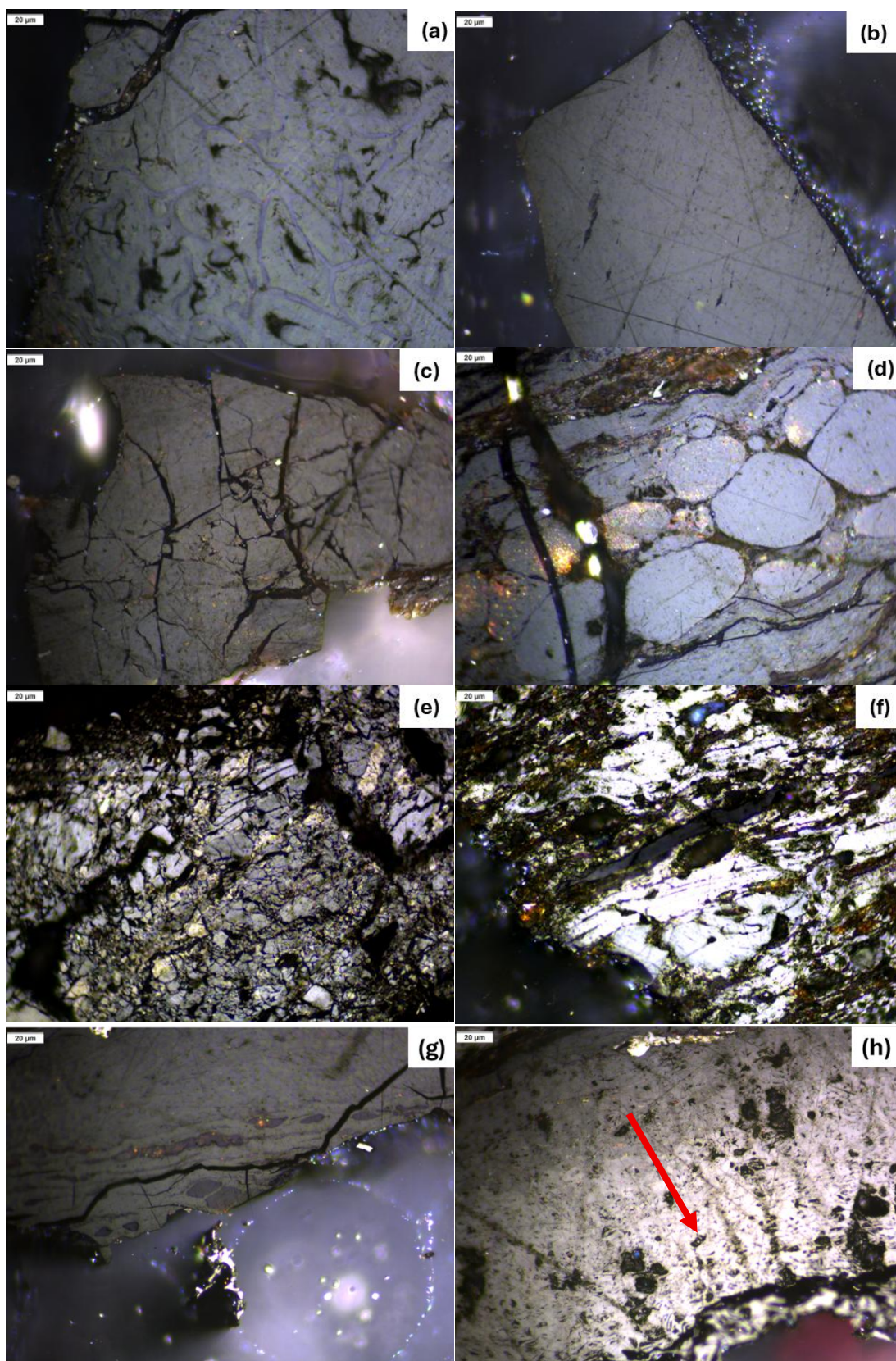


Figure 4.3 Representative photomicrograph of Vitrinite group of macerals (a- Telinite, b- Collotelinite, c- Collodetrinite, d- Corpogelinite, e- Vitrodetrinite, f- Dark Vitrinite, g- small patches of Gelinite, h- Transition from collotelinite to Pseudovitrinite and semifusinite).

4.5.1.2 Liptinite group

Ammosov (1956) proposed the term “liptinite” from the Greek word “Leiptos,” which means “to remain” or “to leave behind,” due to the great perseverance and resistance of these macerals. In the ICCP System 1994, the Liptinite group includes sporinite, cutinite, resinite, suberinite, exsudatinitite, alginite, chlorophyllinite, liptodetrinite, and bituminite (Pickel et al., 2017). Liptinite is generated from non-humifiable plant matter that is quite high in hydrogens, including sporopollen, waxes, resins, and lipids. The old literature used the term Exinite (Stopes 1935) to refer to the outermost wall (skin or exine) that occurs in coals. Later coalified leaf cuticles, as well as algae and resin-derived macerals were added to this group. However, Seyler (1932) had previously used the words resinite, alginite, sporinite, and cutinite to describe macerals generated from resin, algae, spores, and cuticles, respectively. Liptinite macerals appear dark grey to black when reflected in white light. The fluorescence colour of liptinite macerals varies from yellow (under blue light excitation) at low rank to orange at higher rank. They are hydrogen-rich and include more aliphatic elements. Alginite has the largest aliphatic-to-aromatic ratio, followed by bituminite, resinite, cutinite, and sporinite. As coalification progresses, identifying liptinite macerals becomes more difficult due to reflectance convergence with vitrinite and loss of fluorescence property (Pradier et al. 1991). The liptinite macerals, based on their morphology, can be divided into two types, primary liptinite macerals, having definite shape and morphology containing cutinite, resinite, suberinite, sporinite, alginite, and chlorophyllinite, and secondary liptinite macerals exhibiting no particular structure containing bituminite, exsudatinitite, and fluorinite macerals as shown in Table 4.6.

Table 4.6 Classification of Liptinite Group of Macerals (Pickel et al. 2017).

Maceral Group	Type	Maceral
Liptinite	Primary Liptinite Macerals	Cutinite Resinite

Maceral Group	Type	Maceral
		Suberinite
		Sporinite
		Alginite
		Chlorophyllinite
	Secondary Liptinite Macerals	Liptodetrinite
		Fluorinite
		Bituminite
		Exsudatinite

It is hard to identify unstructured liptinite macerals under white incident light because of their similarity with argillaceous minerals, so blue light irradiation was used for the identification of these macerals in Sohagpur coals using their fluorescence properties

4.5.1.2.1 Sporinite

Sporinite maceral is formed from the exines and perines of plant spores and pollen (Seyler, 1943). Low-rank coal retains its natural shape and appears hollow, ranging from spherical to triangular, or spindle-shaped. Guennel (1952) used the term ‘miospore’ to refer to both microsporinite and pollen grains because of their similarity. Sporinite ranges in size from 10 to 2000 μm . They are classified into two categories according to size: miospores (microsporinite), which are smaller in size and range from 20 to 180 microns, and megaspores, which are larger and exceed 200 microns. Megaspores often have weaker fluorescence than miospores. Sporinite is rusty brown, dark grey, or nearly black in low-rank coals. Sporinite can be thin walled (tenuisporinite) or thick-walled (crassisporinite). Thin-walled tenuispores are found in moist, arborescent lycopod swamps, whereas thick-walled crassisporinite occurs in relatively dry environments (Smith 1962). In high-rank coal, the sporinite turns light grey and eventually resembles the color of the vitrinite. Under blue-light radiation, sporinite emits fluorescence ranging from bright yellow to orange to brown, which fades at around 1.3% vitrinite reflectance. It is typically linked with bright layers of coal.

In the coals from Sohagpur coalfield, the occurrence of sporinite is mainly characterized by their brown to black colour in reflected light and bright yellow under blue light radiation (Figure 4.4a,f). It is the most dominant maceral of the liptinite group. The few occurrences of sporangia are also recorded from Sohagpur coals, as shown in Figure 4.4c and 4.4h.

4.5.1.2.2 *Cutinite*

Stopes (1935) introduced the term “cutinite” to describe the waxy cuticular covering seen on the epidermal tissues of leaves, stalks, shoots, needles, and thin stems. The maceral cutinite is composed of the cuticles (skin) of leaves and stems. Under white light, its colour ranges from dark gray to black, but under blue light, it fluoresces yellow or orange. When viewed perpendicular to the strata, it appears as narrow bands with one-sided serrated margins; however, except for the perpendicular plane in other planes, it can be confused with macrospores due to their similar appearance. Occasionally, the underlying epidermal cells can be seen. Cutinite is classified into two categories based on its size. Microcutinite sizes range from 20 to 180 microns, whereas megacutinite sizes exceed 200 microns.

In the Sohagpur coals, the presence of cutinite maceral is the second most abundant maceral of the liptinite group. They are identified by their serrated margin, as shown in Figure 4.4b and 4.4g.

4.5.1.2.3 *Resinite*

Stopes (1935) introduced the term “resinite” to describe the spindle-shaped, oval, spherical resinous substances that are created by plant metabolism. It might appear as infillings in telinite cell cavities, widespread impregnations, or distinct entities. In normal white light, it has a black to dark grey colour and can be round, oval, or rod-shaped. Its

zonal structure is often light gray and occasionally contains gas bubbles. It frequently exhibits orange or yellow hues with internal reflections of crimson. Under blue-light excitation, resinite exhibits fluorescence that ranges from yellow to orange to light brown, with the outer oxidation ring showing lesser fluorescence. Resinites are classified into two categories based on the precursor of liptinite: lipid resinites made from waxes and terpene resinites made from resins. Plant cell lumina are not visible in lipid resinites. Coal is a potential source of liquid hydrocarbons due to its high resinite content (Snowdon 1980; Snowdon and Powell 1982). Additionally, it could serve as a commercial source of multiple chemicals (Teot 1982).

Coal from the Sohagpur coalfield contains a very small amount of resinite maceral. Round to oval shaped of resinite of variable size is found in Sohagpur coals as shown in Figure 4.4d and 4.4i.

4.5.1.2.4 Suberinite

The primary source of suberinite, a maceral of the liptinite group, is coalified cell walls. It appears medium to dark grey, or nearly black, under reflected light. The fluorescence colour can range from lemon-yellow to yellow-orange and brown when excited by blue light. It shows roughly brick-like, rectangular, or irregular polygonal patterns. Suberinite and corpogelinite frequently coexist. It is the result of the suberization process, which forms suberin lamellae as wound tissue in plant bark, roots, and fruits following injury. Although it is uncommon in Mesozoic coals and unknown in Carboniferous coals, suberinite is frequently found in Cenozoic brown coal (Teichmüller 1989).

Coal from the Sohagpur coalfield does not contain the Suberinite maceral.

4.5.1.2.5 Alginite

The maceral of algal origin is called alginite. Hevia Rodríguez (1953) was the first to use the term alginite. Cook (1982) further referred to alginite as telalginite and lamalginite, respectively, after Hutton et al. (1980) classified it as alginite A and alginite B based on morphology. Commonly found in the form of distinct lenses, flattened disks, or fan-shaped masses, telalginite exhibits its botanical structure and appears dark in reflected white light. Its fluorescence intensity is high. In a marine environment, it can come from lipid-rich algae like *Tasmanites* and *Gloeocapsomorpha*; in a non-marine setting, it can come from *Botryococcus* and similar forms. Lamalginite is characterized by thin lamellae (less than 5 μm) and a smaller lateral extent (less than 80 μm). It usually lacks botanical features and is formed from tiny algae. In the marine environment, it can come from *Acritarchs* and *Dinoflagellates*, while in the lacustrine environment, it can come from *Pediastrum*. Both varieties of alginite contain a lot of hydrogen, mostly from aliphatic molecules. During pyrolysis, alginite produces a large amount of hydrocarbons due to its high H/C ratios. Alginite-rich coals can also be used for coal liquefaction. Paleoenvironments can also be inferred due to the presence of some of the algae. The presence of *Tasmanites* suggests a marine paleoenvironment, but *Botryococcus* often indicates a lacustrine environment, and *Pediastrum* indicates a freshwater paleoenvironment.

The alginite maceral is also present in very small amounts in Sohagpur coals; these macerals are a marine indicator of paleodepositional conditions.

4.5.1.2.6 Bituminite

In 1975, the ICCP introduced the term. Bituminite is a liptinite group maceral that lacks structure. White reflected light may result from internal reflection associated with its close relationship with adjacent mineral matter. The breakdown of bacteria, algae, faunal

plankton, and higher animal bodies under anoxic to suboxic conditions is the source of this substance. Numerous rocks that are oil sources have this maceral presence. High yields of bitumen, hydrocarbons, tar, and volatile matter are produced by this bituminous maceral, which is why it is called bituminite (Powell et al. 1982). Amorphous and lamellar forms of bituminite are seen in the decomposition of higher plants or algae, according to Cook (1982).

In Sohagpur coals, the Bituminite maceral is not present.

4.5.1.2.7 Fluorinite

Fluorinite is considered a type of resinite in the 1994 new ICCP System (Pickel et al. 2017). Teichmüller (1974) proposed the word “fluorinite” due to its distinctive fluorescence quality when exposed to incident fluorescence light. Plant oils or other liptinitic plant material are its source (Teichmüller 1974; Hutton 1987). With a lamellar or nodular form, fluorinite ranges in size from 0.1 µm to 0.5 µm. According to Mukhopadhyay et al. (1979), fluorinite is regarded as a secondary maceral that is formed during the oil generation process (Mukhopadhyay et al., 1979).

In the coals of the Sohagpur coalfield, fluorinite is present in very small amounts.

4.5.1.2.8 Exsudatinite

Teichmüller (1974) introduced the term “exsudatinite” to describe a maceral that is closely associated with the generation of liquid hydrocarbons. Exsudatinite is the solid remnant of a secondary petroleum-like substance that is produced during the coalification process by liptinite or maybe by perhydrous vitrinites. It is a secondary maceral that forms in voids such as cell cavities, fissures, and cracks as a result of coalification progresses (Teichmüller 1974). It typically shares characteristics with the maceral from which it is generated, such as colour, reflectance, and fluorescence.

In the coals of the Sohagpur coalfield, exsudatinites are present in low amounts.

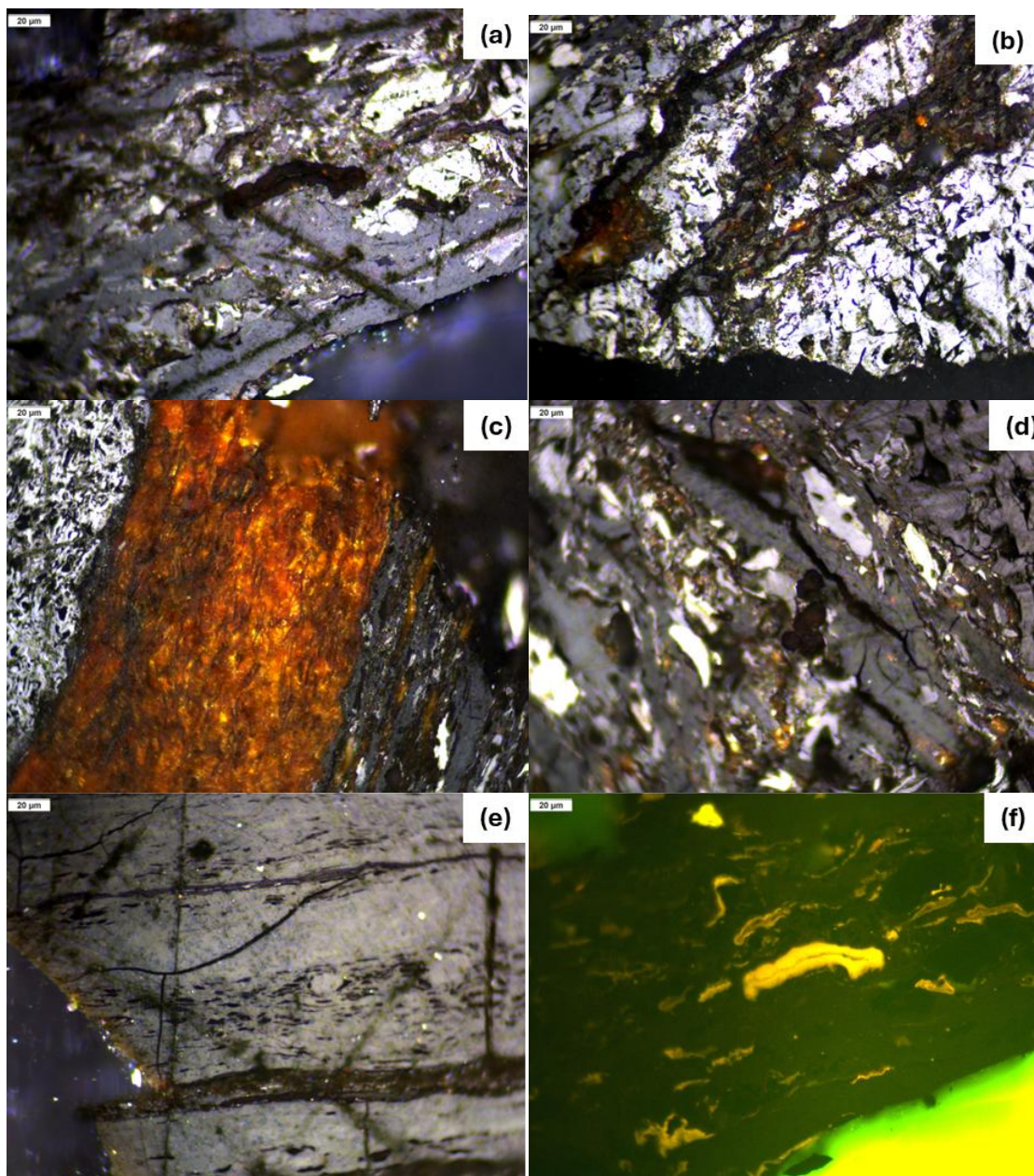
4.5.1.2.9 Liptodetrinite

A maceral of the liptinite group, liptodetrinite, is formed when other liptinite fragments are a result of mechanical or biochemical deterioration. The word was originally used by the ICCP in 1971. It can be either black, dark grey, or dark brown. Depending on the precursor material and coalification stage, the fluorescence colour can range from greenish yellow to yellow, orange, or light brown. It is extensively found in both coal and non-coal sedimentary rocks. Along with detrovitrinite, resinite, and sporinite, liptodetrinite is observed to associate with attrital layers.

Liptodetrinite is present in the coals from Sohagpur coalfield, which shows the presence of mechanical and biochemical degradation of other liptinite macerals as shown in Figure 4.4e and 4.4j.

4.5.1.2.10 Chlorophyllinite

The term chlorophyllinite was originally used by ICCP in 1971. A member of the liptinite group, chlorophyllinite is a tiny, spherical material with a diameter of 1 to 5 μm . It red fluorescence that weakly turns orange after a few minutes of stimulation. When viewed in reflected white light, it appears black and can be mistaken for liptodetrinite. Plant chloroplasts, which are found in leaves, young stems, and fruits, are the source of chlorophyllinite. Chlorophyll fossilization is favoured by a severe anaerobic environment.



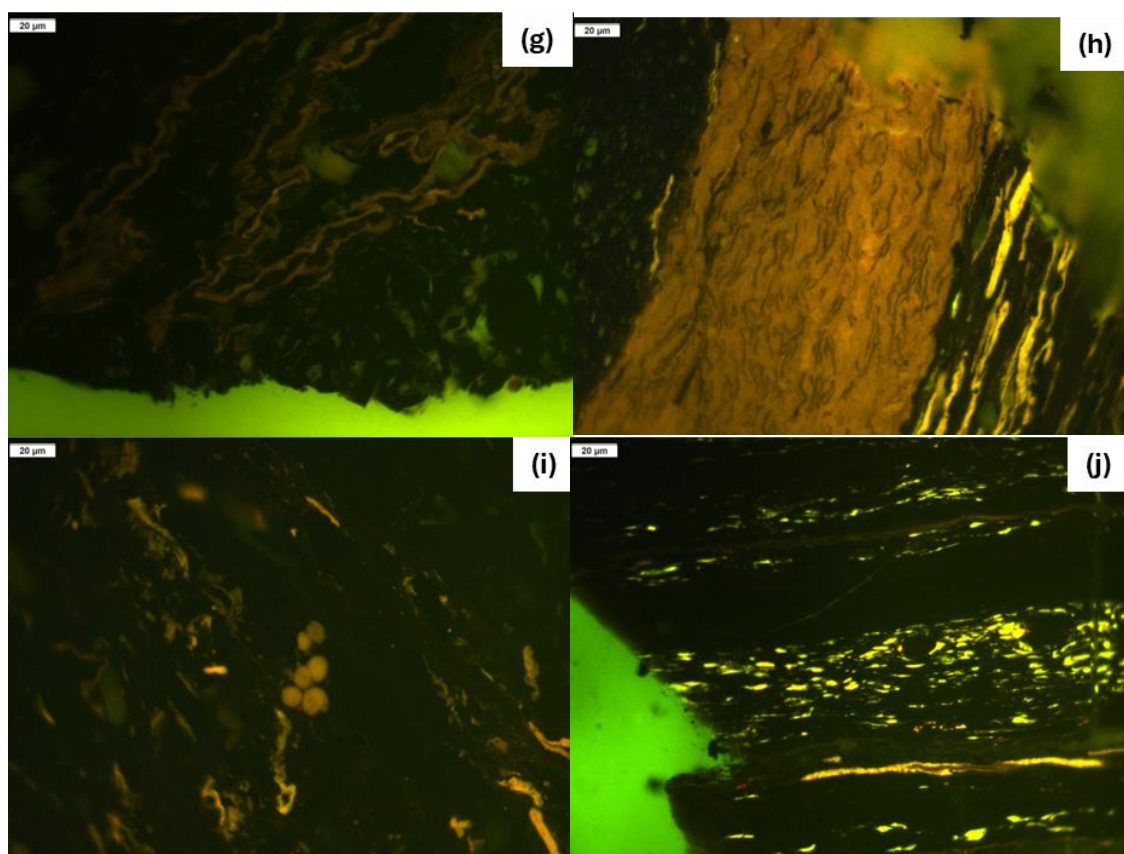


Figure 4.4 Representative photomicrograph of the Liptinite group of macerals (a- Sporinite, b- Cutinite, c- Sporangium, d- Resinite, e- Liptodetrinite, f- fluorescent image of Sporinite (a), g- fluorescent image of Cutinite (b), h- fluorescent image of Sporangium (c), i- fluorescent image of Resinite (d), j- fluorescent image of Liptodetrinite (e)).

4.5.1.3 Inertinite group

Among the macerals of low and medium rank coal, inertinite is a group that shows greater reflectance than those of vitrinite and liptinite groups. The following macerals are classified under the new inertinite classification (ICCP System 1994): fusinite, semifusinite, micrinite, macrinite, inertodetrinite, funginite, and secretinite. This new categorization substitutes funginite and secretinite macerals for the former sclerotinite macerals. The word “inertinite” comes from the Latin “inertia,” which means “inactivity.” Suárez-Ruiz and Crelling (2008) state that throughout the carbonization process, the inertinite group’s macerals are more inert than other macerals. The fluorescence of inertinite macerals is either nonexistent or very weak. Whereas macerals like secretinite,

macrinite, and micrinite lack plant cell structure, the macerals fusinite, semifusinite, and funginite do (Table 4.7). Other inertinite macerals are thought to fragment to generate inertodetrinite. The tissues of fungi or higher plants at different stages of compaction are the source of inertinite macerals, which primarily reflect the depositional environment. It can also come from cell secretions altered by biological redox reactions during coalification, gelified amorphous material, or tiny detrital particles. Compared to other macerals, inertinite macerals have a higher carbon content but lower hydrogen and oxygen content.

Wildfires play a major role in the formation of inertinite, as intense heating and partial combustion of vegetation during fires convert organic matter into highly carbon-rich, inert residues. These fire-derived charred materials become preserved in sediments as inertinite macerals. Additionally, oxidative degradation occurs when plant material is exposed to oxygen during surface weathering or low-temperature burning, leading to chemical alteration, loss of reactive compounds, and increased resistance to further decomposition. Together, wildfire activity and oxidation can form the Inertinite macerals.

Table 4.7 Macerals of the inertinite group (International Committee for Coal and Organic Petrology 2001).

Maceral property	Nomenclature
Macerals with cell structures:	Fusinite Semifusinite Funginite
Macerals lacking plant cell structures:	Secretinite Macrinite Micrinite
Fragmented inertinite:	Inertodetrinite

4.5.1.3.1 Fusinite

Stopes (1935) was the first to use the term fusinite. The well-preserved cell structure of parenchyma, collenchyma, or sclerenchyma made of lignin and cellulose is exhibited by fusinite maceral, which has a high reflectance. Usually empty, fusinite's cell lumina can

occasionally include minerals, gelinite, or exsudatinite. It can appear as arc-shaped pieces of collapsed previous cell tissues (Bogen structure) or as normal, well-preserved tissues with empty cell lumina (sieve structure). The colour of fusinite ranges from greyish white to yellowish-white, it cannot glow. Pyrofusinite is the type of fusinite that is created by wildfire, while degradofusinite is the type that is produced by bacterial action that decarboxylates plant tissues or by dehydration and weathering (Scott 2002). Degradofusinite has a high reflectivity, a greyish-white colour, and a well-developed cellular structure. The stage of transition between collotelinite and degradofusinite can occasionally be observed. Compared to degradofusinite, pyrofusinite has a greater reflectivity and a well-preserved yellowish-white to white cell structure. Fusinite typically concentrates on fine particles since it is friable.

Fusinite is present in all coal samples from the Sohagpur coalfield and makes a great contribution to the inertinite group of macerals (Figure 4.5d). In fusinite, both types of pyro and degradofusinite have been observed in Sohagpur coals. Pyrofusinite forms due to intense heating and charring of plant material during wildfires. High temperatures cause thermal alteration and partial combustion, producing highly carbonized, reflective inertinite macerals. Degradofusinite results from strong oxidative degradation of plant tissues under low-temperature oxidation or prolonged exposure to oxygen. This process alters cell structures, increases carbon concentration, and produces inertinite without direct high-temperature burning.

4.5.1.3.2 Semifusinite

Between fusinite and collotelinite, semifusinite has a structure and reflectance that are in between. Jongmans et al. (1938) introduced the word “semifusinite”. It has hazy or partially visible cell cavities that are usually empty or occasionally filled with minerals such as clay or other macerals such as exsudatinite. Longer wavelength irradiation can

reveal fluorescence in these materials, which diminishes with the degree and rank of oxidation and dehydration. Low reflectance and noticeable fluorescence in semifusinite could be signs that bituminous matter has been absorbed by it.

In coal from the Sohagpur coalfield, semifusinite is also found in a very large amount (Figure 4.5, c).

4.5.1.3.3 Macrinite

Stach and Alpern (1966) introduced the word “macrinite” to describe a large, non-granular, inertinite maceral with high reflectivity. Because of the decreased water table during early peatification, flocculated humic matrix materials, the source of macrinite, go through redox and dehydration processes (International Committee for Coal and Organic Petrology 2001). According to additional research, macrinite was severely altered by non-plant entities (fungi, bacteria, and animals) and may have come from the coprolites of wood-eating and coprophagous insects that have been around for several generations (Hower et al. 2009, 2011, 2013a, b; O’Keefe et al. 2013). It can appear as amorphous matrices ranging in size from 10 μm to 40 μm or as distinct, structureless solids of varying shapes.

The presence of macrinite is noticed in the coals from the Sohagpur coalfield (Figure 4.5, b).

4.5.1.3.4 Micrinite

Stopes (1935) used the term ‘micrinite’ to describe an inertinite maceral with small, spherical grains. Thiessen (1920) was one of the first to recognize and demonstrate the maceral in photomicrographs. Ammosov (1956) named this maceral mixtinite to explain the combination of vitrinite and micrinite. According to Diessel (1992), the micrinite was less than 2 μm in size. It is assumed to have developed from the coalification of previous

sclerenchyma or lipid compounds, particularly bituminite and hydrogen-rich vitrinite (Stach 1968; Teichmüller 1971).

In coals of the Sohagpur coalfield, micrinite shows pale grey to white colour with higher reflectance than vitrinite macerals but often lower than other inertinite macerals of the same coal (Figure 4.5, a).

4.5.1.3.5 Secretinite

Lyons et al. (1986) originally used the term ‘secretinite’ to describe a maceral of the inertinite group with high reflectivity and a round to oblong, non-cellular shape. In 1997, the ICCP officially accepted the word. It may have an oxidized rim with low or high reflectivity and interior notches. It ranges from pale grey to yellowish white in tone. It does not glow when excited with blue light. Secretinite’s greater reflectivity provides significant alleviation. Secretinite sizes typically range from 60 µm to 400 µm.

Coals of the study area show the presence of secretinite macerals, and it is generally recognized by its internal notches and high reflectance (Figure 4.5e)

4.5.1.3.6 Funginite

Funginite maceral is formed by the oxidation or humic gelification of single or multicellular fungal spores, sclerotia, hyphae, mycelia, and other fungal remnants. Funginite ranges in tint from pale grey to white, with a rare yellowish white. It can range from roundish unicellular to multicellular oval in Cenozoic and newer deposits.

4.5.1.3.7 Inertodetrinite

The name ‘inertodetrinite’ was proposed by Stach & Alpern (1966) and used by ICCP in 1971 to describe small (<10 µm) inertinite pieces of different shapes. It is not luminous, but the colour of the coal can change greatly from light grey to white. Its shape and degree are mostly determined by the level of desiccation, mechanical crushing, and

attrition of fusinized plant cell walls, phlobaphene, spores, or fungal-affinity elements. They were most likely caused by wildfires on or near the peatland.

In coals of the Sohagpur coalfield, inertodetrinite is present in good concentration, which shows the mechanical degradation of other macerals of the inertinite group (Figure 4.5f).

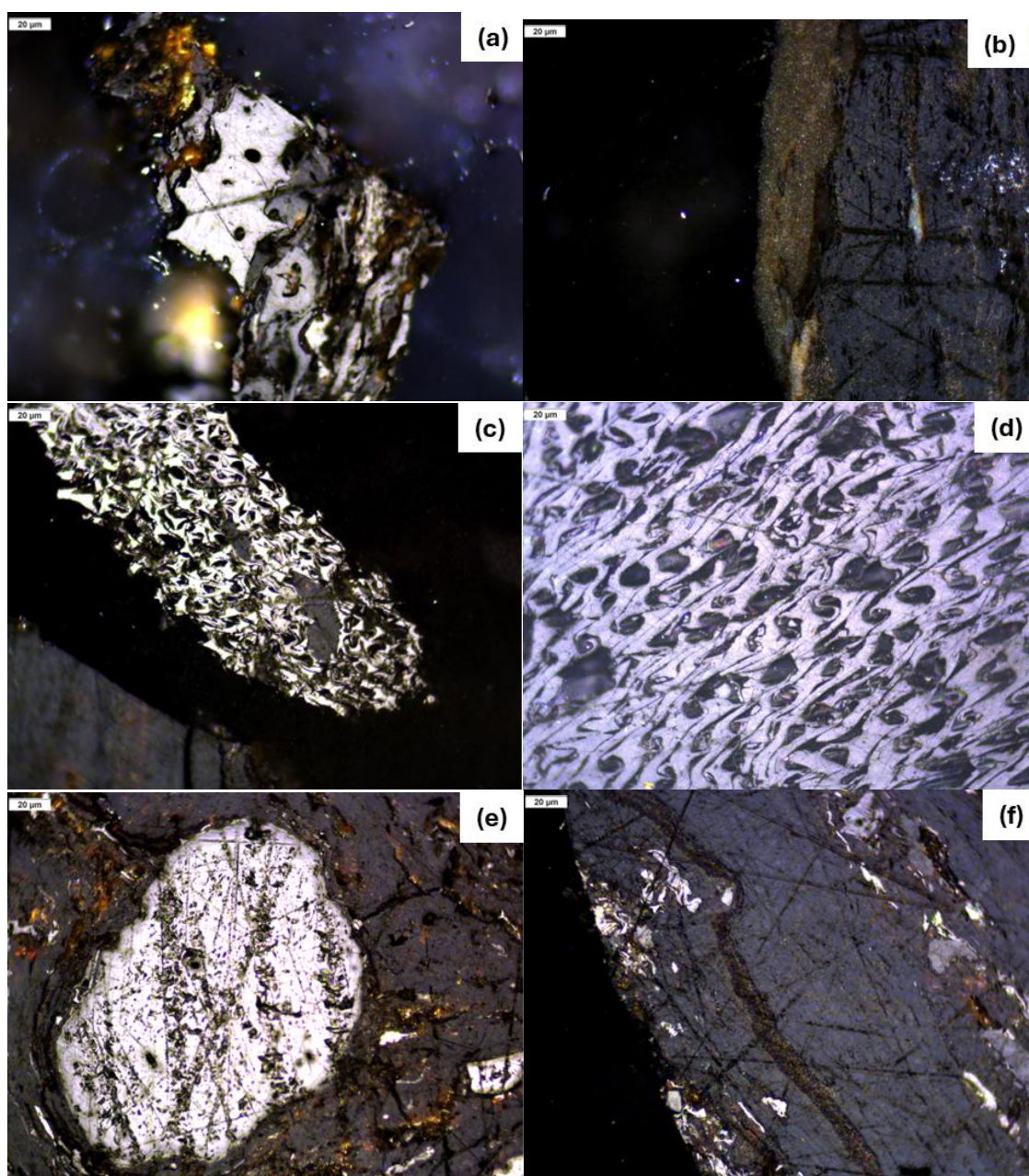


Figure 4.5 Representative photomicrograph of the Inertinite group of macerals (a- Macrinite, b- Micrinite, c- Semifusinite, d- Fusinite, e- Secretinite, f- Inertodetrinite (white particles)).

4.5.2 Mineral matter

Coal is a heterogeneous sedimentary rock composed primarily of organic matter derived from plant material, along with varying proportions of inorganic constituents commonly referred to as mineral matter. The nature, origin, and distribution of mineral matter in coal strongly influence its physical properties, beneficiation behaviour, combustion characteristics, and environmental impact (Ward, 2002). A thorough understanding of mineral matter in coal is therefore essential for coal utilization, coalbed methane studies, and paleodepositional reconstruction.

The inorganic matter in coal comprises all non-organic constituents, including crystalline minerals, amorphous inorganic phases, and inorganic elements associated with the organic matrix. It is commonly estimated indirectly from ash yield, although ash does not represent the original mineral assemblage due to mineral transformations during combustion (Gluskoter, 1967; Ward, 2002).

Major inorganic components of coal include silica (SiO_2), alumina (Al_2O_3), iron oxides, calcium, magnesium, alkalis, and sulfur-bearing phases. These components are hosted in a variety of minerals including quartz, clay minerals, carbonates, sulfides, and sulfates. Trace elements, including environmentally sensitive elements such as arsenic, mercury, and selenium, are also part of the inorganic fraction and may occur in both mineral and organically associated forms. Mineral matter in coal originates from both syngenetic and epigenetic processes and may be present as discrete mineral grains, finely disseminated particles, or organically bound inorganic elements (Taylor et al., 1998). During coal formation, mineral matter undergoes significant physical and chemical modification, particularly during diagenesis, leading to the formation of diagenetic and authigenic minerals. These minerals contribute to the overall inorganic fraction of coal and affect ash yield and composition upon combustion.

Diagenetic minerals are those formed or significantly altered during the early post-depositional stages of coalification, prior to deep burial and metamorphism. These minerals are typically formed by chemical reactions involving pore waters, detrital minerals, and organic matter under low-temperature, low-pressure conditions (Taylor et al., 1998). Common diagenetic minerals in coal include pyrite, siderite, calcite, and certain clay minerals such as kaolinite and illite. Pyrite is one of the most abundant diagenetic minerals and forms under reducing conditions through the reaction of iron with sulfur derived from bacterial sulfate reduction. The morphology of pyrite: framboidal, euhedral, or massive provides valuable information on the redox conditions and timing of mineral formation within the peat and early coal-forming environment.

Diagenetic processes may also involve the recrystallization or chemical alteration of detrital minerals, leading to changes in mineral composition and texture. These transformations play a critical role in determining the final mineral assemblage preserved in coal seams.

Authigenic minerals are those that crystallize in situ within the coal matrix from solution, rather than being transported as detrital grains. In coal, authigenic mineralization commonly occurs during peat accumulation, early diagenesis, or later burial stages, often influenced by changes in pH, redox conditions, and fluid chemistry (Ward, 2002).

Typical authigenic minerals in coal include pyrite, carbonates (calcite, siderite, dolomite), quartz overgrowths, and phosphates. Authigenic clay minerals may also form through the alteration of volcanic ash layers, which are widespread in many coal-bearing sequences and serve as important stratigraphic markers. The distribution of authigenic minerals is often closely associated with specific macerals or microenvironments within the coal seam, reflecting localized geochemical conditions. Their presence has significant

implications for coal cleaning efficiency, ash behaviour, and the pollutants release during coal utilization.

The quantity, composition, and mode of occurrence of mineral matter in coal strongly influence its technological and environmental performance. High mineral matter content generally reduces calorific value and increases ash production, while specific minerals such as pyrite contribute to sulfur emissions and acid mine drainage (Ward, 2002). From a geological perspective, mineral matter provides valuable insights into peat-forming environments, sedimentary processes, and post-depositional history.

4.5.2.1 Argillaceous mineral matter

Clay minerals present in coals are known as argillaceous. They may occur as coal groundmass, as fissure filling, fracture filling, cavities, or mineral filling in cleats. They may also inhabit the cell lumens of telinite, fusinite, and secretinite. These minerals have a dark colour. Coal from the Sohagpur coalfield shows a high amount of argillaceous mineral matter (Figure 4.6, a).

4.5.2.2 Carbonate mineral matter

Carbonate minerals are formed through secondary precipitation. They can appear as infillings in cell cavities, fissures, and cleats. Carbonate mineral matter is also present in a significant amount (Figure 4.6b).

4.5.2.3 Pyrite

Pyrite can be found in a different forms, such as discrete, framboidal masses, fissure or crack infillings, large replacements, and dissemination (Figure 4.6, c, d). It has been observed during the microscopic study that the concentration of pyrite is comparatively lesser than argillaceous and carbonate mineral matter. Framboidal pyrite is a characteristic feature of Tertiary coals.

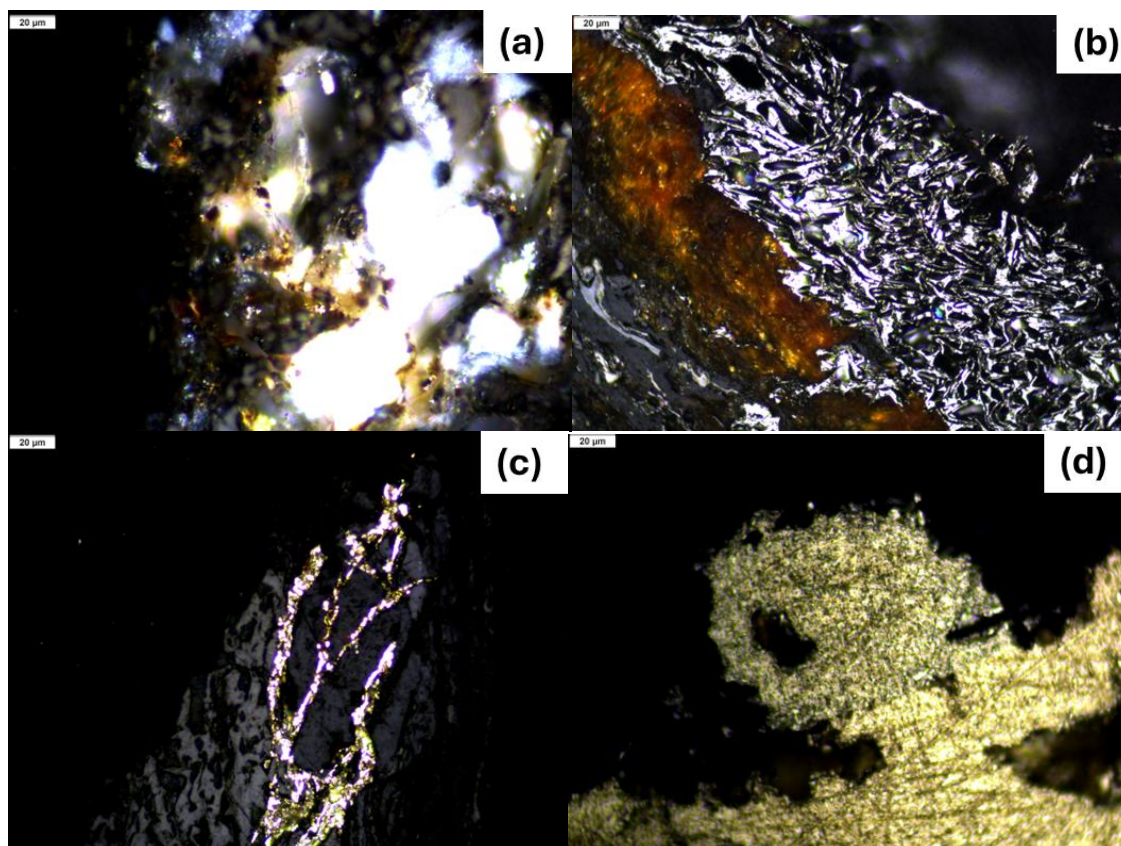


Figure 4.6 Representative photomicrograph of the mineral matters present in these coals (a- Argillaceous mineral matter, b- Carbonate mineral matter, c- Pyrite in disseminated form filled in cracks, d- a single patch of Pyrite).

4.5.3 Microlithotype and Carbominerite

Seyler (1952) introduced the term ‘microlithotype’. The maceral and mineral content of a coal seam can vary over short distances both vertically and laterally, depending on the conditions that existed during the development of the initial peat bogs (Stach et al., 1982). These variations can be evaluated through petrographic analysis of the maceral-maceral and maceral-mineral assemblages known as microlithotype and carbominerite, respectively. It may also aid in assessing coal properties for technological and industrial applications.

Natural occurrence of combinations of macerals known as microlithotype. In 1971, the ICCP established two criteria for the identification of microlithotypes. According to these

rules, the minimum area required to define a microlithotype is $50\ \mu\text{m} \times 50\ \mu\text{m}$. Additionally, the “5% rule” states that a microlithotype may contain up to 5% accessory macerals. The microlithotype is characterized as monomaceral (macerals from one group covering more than 95% of the surface area of $50\ \mu\text{m} \times 50\ \mu\text{m}$), bimaceral (association of macerals from two groups), or trimaceral (combination of macerals from all three groups combined). The assemblage of maceral and mineral matter is known as a carbominerite. The analysis of microlithotype and carbominerite was performed simultaneously to maceral and mineral matter analysis under white and fluorescent light.

4.5.3.1 Monomaceral microlithotype

4.5.3.1.1 Vitrite

When more than 95% area in the Kotter graticule is covered by the Vitrinite group, then microlithotype is known as vitrite. This group may be further subdivided into collite and telite microlithotypes based on the presence of collotelinite and telinite macerals. Figure 4.7a shows the vitrite microlithotype.

4.5.3.1.2 Liptite

A Liptite microlithotype is a region in the Kotter graticule, where more than 95% of the area is covered by the liptinite group of macerals. This can be further subdivided into the sporite, cutite, resite and algite based on the concentration of representative macerals. Figure 4.7b shows the liptite microlithotype.

4.5.3.1.3 Inertite

In Inertite microlithotype, the inertinite group maceral cover of more than 95% area in the Kotter graticule region. This can be further subdivided into semifusite, fusite, sclerotite, inertodetrinite and macrite based on the concentration of representative macerals. In Figure 4.7c the presence of inertite macerals is shown.

4.5.3.2 Bimaceral microlithotype

4.5.3.2.1 *Clarite*

A combination of vitrinite and liptinite is known as the clarite bimaceral microlithotype. In the Kotter graticule region, there should be at least 95% relationship between these two macerals. “Clarite-V” refers to a clarite bimaceral that is dominated by vitrinite group macerals, while “clarite-L” refers to a dominant liptinite group.

4.5.3.2.2 *Durite*

The combination of liptinite and inertinite group macerals is known as the durite bimaceral microlithotype. In the Kotter graticule region, these two maceral groupings ought to be at least 95% associated. The terms durite-L and durite-I are used according to the dominance of liptinite and inertinite, respectively.

4.5.3.2.3 *Vitrinertite*

The vitrinertite is formed by the combination of vitrinite and inertinite. At least 95% of these two maceral groups should lie in the Kotter graticule region. Vitrinertite-V or vitrinertite-I, respectively, are used to indicate whether vitrinite or inertinite is dominant. In Figure 4.7d, the vitrinertite V is shown.

4.5.3.3 Trimaceral microlithotype

When all the 3 groups of macerals are present in the Kotter graticule region, and each group covers at least 5% region, the term known as trimaceral microlithotype. Depending on the dominance of individual maceral groups this divide into three sections-

4.5.3.3.1 *Duroclarite*

The combination of the three macerals (liptinite, inertinite, and vitrinite) is known as the duroclarite trimaceral microlithotype. Vitrinite dominates the association of these three

macerals, followed by liptinite and inertinite. Each maceral's concentration in the Kotter graticule region should be greater than 5%.

4.5.3.3.2 *Clarodurite*

The combination of the three macerals (liptinite, inertinite, and vitrinite) is known as the clarodurite trimaceral microlithotype. The concentration of each of these three macerals should be greater than 5% in the Kotter graticule region, with inertinite dominating the association, followed by vitrinite and liptinite. The representative photomicrograph of clarodurite is shown in Figure 4.7, f.

4.5.3.3.3 *Vitrinertoliptite*

A combination of the three macerals (liptinite, inertinite, and vitrinite) is known as the vitrinertoliptite trimaceral microlithotype. Liptinite dominates the association of these three macerals, with huminite and inertinite following. Each maceral's concentration in the Kotter graticule region should be greater than 5%. The classification scheme for the microlithotype of hard coal is shown in Table 4.8.

Table 4.8 Microlithotype classification scheme for hard coal.

Microlithotype Group	Maceral composition and quantity (Vol.%)	Microlithotype
Monomaceral	V > 95%	Vitrite
	L > 95%	Liptite
	I > 95%	Inertite
Bimaceral	V + L > 95% and V > L (Each >5%)	Clarite V
	V + L > 95% and L > V (Each >5%)	Clarite L
	V + I > 95% and V > I (Each >5%)	Vitrinertite V
	V + I > 95% and I > V (Each >5%)	Vitrinertite I
	I + L > 95% and I > L (Each >5%)	Durite I
	I + L > 95% and L > I (Each >5%)	Durite L
Trimaceral	V + I + L > 95% and V > I & L (Each >5%)	Duroclarite
	V + I + L > 95% and L > I & V (Each >5%)	Vitrinertoliptite
	V + I + L > 95% and I > V & L (Each >5%)	Clarodurite

At the microlithotype level, the coals from the Sohagpur coalfield are rich in monomaceral with Vitrite and Inertite as the dominant microlithotype (Figure 4.7a and 4.7c). Liptite is also identified where the sporangium of another patch of liptinite maceral

is found (Figure 4.7b). The Bimaceral is the second most dominant, with Vitrinertite being the most dominant microlithotype in these coals (Figure 4.7d and 4.7e). The presence of trimaceral is also shown in Sohagpur coals, which are dominated by Clarodurite (Figure 4.7f).

4.5.3.4 Carbominerite

4.5.3.4.1 Carbargilite

An association between clay minerals and another maceral group is known as the carbargilite carbominerite microlithotype. In this association, the Kotter graticule region should contain 20–60% clay minerals.

This is the most dominant carbominerite group that observed in the Sohagpur coals, as shown in Figure 4.7, h.

4.5.3.4.2 Carbankerite

Carbankerite carbominerite microlithotype is defined as the combination of carbonate minerals and another maceral group. In this association, the Kotter graticule should contain 20-60% carbonate minerals.

This is the second most dominant group of carbominerite, which is present in Sohagpur coals (Figure 4.7, g).

4.5.3.4.3 Carbopyrite

Carbopyrite carbominerite microlithotype is defined as the association of pyrite (sulphide mineral) with other maceral groups. In this association, the Kotter graticule region should contain at least 5-20% pyrite. This is also present in a significant amount in the Sohagpur coals.

4.5.3.4.4 Carbopolyminerite

The word carbopolyminerite refers to the connection of different minerals with other maceral groups. In this association, the percentage of different minerals in the Kotter graticule region should range from 20 to 60%. The presence of carbominerite also occurred in a few samples.

The Carbominerite classification scheme is shown in Table 4.9.

Table 4.9 Classification scheme of carbominerite.

Carbominerite Group	Mineral composition and quantity (Vol. %)	Carbominerite
	Coal macerals + 20-60% clay minerals	Carbargilite
	Coal macerals + 20-60% carbonate minerals	Carbankerite
	Coal macerals + 20-60% various minerals	Carbopolyminerite
	Coal macerals + 5-20% sulphide minerals	Carbopyrite

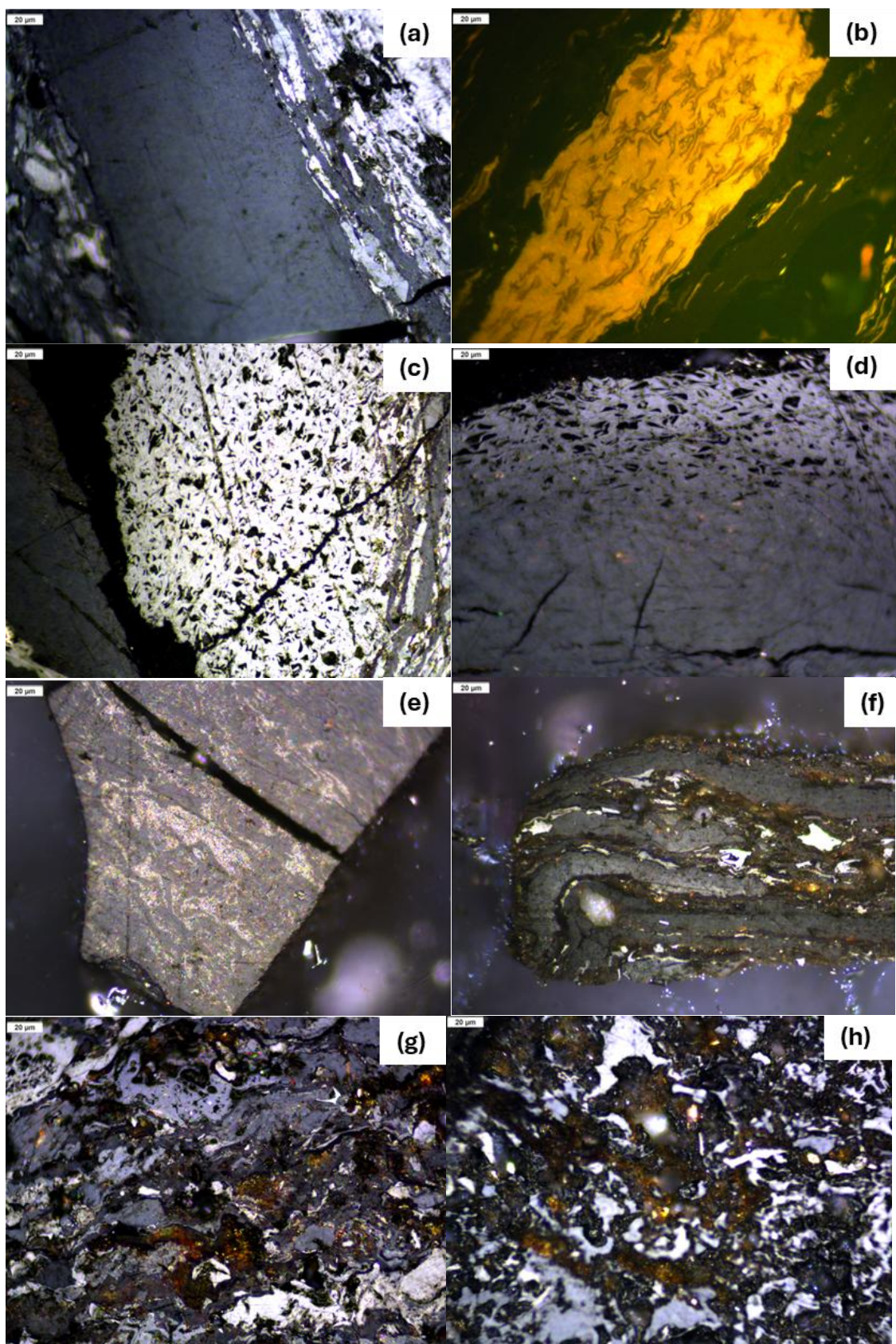


Figure 4.7 Representative photomicrograph of the Microlithotype and carbominerite (a- Vitrite, b-Liptite, c- Inertite, d- Vitrinertite V, e- Vitrinertite I, f- Clarodurite, g- Carbankerite, h- Carbargilite).

4.6 Occurrence of microscopic constituents in Sohagpur coals

The ternary diagram shows the relative percentage of all three maceral groups present in the different seams of the Sohagpur coalfield, shown in Figure 4.8 and Table 4.10. This figure clearly shows the dominance of vitrinite and inertinite group macerals in comparison with liptinite macerals.

In the Sharda seam, vitrinite is the dominant maceral among the three maceral groups, with a mean value of 47.76% on a mineral-matter-free (mmf) basis. In contrast, the Dhanpuri mine is characterized by the dominance of inertinite macerals, which average value 48.07% (mmf basis), indicating a comparatively higher contribution from oxidized or inert organic matter. The Rajendra and Khairaha VI seams are again vitrinite-rich, with vitrinite contents of 46.67% and 52.97%, respectively, suggesting favourable conditions for the preservation of gelified plant material. Conversely, the Khairaha VII seam shows inertinite as the dominant maceral group, accounting for 49.76% on an mmf basis, reflecting relatively drier or more oxidizing peat-forming conditions.

Within the Damini VI seam, notable site-specific variation is observed. The first site is dominated by vitrinite macerals, comprising 53.16% (mmf basis), whereas the second site is dominated by inertinite macerals, with a mean value of 45.64%. This variation highlights localized changes in depositional or post-depositional conditions within the same seam. Furthermore, the Damini V, Bangwar, and Amalai seams are all characterized by inertinite dominance, with inertinite contents of 53.45%, 47.13%, and 53.09% (mmf basis), respectively. Overall, the maceral distribution patterns across the studied seams indicate significant spatial variability, reflecting differences in peat accumulation environments, degrees of oxidation, and organic matter preservation.

Petrographic analysis was carried out using both white reflected light and fluorescent light. White light microscopy was used for the identification of vitrinite and inertinite

macerals. In contrast, liptinite macerals were identified using a combination of white and fluorescent light due to their characteristic fluorescence behaviour, similar to that observed for certain mineral matter. The quantification was performed using the point counting method on a volume % basis, in accordance with ISO standard for the petrographic analysis.

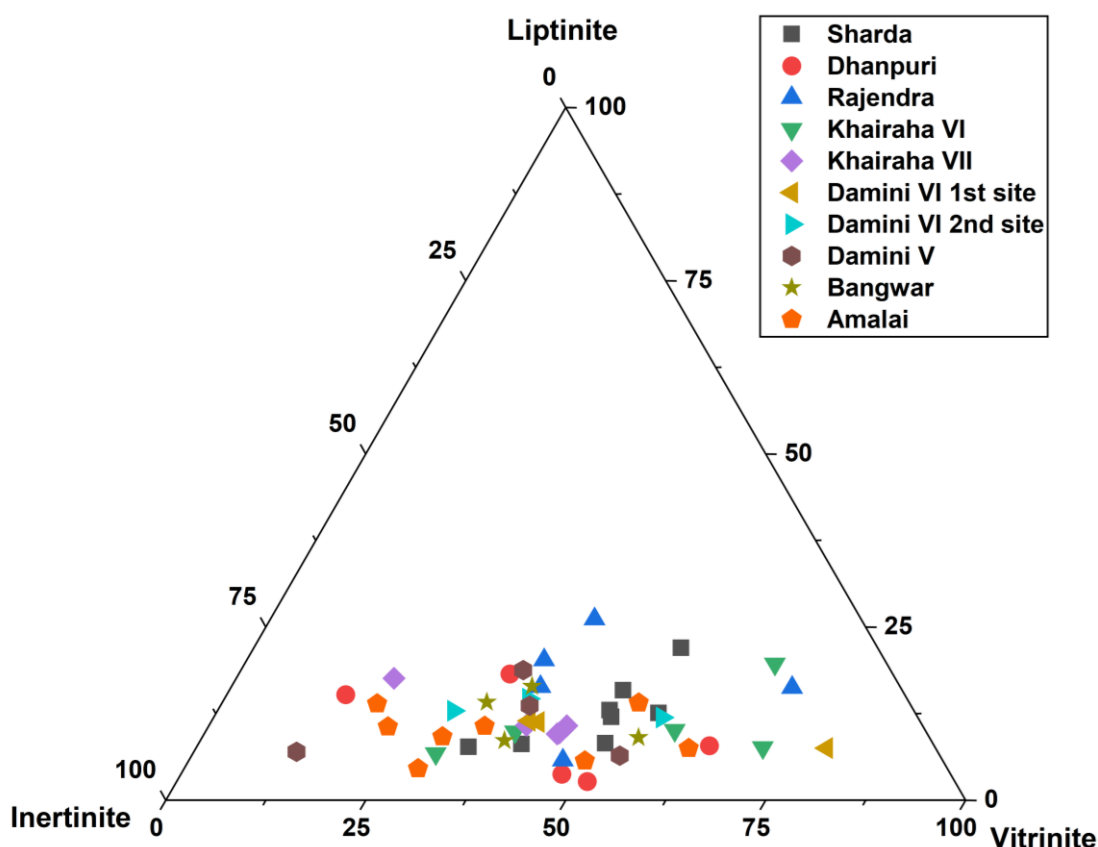


Figure 4.8 Distribution of a group of macerals in Sohagpur coals.

Table 4.10 Frequency distribution of group maceral and mineral matter (in volume %) in coals from Sohagpur coalfield.

Mine/Seam with band no.	with mineral matter				on mineral matter free basis		
	Vitrinite	Liptinite	Inertinite	Mineral Matter	Vitrinite	Liptinite	Inertinite
Sharda							
1	42.0	6.8	33.8	17.4	50.9	8.2	40.9
2	26.9	6.1	46.1	20.9	34.0	7.7	58.3
3	43.9	10.6	33.8	11.7	49.7	12.0	38.3
4	46.9	10.7	27.2	15.3	55.3	12.6	32.1
5	44.1	11.7	34.2	10.1	49.0	13.0	38.0
6	43.3	14.0	30.7	12.1	49.3	15.9	34.9
7	46.1	19.0	21.2	13.7	53.4	22.0	24.6

Mine/Seam with band no.	with mineral matter				on mineral matter free basis		
	Vitrinite	Liptinite	Inertinite	Mineral Matter	Vitrinite	Liptinite	Inertinite
8	36.7	7.3	46.7	9.2	40.4	8.1	51.5
Avg	41.2	10.8	34.2	13.8	47.8	12.4	39.8
Min	26.9	6.1	21.2	9.2	34.0	7.7	24.6
Max	46.9	19.0	46.7	20.9	55.3	22.0	58.3
Dhanpuri							
1	12.4	12.7	58.2	16.8	14.9	15.3	69.9
2	44.6	2.4	39.9	13.2	51.4	2.7	46.0
3	39.8	3.1	40.6	16.5	47.6	3.8	48.6
4	49.2	6.0	21.6	23.2	64.0	7.9	28.1
5	24.6	13.2	34.7	27.5	33.9	18.2	47.9
Avg	34.1	7.5	39.0	19.4	42.4	9.6	48.1
Min	12.4	2.4	21.6	13.2	14.9	2.7	28.1
Max	49.2	13.2	58.2	27.5	64.0	18.2	69.9
Rajendra							
1	32.1	17.5	36.8	13.5	37.2	20.3	42.6
2	36.7	23.7	30.2	9.5	40.5	26.2	33.3
3	61.0	14.1	11.8	13.1	70.2	16.3	13.6
4	31.7	13.4	36.9	18.0	38.7	16.4	45.0
5	39.0	4.8	39.6	16.6	46.8	5.8	47.5
Avg	40.1	14.7	31.0	14.1	46.7	17.0	36.4
Min	31.7	4.8	11.8	9.5	37.2	5.8	13.6
Max	61.0	23.7	39.6	18.0	70.2	26.2	47.5
Khairaha VI seam							
1	60.3	6.5	18.3	14.9	70.8	7.6	21.6
2	49.4	8.5	26.4	15.7	58.6	10.1	31.3
3	58.0	17.2	12.3	12.5	66.3	19.7	14.0
4	34.3	8.8	45.5	11.4	38.7	9.9	51.4
5	26.0	5.8	53.8	14.4	30.4	6.8	62.9
Avg	45.6	9.4	31.3	13.8	53.0	10.8	36.2
Min	26.0	5.8	12.3	11.4	30.4	6.8	14.0
Max	60.3	17.2	53.8	15.7	70.8	19.7	62.9
Khairaha VII seam							
1	37.0	10.1	46.2	6.7	39.7	10.8	49.5
2	17.6	15.7	55.7	11.1	19.7	17.6	62.7
3	35.7	8.6	35.5	20.1	44.8	10.8	44.5
4	37.5	8.2	38.8	15.5	44.4	9.7	45.9
5	38.7	8.4	40.6	12.2	44.1	9.6	46.3
Avg	33.3	10.2	43.4	13.1	38.5	11.7	49.8
Min	17.6	8.2	35.5	6.7	19.7	9.6	44.5
Max	38.7	15.7	55.7	20.1	44.8	17.6	62.7
Damini VI seam 1st site							

Mine/Seam with band no.	with mineral matter				on mineral matter free basis		
	Vitrinite	Liptinite	Inertinite	Mineral Matter	Vitrinite	Liptinite	Inertinite
1	33.1	9.6	40.6	16.7	39.7	11.5	48.8
2	51.6	4.9	8.9	34.5	78.9	7.5	13.6
3	33.1	9.1	38.6	19.1	40.9	11.3	47.8
Avg	39.3	7.9	29.4	23.5	53.2	10.1	36.7
Min	33.1	4.9	8.9	16.7	39.7	7.5	13.6
Max	51.6	9.6	40.6	34.5	78.9	11.5	48.8
Damini VI seam 2nd site							
1	26.8	11.7	52.3	9.2	29.5	12.9	57.6
2	43.7	9.3	24.9	22.1	56.1	12.0	32.0
3	30.9	11.9	38.5	18.8	38.0	14.6	47.4
Avg	33.8	11.0	38.6	16.7	41.2	13.2	45.6
Min	26.8	9.3	24.9	9.2	29.5	12.0	32.0
Max	43.7	11.9	52.3	22.1	56.1	14.6	57.6
Damini V							
1	7.8	4.3	48.8	39.2	12.9	7.0	80.2
2	29.0	15.4	37.7	18.0	35.3	18.8	45.9
3	44.6	5.4	33.3	16.7	53.5	6.5	40.0
4	33.1	11.7	40.8	14.5	38.7	13.7	47.7
Avg	28.6	9.2	40.1	22.1	35.1	11.5	53.5
Min	7.8	4.3	33.3	14.5	12.9	6.5	40.0
Max	44.6	15.4	48.8	39.2	53.5	18.8	80.2
Bangwar							
1	31.6	13.8	38.7	15.9	37.6	16.4	46.0
2	26.3	11.2	41.9	20.6	33.1	14.1	52.8
3	46.6	7.7	31.0	14.7	54.6	9.1	36.4
4	34.7	7.9	48.7	8.8	38.0	8.6	53.4
Avg	34.8	10.2	40.1	15.0	40.8	12.1	47.1
Min	26.3	7.7	31.0	8.8	33.1	8.6	36.4
Max	46.6	13.8	48.7	20.6	54.6	16.4	53.4
Amalai							
1	55.9	6.8	28.0	9.4	61.6	7.5	30.9
2	22.9	3.6	51.8	21.6	29.3	4.6	66.2
3	30.1	9.3	47.7	12.9	34.5	10.7	54.8
4	42.0	4.8	37.9	15.3	49.5	5.7	44.8
5	16.2	7.6	48.2	28.1	22.5	10.6	66.9
6	16.5	11.8	56.4	15.4	19.5	13.9	66.6
7	23.4	7.1	47.4	22.2	30.0	9.2	60.8
8	46.2	12.4	30.0	11.4	52.1	14.1	33.8
Avg	31.6	7.9	43.4	17.0	37.4	9.5	53.1
Min	16.2	3.6	28.0	9.4	19.5	4.6	30.9
Max	55.9	12.4	56.4	28.1	61.6	14.1	66.9

4.6.1 Variation and qualitative distribution of maceral and mineral matter in Sohagpur coals

The qualitative vertical distribution of coal seams from the Sohagpur Coalfield is illustrated through macroscopic and microscopic vertical profiles presented in Figure 4.9. These profiles reveal significant heterogeneity in coal lithotypes, maceral composition, and mineral matter content, reflecting variations in peat-forming environments, oxidation conditions, and depositional settings.

In the Sharda coal mine, the coal seam exhibits a distinctly heterogeneous vertical profile, with banded dull coal dominating the upper portion and banded coal at the bottom. This vertical variation is strongly influenced by megascopic characteristics, which are closely linked to changes in maceral composition. The bottom band, characterized by a well-developed banded nature, shows a high abundance of inertinite macerals. This indicates intense oxidation and possible wildfire activity during peat accumulation, as shown in Figure 4.9(a).

The Dhanpuri coal mine seam shows systematic variation from top to bottom. The upper band is characterized by a low vitrinite concentration and a relatively high inertinite abundance, suggesting oxidizing conditions and possible exposure of peat surfaces. With increasing depth, vitrinite concentration progressively increases, indicating enhanced preservation of woody plant material under more reducing conditions. The bottom band shows a high concentration of mineral matter, expressed megascopically as a dull band, reflecting increased clastic input during peat deposition (Figure 4.9(b)).

In the Rajendra coal mine, the vertical profile is marked by a vitrinite-rich middle band, containing more than 60% vitrinite macerals. This suggests optimal peat preservation conditions, likely in waterlogged, reducing environments. In contrast, both the upper and

lower bands show increased inertinite content, indicating episodes of oxidation and peat degradation. The presence of oxidized macerals suggests fluctuating water table conditions during seam formation (Figure 4.9(c)).

For Khairaha Seam VI, the vertical maceral distribution shows a zigzag pattern. The top and middle bands are enriched in vitrinite macerals, reflecting relatively stable, reducing depositional environments. However, below the middle band, there is a marked increase in inertinite macerals, suggesting a shift towards more oxidizing conditions or increased fire influence during the later stages of peat accumulation (Figure 4.9(d)).

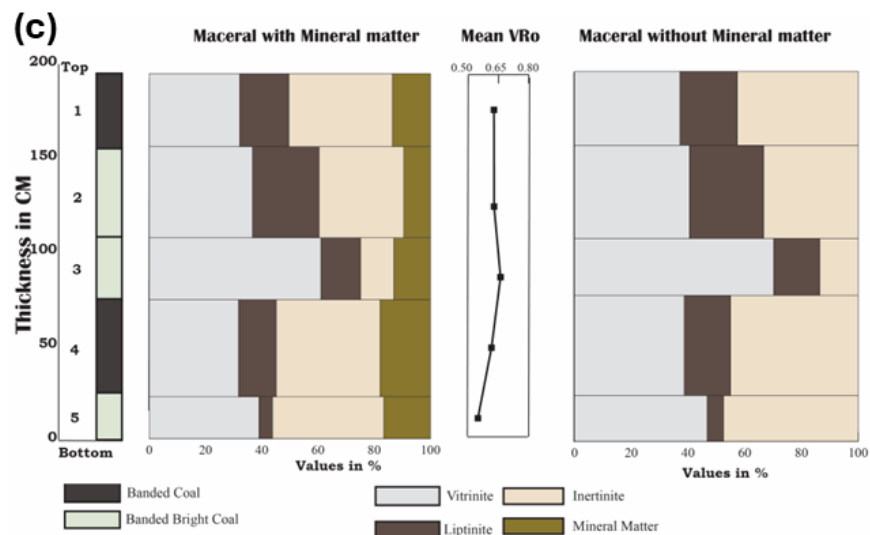
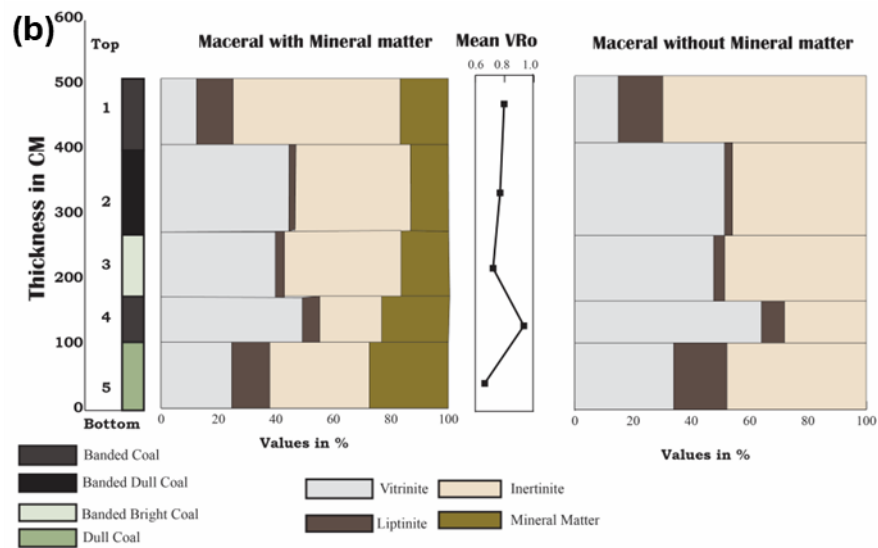
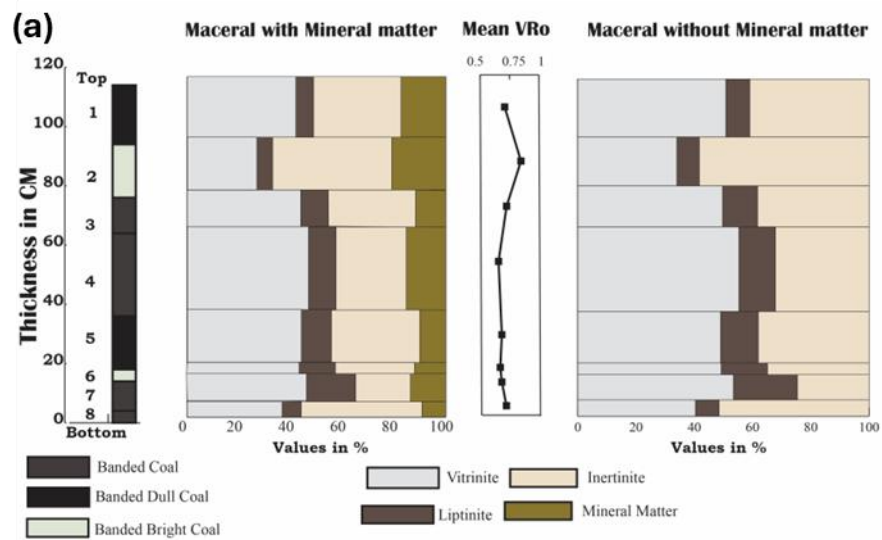
In Khairaha Seam VII, the central band is predominantly banded dull coal and shows a high abundance of inertinite macerals. This indicates significant oxidation of organic matter during peat formation. Moving upward or downward from this band, the concentration of vitrinite macerals increases relative to inertinite, implying improved preservation conditions in adjacent stratigraphic intervals (Figure 4.9(e)).

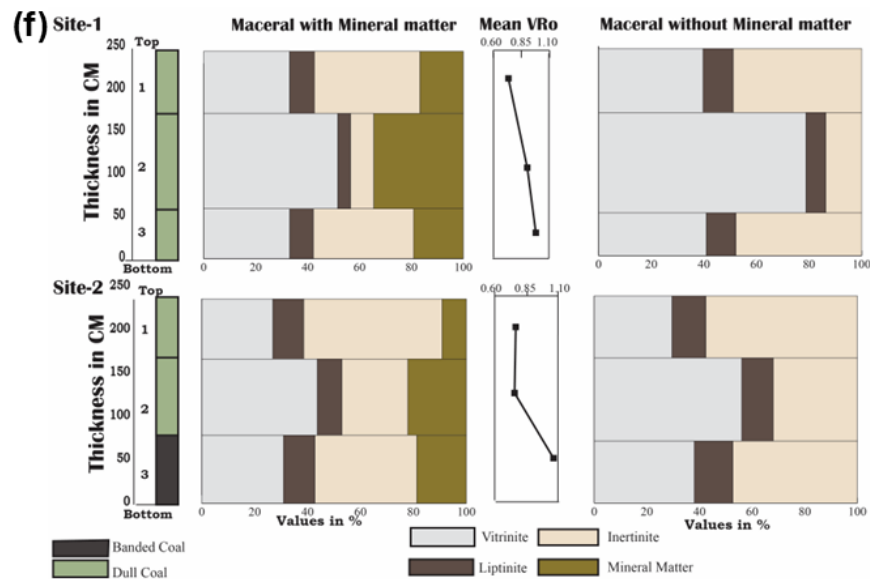
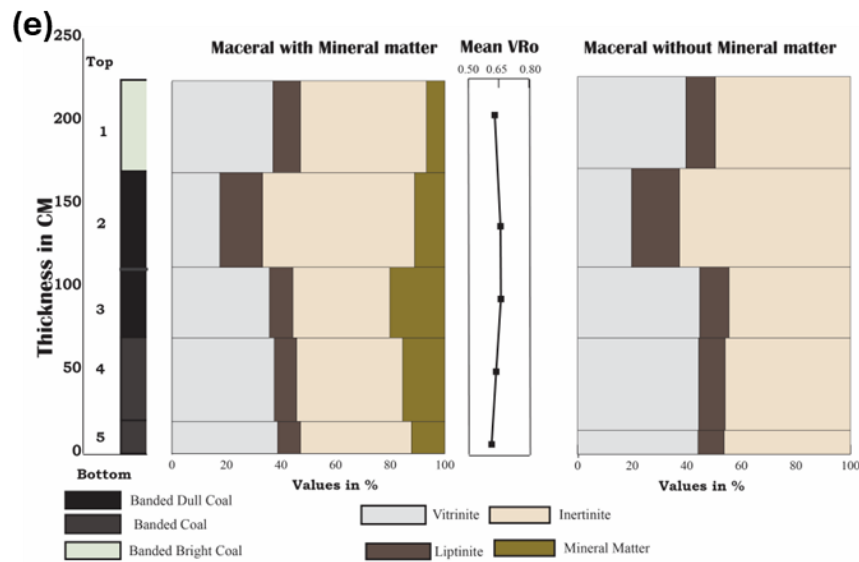
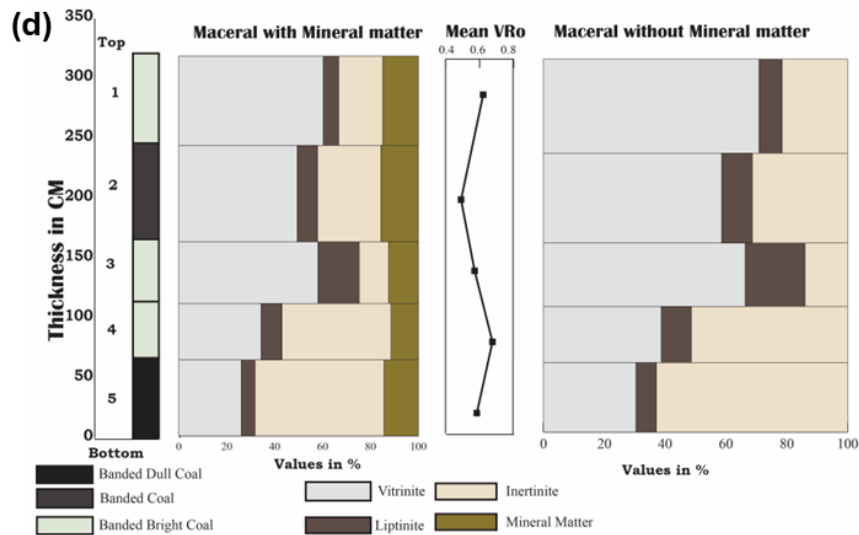
The Damini Seam VI is dominated by dull coal bands throughout the seam profile, reflecting high concentrations of inertinite macerals and mineral matter. Microscopic analysis confirms this dominance. A notable feature of this seam is that the middle band exhibits comparatively lower inertinite content than the upper and lower bands, suggesting a brief interval of reduced oxidation and better peat preservation (Figure 4.9(f)).

In the Damini Seam V, the upper band is dull in nature, which correlates with a high concentration of mineral matter. This indicates increased detrital input during the early stages of peat deposition. With increasing depth, the mineral matter content decreases, suggesting a transition to more organic-rich peat accumulation under reduced clastic influence (Figure 4.9(g)).

In the Bangwar coal seam, the coal bands alternate between banded and dull lithotypes. The inertinite maceral group is dominant compared to vitrinite and liptinite macerals, indicating widespread oxidation of peat material and possible frequent exposure of the peat surface during deposition (Figure 4.9(h)).

The Amalai coal seam exhibits a pronounced zigzag pattern in maceral distribution. The top band is enriched in vitrinite, followed by a sudden decrease, then a gradual increase towards the middle band. This pattern repeats downward, with alternating decreases and increases in vitrinite concentration toward the bottom band. Such cyclic variation reflects repeated fluctuations in depositional conditions, water table levels, and oxidation states, leading to alternating dominance of organic preservation and degradation processes (Figure 4.9(i)).





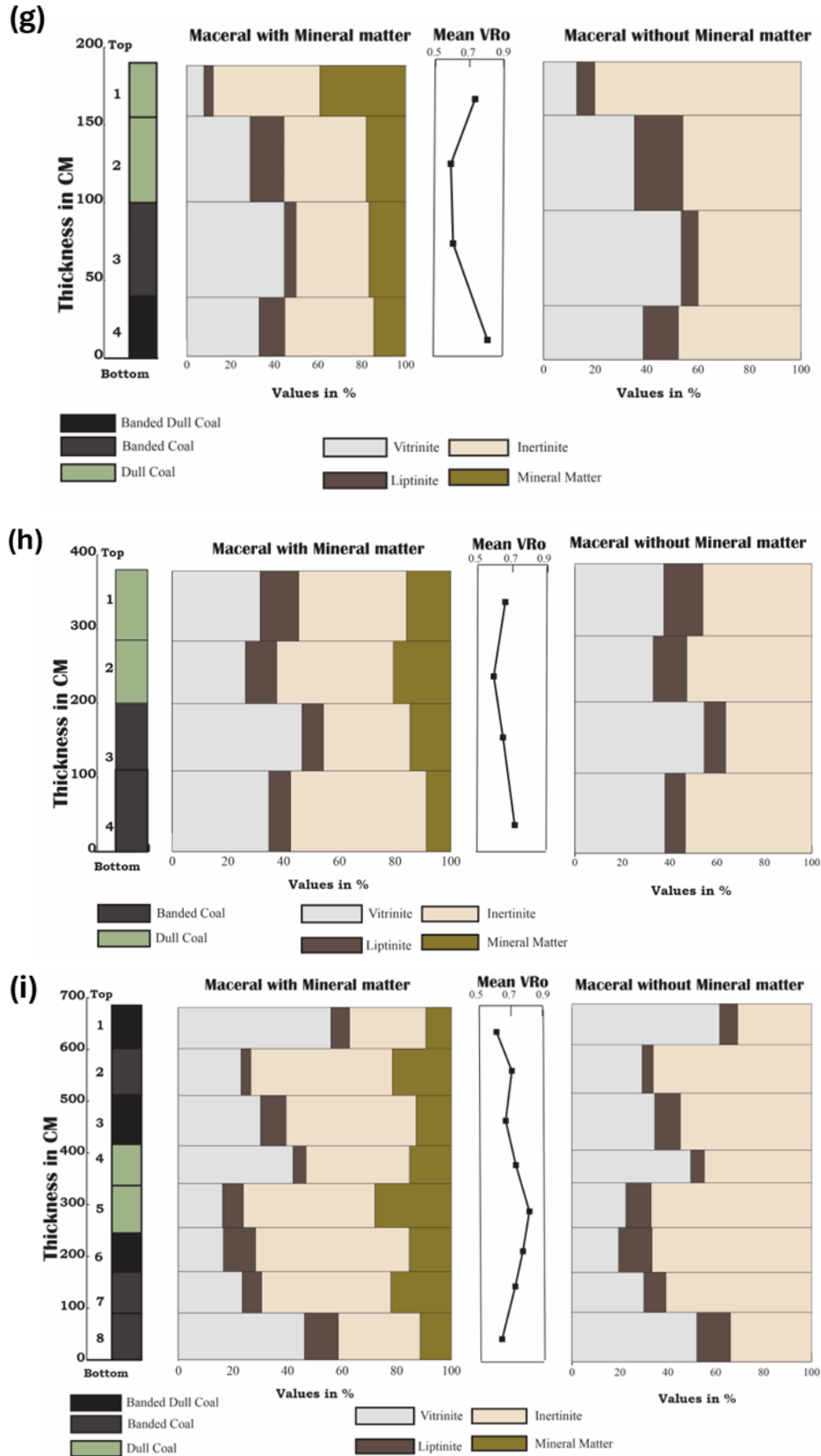


Figure 4.9 Vertical profile of coal seams with variation in maceral with mineral matter and maceral without mineral matter in Sohagpur coals (a) Sharda, (b) Dhanpuri, (c) Rajendra, (d) Khairaha Seam VI, (e) Khairaha Seam VII (f) Damini Seam VI, (g) Damini Seam V, (h) Bangwar, and (i) Amalai coal mine.

4.6.2 Quantitative distribution of maceral and mineral matter in Sohagpur coals

The petrographic composition of the studied coal seams exhibits marked variability in maceral group proportions and mineral matter content. The Sharda mine records vitrinite maceral with an average of 41.24% (ranges from 26.91 to 46.85%), liptinite with an average of 10.76% (ranges from 6.07 to 18.97%), inertinite with an average of 34.21% (ranges from 21.22 to 46.73%) and mineral matter with an average of 13.79% (ranges from 9.22 to 20.94%). The Dhanpuri mine records vitrinite with an average of 34.11% (ranges from 12.38 to 49.18%), liptinite with an average of 7.49% (ranges from 2.35 to 13.22%), inertinite with an average of 38.98% (ranges from 21.57 to 58.15%) and mineral matter with an average of 19.42% (ranges from 13.21 to 27.47%). The Rajendra mine records vitrinite with an average of 40.12% (ranges from 31.72 to 61.03%), liptinite with an average of 14.72% (ranges from 4.81 to 23.69%), inertinite with an average of 31.04% (ranges from 11.78 to 39.59%) and mineral matter with an average of 14.12% (ranges from 9.46 to 17.95%). The Khairaha VI mine records vitrinite with an average of 45.61% (ranges from 26.03 to 60.26%), liptinite with an average of 9.35% (ranges from 5.78 to 17.24%), inertinite with an average of 31.27% (ranges from 12.25 to 53.84%) and mineral matter with an average of 13.77% (ranges from 11.41 to 15.67%). The Khairaha VII mine records vitrinite with an average of 33.30% (ranges from 17.55 to 38.72%), liptinite with an average of 10.20% (ranges from 8.23 to 15.66%), inertinite with an average of 43.36% (ranges from 35.53 to 55.72%) and mineral matter with an average of 13.13% (ranges from 6.73 to 20.13%). The Damini VI (first site) records vitrinite with an average of 39.26% (ranges from 33.06 to 51.62%), liptinite with an average of 7.88% (ranges from 4.93 to 9.56%), inertinite with an average of 29.39% (ranges from 8.90 to 40.64%) and mineral matter with an average of 23.47% (ranges from 16.74 to 34.54%). The Damini VI (second site) records vitrinite with an average of 33.79% (ranges from 26.82 to 43.65%), liptinite

with an average of 10.98% (ranges from 9.31 to 11.89%), inertinite with an average of 38.56% (ranges from 24.91 to 52.31%) and mineral matter with an average of 16.68% (ranges from 9.15 to 22.13%). The Damini V mine records vitrinite with an average of 28.60% (ranges from 7.81 to 44.58%), liptinite with an average of 9.18% (ranges from 4.25 to 15.42%), inertinite with an average of 40.13% (ranges from 33.33 to 48.76%) and mineral matter with an average of 22.09% (ranges from 14.50 to 39.17%). The Bangwar mine records vitrinite with an average of 34.77% (ranges from 26.25 to 46.56%), liptinite with an average of 10.15% (ranges from 7.72 to 13.82%), inertinite with an average of 40.06% (ranges from 31.04 to 48.65%) and mineral matter with an average of 15.02% (ranges from 8.82 to 20.63%). The Amalai mine records vitrinite with an average of 31.62% (ranges from 16.16 to 55.86%), liptinite with an average of 7.94% (ranges from 3.59 to 12.44%), inertinite with an average of 43.40% (ranges from 27.98 to 56.35%) and mineral matter with an average of 17.04% (ranges from 9.36 to 28.06%). Table 4.11 and Table 4.12 show the maceral composition with mineral matter and maceral composition on mineral matter-free basis values of Sohagpur coals, respectively.

Table 4.11 Occurrence and distribution of maceral and mineral matter content (vol%) of Sohagpur coals.

Mine/Seam with band no.	Tl	Ct	Vt	Cd	Cp	G	DV	PD	SV	Sp	Ct	Rs	Al	Sb	Ld	Fl
Sharda																
1	0.0	37.9	2.6	0.7	0.7	0.0	0.0	0.2	42.0	4.1	2.2	0.3	0.0	0.0	0.2	0.0
2	0.0	11.2	15.5	0.0	0.0	0.0	0.0	0.2	26.9	1.5	3.0	0.2	0.0	0.0	0.6	0.0
3	0.3	39.4	2.1	0.4	0.1	0.0	0.0	1.6	43.9	5.7	3.8	0.4	0.0	0.0	0.4	0.0
4	0.0	32.1	12.4	0.2	0.1	0.0	0.0	2.0	46.9	5.6	3.0	0.3	0.0	0.0	0.7	0.0
5	0.0	35.4	3.8	0.2	0.0	0.0	0.0	4.7	44.1	6.8	3.6	0.2	0.0	0.0	0.2	0.0
6	0.0	37.2	2.8	0.3	0.0	0.0	0.0	3.0	43.3	5.3	5.0	1.5	0.3	0.0	0.2	0.2
7	0.3	43.3	2.0	0.3	0.0	0.1	0.0	0.3	46.1	9.2	5.3	1.2	0.4	0.0	0.5	0.0
8	0.0	25.2	10.5	0.5	0.0	0.0	0.0	0.5	36.7	2.3	3.5	0.5	0.0	0.0	0.5	0.0
Avg	0.1	32.7	6.5	0.3	0.1	0.0	0.0	1.6	41.2	5.1	3.7	0.6	0.1	0.0	0.4	0.0
Min	0.0	11.2	2.0	0.0	0.0	0.0	0.0	0.2	26.9	1.5	2.2	0.2	0.0	0.0	0.2	0.0
Max	0.3	43.3	15.5	0.7	0.7	0.1	0.0	4.7	46.9	9.2	5.3	1.5	0.4	0.0	0.7	0.2
Dhanpuri																
1	0.0	4.5	7.3	0.2	0.1	0.0	0.0	0.3	12.4	0.3	12.4	0.0	0.0	0.0	0.0	0.0
2	0.0	40.1	2.9	1.0	0.0	0.0	0.2	0.4	44.6	0.4	1.9	0.0	0.0	0.0	0.0	0.0
3	0.0	25.9	11.4	0.2	0.0	0.0	0.0	2.3	39.8	0.3	1.3	0.2	0.0	0.0	0.4	0.0
4	0.0	31.4	14.5	0.5	0.0	0.0	0.4	2.4	49.2	2.2	0.7	0.7	0.4	0.0	2.0	0.0
5	1.3	3.8	19.3	0.0	0.0	0.0	0.0	0.2	24.6	5.3	7.0	0.2	0.0	0.0	0.2	0.1
Avg	0.3	21.1	11.1	0.4	0.0	0.0	0.1	1.1	34.1	1.7	4.7	0.2	0.1	0.0	0.5	0.0
Min	0.0	3.8	2.9	0.0	0.0	0.0	0.0	0.2	12.4	0.3	0.7	0.0	0.0	0.0	0.0	0.0
Max	1.3	40.1	19.3	1.0	0.1	0.0	0.4	2.4	49.2	5.3	12.4	0.7	0.4	0.0	2.0	0.1
Rajendra																
1	0.4	14.0	13.2	0.3	0.1	0.0	0.0	4.1	32.1	8.4	6.0	1.2	0.0	0.0	0.6	0.0
2	0.2	5.9	17.4	0.8	0.0	0.0	7.6	4.8	36.7	11.7	9.1	1.4	0.0	0.0	1.1	0.0
3	0.0	49.1	4.7	0.1	5.7	0.0	0.0	1.4	61.0	2.4	9.0	0.0	0.0	0.0	1.0	0.0
4	0.9	21.7	5.5	0.2	0.3	0.0	0.0	3.1	31.7	4.3	6.0	2.4	0.0	0.0	0.3	0.0
5	0.0	32.1	6.1	0.0	0.0	0.0	0.0	0.8	39.0	2.0	1.3	0.0	0.0	0.0	0.4	0.0
Avg	0.3	24.6	9.4	0.3	1.2	0.0	1.5	2.8	40.1	5.7	6.3	1.0	0.0	0.0	0.7	0.0
Min	0.0	5.9	4.7	0.0	0.0	0.0	0.0	0.8	31.7	2.0	1.3	0.0	0.0	0.0	0.3	0.0
Max	0.9	49.1	17.4	0.8	5.7	0.0	7.6	4.8	61.0	11.7	9.1	2.4	0.0	0.0	1.1	0.0
Khairaha VI seam																
1	0.0	52.1	7.1	0.2	0.0	0.2	0.0	0.7	60.3	0.4	3.9	1.3	0.0	0.0	0.2	0.1

Mine/Seam with band no.	Tl	Ct	Vt	Cd	Cp	G	DV	PD	SV	Sp	Ct	Rs	Al	Sb	Ld	Fl
2	0.2	48.1	0.6	0.2	0.1	0.0	0.0	0.2	49.4	4.9	2.2	0.5	0.2	0.0	0.0	0.2
3	0.2	48.1	8.7	0.0	0.6	0.0	0.1	0.4	58.0	6.7	8.0	0.2	0.0	0.0	0.6	0.0
4	0.0	26.8	4.5	0.0	0.0	0.0	0.0	3.0	34.3	1.6	6.2	0.3	0.0	0.0	0.0	0.1
5	0.0	21.0	4.1	0.6	0.0	0.0	0.0	0.3	26.0	1.8	2.6	0.0	0.0	0.0	0.3	0.0
Avg	0.1	39.2	5.0	0.2	0.1	0.0	0.0	0.9	45.6	3.1	4.6	0.5	0.1	0.0	0.2	0.1
Min	0.0	21.0	0.6	0.0	0.0	0.0	0.0	0.2	26.0	0.4	2.2	0.0	0.0	0.0	0.0	0.0
Max	0.2	52.1	8.7	0.6	0.6	0.2	0.1	3.0	60.3	6.7	8.0	1.3	0.2	0.0	0.6	0.2
Khairaha VII seam																
1	0.2	29.9	3.9	0.7	0.1	0.0	0.4	2.0	37.0	2.3	5.9	0.0	0.0	0.0	0.4	0.0
2	0.7	10.9	3.7	0.5	0.3	0.0	0.0	1.5	17.6	5.0	8.6	0.5	0.0	0.0	1.1	0.0
3	0.8	20.3	11.3	0.2	0.0	0.0	0.0	3.0	35.7	0.1	7.6	0.0	0.0	0.0	0.3	0.0
4	0.0	28.9	8.2	0.3	0.0	0.0	0.0	0.0	37.5	2.4	3.6	0.3	0.0	0.0	0.8	0.0
5	0.2	32.9	3.6	0.0	0.1	0.0	0.0	1.9	38.7	3.3	3.4	0.2	0.0	0.0	0.5	0.7
Avg	0.4	24.6	6.1	0.3	0.1	0.0	0.1	1.7	33.3	2.6	5.8	0.2	0.0	0.0	0.6	0.1
Min	0.0	10.9	3.6	0.0	0.0	0.0	0.0	0.0	17.6	0.1	3.4	0.0	0.0	0.0	0.3	0.0
Max	0.8	32.9	11.3	0.7	0.3	0.0	0.4	3.0	38.7	5.0	8.6	0.5	0.0	0.0	1.1	0.7
Damini VI seam 1st site																
1	0.2	10.6	20.5	0.3	0.2	0.0	0.0	1.3	33.1	1.8	6.3	0.7	0.0	0.0	0.5	0.0
2	0.0	2.2	48.3	0.4	0.0	0.0	0.8	0.0	51.6	0.4	2.1	1.0	0.0	0.0	1.6	0.0
3	0.0	4.7	25.6	2.0	0.2	0.0	0.0	0.6	33.1	1.5	6.3	0.2	0.0	0.0	1.0	0.0
Avg	0.1	5.8	31.5	0.9	0.1	0.0	0.3	0.6	39.3	1.2	4.9	0.6	0.0	0.0	1.0	0.0
Min	0.0	2.2	20.5	0.3	0.0	0.0	0.0	0.0	33.1	0.4	2.1	0.2	0.0	0.0	0.5	0.0
Max	0.2	10.6	48.3	2.0	0.2	0.0	0.8	1.3	51.6	1.8	6.3	1.0	0.0	0.0	1.6	0.0
Damini VI seam 2nd site																
1	0.0	8.9	14.7	0.7	0.0	0.0	0.6	2.0	26.8	4.0	6.9	0.0	0.0	0.0	0.3	0.1
2	0.0	3.9	37.2	0.2	0.0	0.0	1.3	1.0	43.7	2.1	5.2	0.2	0.0	0.2	1.6	0.0
3	0.0	1.1	29.8	0.0	0.0	0.0	0.0	0.0	30.9	4.2	5.4	1.0	0.0	0.0	1.4	0.0
Avg	0.0	4.6	27.2	0.3	0.0	0.0	0.7	1.0	33.8	3.4	5.8	0.4	0.0	0.1	1.1	0.0
Min	0.0	1.1	14.7	0.0	0.0	0.0	0.0	0.0	26.8	2.1	5.2	0.0	0.0	0.0	0.3	0.0
Max	0.0	8.9	37.2	0.7	0.0	0.0	1.3	2.0	43.7	4.2	6.9	1.0	0.0	0.2	1.6	0.1
Damini V																
1	0.0	3.6	4.3	0.0	0.0	0.0	0.0	0.0	7.8	1.2	2.4	0.0	0.0	0.0	0.7	0.0
2	0.0	15.8	9.7	0.2	0.4	0.0	0.6	2.3	29.0	6.0	7.4	0.7	0.0	0.0	0.6	0.0
3	0.2	39.6	3.5	0.0	0.1	0.1	0.2	0.9	44.6	3.6	0.9	0.1	0.0	0.0	0.0	0.1
4	0.0	10.6	14.7	0.5	0.0	0.0	0.0	7.3	33.1	4.1	6.4	0.0	0.0	0.0	0.5	0.0

Mine/Seam with band no.	Tl	Ct	Vt	Cd	Cp	G	DV	PD	SV	Sp	Ct	Rs	Al	Sb	Ld	Fl
Avg	0.1	17.4	8.0	0.2	0.1	0.0	0.2	2.6	28.6	3.7	4.3	0.2	0.0	0.0	0.5	0.0
Min	0.0	3.6	3.5	0.0	0.0	0.0	0.0	0.0	7.8	1.2	0.9	0.0	0.0	0.0	0.0	0.0
Max	0.2	39.6	14.7	0.5	0.4	0.1	0.6	7.3	44.6	6.0	7.4	0.7	0.0	0.0	0.7	0.1
Bangwar																
1	0.0	21.7	7.6	0.3	0.0	0.0	0.0	2.0	31.6	4.1	8.1	0.4	0.5	0.0	0.6	0.0
2	0.0	17.3	8.1	0.6	0.0	0.0	0.0	0.2	26.3	4.1	2.5	0.5	1.3	0.0	1.0	0.0
3	0.4	43.2	1.0	0.2	0.0	0.0	0.0	1.8	46.6	4.4	2.6	0.0	0.0	0.0	0.0	0.0
4	0.0	24.1	5.5	2.5	0.2	0.5	0.0	1.9	34.7	1.9	4.0	0.5	0.0	0.0	0.6	0.0
Avg	0.1	26.6	5.6	0.9	0.1	0.1	0.0	1.5	34.8	3.6	4.3	0.3	0.5	0.0	0.5	0.0
Min	0.0	17.3	1.0	0.2	0.0	0.0	0.0	0.2	26.3	1.9	2.5	0.0	0.0	0.0	0.0	0.0
Max	0.4	43.2	8.1	2.5	0.2	0.5	0.0	2.0	46.6	4.4	8.1	0.5	1.3	0.0	1.0	0.0
Amalai																
1	0.0	40.1	12.0	0.2	0.0	0.0	0.0	3.6	55.9	4.8	0.6	0.3	0.0	0.0	0.3	0.0
2	0.0	1.0	17.5	0.0	0.0	0.0	0.4	4.0	22.9	1.7	0.8	0.1	0.0	0.0	0.9	0.0
3	0.0	24.6	5.0	0.1	0.0	0.1	0.1	0.2	30.1	4.4	3.5	0.3	0.1	0.0	0.6	0.2
4	0.0	3.7	35.1	0.2	0.0	0.0	0.3	2.7	42.0	2.0	1.5	0.4	0.3	0.0	0.6	0.0
5	0.7	5.3	7.6	1.0	0.0	0.0	0.9	0.7	16.2	2.2	4.3	0.5	0.0	0.0	0.0	0.2
6	0.3	5.2	8.9	0.8	0.0	0.0	0.0	1.3	16.5	4.4	6.9	0.5	0.0	0.0	0.0	0.0
7	0.0	5.2	16.9	0.0	0.0	0.0	0.0	1.3	23.4	3.7	2.3	0.3	0.0	0.0	0.7	0.0
8	0.7	39.9	4.6	0.0	0.0	0.0	0.0	0.9	46.2	2.7	7.1	0.5	0.5	0.0	1.2	0.0
Avg	0.2	15.6	13.5	0.3	0.0	0.0	0.2	1.8	31.6	3.2	3.4	0.4	0.1	0.0	0.5	0.1
Min	0.0	1.0	4.6	0.0	0.0	0.0	0.0	0.2	16.2	1.7	0.6	0.1	0.0	0.0	0.0	0.0
Max	0.7	40.1	35.1	1.0	0.0	0.1	0.9	4.0	55.9	4.8	7.1	0.5	0.5	0.0	1.2	0.2

Mine/Seam with band no.	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI	Arg	Car	Py	SMM
Sharda															
1	0.0	0.0	0.0	6.8	0.2	0.5	17.4	1.7	6.1	7.9	33.8	14.2	2.4	0.8	17.4
2	0.7	0.0	0.0	6.1	2.2	1.2	23.1	5.7	1.2	12.8	46.1	13.5	5.0	2.4	20.9
3	0.3	0.0	0.0	10.6	0.2	0.8	9.6	12.7	2.5	8.0	33.8	9.0	1.9	0.7	11.7
4	1.1	0.0	0.0	10.7	0.0	0.3	6.9	9.0	3.9	7.2	27.2	13.2	1.2	1.0	15.3
5	0.9	0.0	0.0	11.7	0.1	1.2	9.3	5.5	8.2	9.8	34.2	7.2	1.9	1.0	10.1
6	1.4	0.0	0.0	14.0	0.3	0.8	8.8	3.2	2.5	15.0	30.7	7.5	2.8	1.8	12.1
7	2.2	0.3	0.0	19.0	0.3	0.6	7.9	3.4	4.0	5.0	21.2	8.7	3.3	1.6	13.7
8	0.5	0.0	0.0	7.3	0.2	0.7	28.6	5.6	2.3	9.3	46.7	6.5	2.4	0.3	9.2
Avg	0.9	0.0	0.0	10.8	0.4	0.8	13.9	5.9	3.8	9.4	34.2	10.0	2.6	1.2	13.8

Mine/Seam with band no.	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI	Arg	Car	Py	SMM
Min	0.0	0.0	0.0	6.1	0.0	0.3	6.9	1.7	1.2	5.0	21.2	6.5	1.2	0.3	9.2
Max	2.2	0.3	0.0	19.0	2.2	1.2	28.6	12.7	8.2	15.0	46.7	14.2	5.0	2.4	20.9
Dhanpuri															
1	0.0	0.0	0.0	12.7	0.2	1.1	2.5	34.6	8.2	11.5	58.2	14.7	0.9	1.1	16.8
2	0.0	0.0	0.0	2.4	0.3	0.7	17.6	11.0	3.3	7.1	39.9	8.9	1.2	3.1	13.2
3	0.9	0.0	0.0	3.1	0.0	0.2	22.3	8.4	2.3	7.4	40.6	9.4	1.7	5.4	16.5
4	0.1	0.0	0.0	6.0	1.0	2.3	3.9	2.1	1.2	11.0	21.6	14.6	7.2	1.5	23.2
5	0.3	0.0	0.0	13.2	0.2	0.8	1.3	4.1	3.3	24.9	34.7	23.6	2.5	1.4	27.5
Avg	0.3	0.0	0.0	7.5	0.3	1.0	9.5	12.0	3.7	12.4	39.0	14.2	2.7	2.5	19.4
Min	0.0	0.0	0.0	2.4	0.0	0.2	1.3	2.1	1.2	7.1	21.6	8.9	0.9	1.1	13.2
Max	0.9	0.0	0.0	13.2	1.0	2.3	22.3	34.6	8.2	24.9	58.2	23.6	7.2	5.4	27.5
Rajendra															
1	1.4	0.0	0.0	17.5	1.2	0.9	7.4	14.9	4.2	8.3	36.8	9.3	3.6	0.7	13.5
2	0.4	0.0	0.0	23.7	0.2	2.0	8.6	10.5	4.5	4.4	30.2	7.9	1.0	0.6	9.5
3	1.8	0.0	0.0	14.1	0.1	0.0	1.5	6.6	0.1	3.4	11.8	5.7	6.0	1.4	13.1
4	0.2	0.3	0.0	13.4	0.1	0.3	3.8	20.7	4.7	7.4	36.9	5.1	9.7	3.2	18.0
5	1.2	0.0	0.0	4.8	0.0	0.2	22.0	8.6	3.1	5.6	39.6	11.8	4.2	0.6	16.6
Avg	1.0	0.1	0.0	14.7	0.3	0.7	8.7	12.3	3.3	5.8	31.0	7.9	4.9	1.3	14.1
Min	0.2	0.0	0.0	4.8	0.0	0.0	1.5	6.6	0.1	3.4	11.8	5.1	1.0	0.6	9.5
Max	1.8	0.3	0.0	23.7	1.2	2.0	22.0	20.7	4.7	8.3	39.6	11.8	9.7	3.2	18.0
Khairaha VI seam															
1	0.6	0.0	0.0	6.5	0.0	0.1	2.2	8.5	2.7	4.9	18.3	12.3	1.6	1.1	14.9
2	0.5	0.0	0.0	8.5	0.2	1.2	4.9	11.5	1.4	7.3	26.4	11.9	3.3	0.5	15.7
3	1.6	0.0	0.0	17.2	0.2	0.0	3.4	5.9	0.2	2.7	12.3	11.4	0.3	0.8	12.5
4	0.6	0.0	0.0	8.8	0.0	1.1	12.9	19.1	0.8	11.7	45.5	9.0	1.9	0.5	11.4
5	1.1	0.0	0.0	5.8	0.1	0.3	32.0	11.6	3.0	6.8	53.8	10.9	3.1	0.3	14.4
Avg	0.9	0.0	0.0	9.4	0.1	0.5	11.1	11.3	1.6	6.7	31.3	11.1	2.1	0.6	13.8
Min	0.5	0.0	0.0	5.8	0.0	0.0	2.2	5.9	0.2	2.7	12.3	9.0	0.3	0.3	11.4
Max	1.6	0.0	0.0	17.2	0.2	1.2	32.0	19.1	3.0	11.7	53.8	12.3	3.3	1.1	15.7
Khairaha VII seam															
1	1.4	0.0	0.0	10.1	0.5	1.9	3.3	26.5	2.4	11.6	46.2	6.4	0.2	0.2	6.7
2	0.3	0.2	0.0	15.7	1.0	2.2	6.8	24.0	2.4	19.3	55.7	9.8	0.7	0.5	11.1
3	0.6	0.0	0.0	8.6	1.1	1.6	7.9	11.8	0.6	12.6	35.5	19.3	0.5	0.3	20.1
4	1.2	0.0	0.0	8.2	0.2	0.8	20.7	6.3	4.1	6.7	38.8	12.6	2.5	0.4	15.5
5	0.5	0.0	0.0	8.4	0.1	2.0	14.7	7.4	4.3	12.1	40.6	9.8	1.8	0.7	12.2

Mine/Seam with band no.	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI	Arg	Car	Py	SMM
Avg	0.8	0.0	0.0	10.2	0.6	1.7	10.7	15.2	2.8	12.5	43.4	11.6	1.1	0.4	13.1
Min	0.3	0.0	0.0	8.2	0.1	0.8	3.3	6.3	0.6	6.7	35.5	6.4	0.2	0.2	6.7
Max	1.4	0.2	0.0	15.7	1.1	2.2	20.7	26.5	4.3	19.3	55.7	19.3	2.5	0.7	20.1
Damini VI seam 1st site															
1	0.2	0.0	0.0	9.6	0.0	0.5	2.9	24.1	4.4	8.7	40.6	13.1	2.9	0.7	16.7
2	0.0	0.0	0.0	4.9	0.2	1.3	1.8	2.8	1.0	1.8	8.9	31.5	0.8	2.2	34.5
3	0.2	0.0	0.0	9.1	0.6	3.4	6.7	6.0	2.4	19.6	38.6	15.5	0.4	3.3	19.1
Avg	0.1	0.0	0.0	7.9	0.3	1.8	3.8	11.0	2.6	10.0	29.4	20.1	1.4	2.1	23.5
Min	0.0	0.0	0.0	4.9	0.0	0.5	1.8	2.8	1.0	1.8	8.9	13.1	0.4	0.7	16.7
Max	0.2	0.0	0.0	9.6	0.6	3.4	6.7	24.1	4.4	19.6	40.6	31.5	2.9	3.3	34.5
Damini VI seam 2nd site															
1	0.4	0.0	0.0	11.7	0.7	3.5	8.2	10.7	3.3	26.0	52.3	6.2	1.9	1.1	9.2
2	0.0	0.0	0.0	9.3	0.9	1.3	4.4	9.6	4.4	4.5	24.9	20.2	0.5	1.5	22.1
3	0.0	0.0	0.0	11.9	0.5	3.0	3.4	6.7	3.8	21.0	38.5	16.5	0.5	1.8	18.8
Avg	0.2	0.0	0.0	11.0	0.7	2.6	5.3	9.0	3.8	17.2	38.6	14.3	0.9	1.4	16.7
Min	0.0	0.0	0.0	9.3	0.5	1.3	3.4	6.7	3.3	4.5	24.9	6.2	0.5	1.1	9.2
Max	0.4	0.0	0.0	11.9	0.9	3.5	8.2	10.7	4.4	26.0	52.3	20.2	1.9	1.8	22.1
Damini V															
1	0.0	0.0	0.0	4.3	0.3	2.8	1.1	9.5	2.2	32.9	48.8	33.0	4.4	1.8	39.2
2	0.8	0.0	0.0	15.4	0.2	1.4	6.0	15.8	3.6	10.7	37.7	15.4	0.6	2.0	18.0
3	0.7	0.0	0.0	5.4	0.7	2.0	6.7	7.1	6.9	10.1	33.3	13.4	2.9	0.4	16.7
4	0.7	0.0	0.0	11.7	0.4	3.1	10.4	5.2	2.9	18.7	40.8	12.1	1.5	0.9	14.5
Avg	0.6	0.0	0.0	9.2	0.4	2.3	6.0	9.4	3.9	18.1	40.1	18.5	2.3	1.3	22.1
Min	0.0	0.0	0.0	4.3	0.2	1.4	1.1	5.2	2.2	10.1	33.3	12.1	0.6	0.4	14.5
Max	0.8	0.0	0.0	15.4	0.7	3.1	10.4	15.8	6.9	32.9	48.8	33.0	4.4	2.0	39.2
Bangwar															
1	0.0	0.0	0.0	13.8	0.1	0.2	20.9	6.8	7.3	3.4	38.7	9.4	5.5	1.1	15.9
2	1.8	0.0	0.0	11.2	0.3	1.3	16.4	7.7	1.7	14.4	41.9	13.4	6.3	1.0	20.6
3	0.8	0.0	0.0	7.7	0.6	3.0	7.2	5.6	1.7	13.0	31.0	11.2	2.7	0.8	14.7
4	0.9	0.0	0.0	7.9	0.3	1.2	7.6	29.0	2.5	8.0	48.7	7.0	1.4	0.5	8.8
Avg	0.9	0.0	0.0	10.2	0.3	1.4	13.1	12.3	3.3	9.7	40.1	10.2	4.0	0.8	15.0
Min	0.0	0.0	0.0	7.7	0.1	0.2	7.2	5.6	1.7	3.4	31.0	7.0	1.4	0.5	8.8
Max	1.8	0.0	0.0	13.8	0.6	3.0	20.9	29.0	7.3	14.4	48.7	13.4	6.3	1.1	20.6
Amalai															
1	0.9	0.0	0.0	6.8	0.0	0.0	2.1	14.7	3.4	7.8	28.0	8.3	0.3	0.8	9.4

Mine/Seam with band no.	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI	Arg	Car	Py	SMM
2	0.1	0.0	0.0	3.6	1.2	2.4	19.9	4.0	2.2	22.1	51.8	12.8	4.8	4.0	21.6
3	0.3	0.0	0.0	9.3	0.2	2.8	16.2	5.3	2.5	20.7	47.7	7.5	3.8	1.6	12.9
4	0.1	0.0	0.0	4.8	0.5	4.9	12.3	2.0	1.0	17.1	37.9	10.7	3.6	1.0	15.3
5	0.5	0.0	0.0	7.6	0.3	3.1	5.3	25.1	7.3	7.0	48.2	22.7	4.4	1.0	28.1
6	0.0	0.0	0.0	11.8	0.0	2.7	7.6	30.7	3.0	12.3	56.4	13.1	0.3	2.1	15.4
7	0.2	0.0	0.0	7.1	0.2	0.4	7.4	23.1	1.2	15.0	47.4	17.4	4.0	0.8	22.2
8	0.5	0.0	0.0	12.4	0.0	0.2	4.8	13.9	1.4	9.7	30.0	7.6	2.6	1.2	11.4
Avg	0.3	0.0	0.0	7.9	0.3	2.1	9.4	14.9	2.8	14.0	43.4	12.5	3.0	1.6	17.0
Min	0.0	0.0	0.0	3.6	0.0	0.0	2.1	2.0	1.0	7.0	28.0	7.5	0.3	0.8	9.4
Max	0.9	0.0	0.0	12.4	1.2	4.9	19.9	30.7	7.3	22.1	56.4	22.7	4.8	4.0	28.1

Table 4.12 Occurrence and distribution of maceral content (vol.%) on mineral matter free basis.

Mine/Seam with band no.	TI	Ct	Vt	Cd	Cp	G	DV	PD	SV	Sp	Ct	Rs	Al	Sb
Sharda														
1	0.0	45.9	3.1	0.8	0.8	0.0	0.0	0.3	50.9	5.0	2.6	0.4	0.0	0.0
2	0.0	14.2	19.6	0.0	0.0	0.0	0.0	0.3	34.0	1.9	3.8	0.3	0.0	0.0
3	0.4	44.6	2.4	0.5	0.1	0.0	0.0	1.8	49.7	6.4	4.3	0.5	0.0	0.0
4	0.0	37.9	14.6	0.2	0.1	0.0	0.0	2.4	55.3	6.6	3.5	0.3	0.0	0.0
5	0.0	39.4	4.2	0.2	0.0	0.0	0.0	5.2	49.0	7.5	4.0	0.2	0.0	0.0
6	0.0	42.3	3.1	0.4	0.0	0.0	0.0	3.4	49.3	6.0	5.7	1.8	0.4	0.0
7	0.3	50.1	2.3	0.3	0.0	0.1	0.0	0.3	53.4	10.6	6.2	1.4	0.4	0.0
8	0.0	27.7	11.5	0.6	0.0	0.0	0.0	0.6	40.4	2.6	3.9	0.6	0.0	0.0
Avg	0.1	37.8	7.6	0.4	0.1	0.0	0.0	1.8	47.8	5.8	4.3	0.7	0.1	0.0
Min	0.0	14.2	2.3	0.0	0.0	0.0	0.0	0.3	34.0	1.9	2.6	0.2	0.0	0.0
Max	0.4	50.1	19.6	0.8	0.8	0.1	0.0	5.2	55.3	10.6	6.2	1.8	0.4	0.0
Dhanpuri														

Mine/Seam with band no.	Tl	Ct	Vt	Cd	Cp	G	DV	PD	SV	Sp	Ct	Rs	Al	Sb
1	0.0	5.4	8.8	0.3	0.1	0.0	0.0	0.4	14.9	0.4	14.9	0.0	0.0	0.0
2	0.0	46.3	3.3	1.1	0.0	0.0	0.2	0.5	51.4	0.5	2.2	0.0	0.0	0.0
3	0.0	31.0	13.7	0.2	0.0	0.0	0.0	2.8	47.6	0.4	1.6	0.2	0.0	0.0
4	0.0	40.9	18.9	0.7	0.0	0.0	0.5	3.2	64.0	2.9	0.9	0.9	0.5	0.0
5	1.7	5.2	26.6	0.0	0.0	0.0	0.0	0.3	33.9	7.3	9.7	0.3	0.0	0.0
Avg	0.4	25.7	14.3	0.5	0.0	0.0	0.1	1.4	42.4	2.3	5.8	0.3	0.1	0.0
Min	0.0	5.2	3.3	0.0	0.0	0.0	0.0	0.3	14.9	0.4	0.9	0.0	0.0	0.0
Max	1.7	46.3	26.6	1.1	0.1	0.0	0.5	3.2	64.0	7.3	14.9	0.9	0.5	0.0
Rajendra														
1	0.5	16.2	15.3	0.4	0.1	0.0	0.0	4.7	37.2	9.7	6.9	1.4	0.0	0.0
2	0.2	6.5	19.2	0.9	0.0	0.0	8.4	5.3	40.5	12.9	10.0	1.6	0.0	0.0
3	0.0	56.5	5.4	0.1	6.5	0.0	0.0	1.6	70.2	2.7	10.3	0.0	0.0	0.0
4	1.1	26.5	6.7	0.2	0.4	0.0	0.0	3.8	38.7	5.2	7.3	2.9	0.0	0.0
5	0.0	38.5	7.3	0.0	0.0	0.0	0.0	0.9	46.8	2.4	1.5	0.0	0.0	0.0
Avg	0.4	28.9	10.8	0.3	1.4	0.0	1.7	3.3	46.7	6.6	7.2	1.2	0.0	0.0
Min	0.0	6.5	5.4	0.0	0.0	0.0	0.0	0.9	37.2	2.4	1.5	0.0	0.0	0.0
Max	1.1	56.5	19.2	0.9	6.5	0.0	8.4	5.3	70.2	12.9	10.3	2.9	0.0	0.0
Khairaha VI seam														
1	0.0	61.2	8.3	0.2	0.0	0.2	0.0	0.8	70.8	0.5	4.6	1.5	0.0	0.0
2	0.3	57.0	0.8	0.2	0.1	0.0	0.0	0.3	58.6	5.9	2.6	0.6	0.3	0.0
3	0.3	55.0	9.9	0.0	0.6	0.0	0.1	0.5	66.3	7.7	9.2	0.3	0.0	0.0
4	0.0	30.3	5.1	0.0	0.0	0.0	0.0	3.4	38.7	1.9	7.0	0.3	0.0	0.0
5	0.0	24.6	4.8	0.7	0.0	0.0	0.0	0.4	30.4	2.1	3.0	0.0	0.0	0.0
Avg	0.1	45.6	5.8	0.2	0.1	0.1	0.0	1.1	53.0	3.6	5.3	0.5	0.1	0.0
Min	0.0	24.6	0.8	0.0	0.0	0.0	0.0	0.3	30.4	0.5	2.6	0.0	0.0	0.0
Max	0.3	61.2	9.9	0.7	0.6	0.2	0.1	3.4	70.8	7.7	9.2	1.5	0.3	0.0
Khairaha VII seam														

Mine/Seam with band no.	Tl	Ct	Vt	Cd	Cp	G	DV	PD	SV	Sp	Ct	Rs	Al	Sb
1	0.2	32.0	4.2	0.7	0.1	0.0	0.5	2.1	39.7	2.5	6.4	0.0	0.0	0.0
2	0.8	12.3	4.2	0.5	0.3	0.0	0.0	1.7	19.7	5.7	9.7	0.5	0.0	0.0
3	1.1	25.5	14.2	0.3	0.0	0.0	0.0	3.8	44.8	0.1	9.5	0.0	0.0	0.0
4	0.0	34.2	9.7	0.4	0.0	0.0	0.0	0.0	44.4	2.8	4.2	0.4	0.0	0.0
5	0.3	37.5	4.1	0.0	0.1	0.0	0.0	2.2	44.1	3.7	3.8	0.3	0.0	0.0
Avg	0.5	28.3	7.3	0.4	0.1	0.0	0.1	2.0	38.5	3.0	6.7	0.2	0.0	0.0
Min	0.0	12.3	4.1	0.0	0.0	0.0	0.0	0.0	19.7	0.1	3.8	0.0	0.0	0.0
Max	1.1	37.5	14.2	0.7	0.3	0.0	0.5	3.8	44.8	5.7	9.7	0.5	0.0	0.0
Damini VI seam 1st site														
1	0.3	12.7	24.6	0.4	0.3	0.0	0.0	1.5	39.7	2.1	7.6	0.9	0.0	0.0
2	0.0	3.3	73.7	0.6	0.0	0.0	1.3	0.0	78.9	0.6	3.1	1.5	0.0	0.0
3	0.0	5.8	31.7	2.5	0.2	0.0	0.0	0.8	40.9	1.9	7.8	0.2	0.0	0.0
Avg	0.1	7.3	43.3	1.1	0.2	0.0	0.4	0.8	53.2	1.5	6.2	0.9	0.0	0.0
Min	0.0	3.3	24.6	0.4	0.0	0.0	0.0	0.0	39.7	0.6	3.1	0.2	0.0	0.0
Max	0.3	12.7	73.7	2.5	0.3	0.0	1.3	1.5	78.9	2.1	7.8	1.5	0.0	0.0
Damini VI seam 2nd site														
1	0.0	9.8	16.1	0.8	0.0	0.0	0.7	2.2	29.5	4.4	7.6	0.0	0.0	0.0
2	0.0	5.0	47.8	0.3	0.0	0.0	1.7	1.2	56.1	2.6	6.7	0.3	0.0	0.3
3	0.0	1.4	36.6	0.0	0.0	0.0	0.0	0.0	38.0	5.1	6.6	1.2	0.0	0.0
Avg	0.0	5.4	33.5	0.4	0.0	0.0	0.8	1.1	41.2	4.1	7.0	0.5	0.0	0.1
Min	0.0	1.4	16.1	0.0	0.0	0.0	0.0	0.0	29.5	2.6	6.6	0.0	0.0	0.0
Max	0.0	9.8	47.8	0.8	0.0	0.0	1.7	2.2	56.1	5.1	7.6	1.2	0.0	0.3
Damini V														
1	0.0	5.9	7.0	0.0	0.0	0.0	0.0	0.0	12.9	2.0	3.9	0.0	0.0	0.0
2	0.0	19.2	11.8	0.2	0.5	0.0	0.7	2.8	35.3	7.3	9.0	0.8	0.0	0.0
3	0.2	47.6	4.2	0.0	0.1	0.1	0.2	1.1	53.5	4.3	1.1	0.1	0.0	0.0
4	0.0	12.4	17.2	0.6	0.0	0.0	0.0	8.5	38.7	4.8	7.5	0.0	0.0	0.0

Mine/Seam with band no.	Tl	Ct	Vt	Cd	Cp	G	DV	PD	SV	Sp	Ct	Rs	Al	Sb
Avg	0.1	21.3	10.0	0.2	0.2	0.0	0.2	3.1	35.1	4.6	5.4	0.2	0.0	0.0
Min	0.0	5.9	4.2	0.0	0.0	0.0	0.0	0.0	12.9	2.0	1.1	0.0	0.0	0.0
Max	0.2	47.6	17.2	0.6	0.5	0.1	0.7	8.5	53.5	7.3	9.0	0.8	0.0	0.0
Bangwar														
1	0.0	25.8	9.1	0.3	0.0	0.0	0.0	2.4	37.6	4.9	9.7	0.5	0.6	0.0
2	0.0	21.8	10.3	0.7	0.0	0.0	0.0	0.3	33.1	5.2	3.2	0.6	1.7	0.0
3	0.5	50.6	1.2	0.2	0.0	0.0	0.0	2.1	54.6	5.2	3.0	0.0	0.0	0.0
4	0.0	26.4	6.0	2.7	0.3	0.6	0.0	2.1	38.0	2.1	4.4	0.5	0.0	0.0
Avg	0.1	31.2	6.6	1.0	0.1	0.1	0.0	1.7	40.8	4.3	5.1	0.4	0.6	0.0
Min	0.0	21.8	1.2	0.2	0.0	0.0	0.0	0.3	33.1	2.1	3.0	0.0	0.0	0.0
Max	0.5	50.6	10.3	2.7	0.3	0.6	0.0	2.4	54.6	5.2	9.7	0.6	1.7	0.0
Amalai														
1	0.0	44.2	13.2	0.2	0.0	0.0	0.0	4.0	61.6	5.3	0.6	0.3	0.0	0.0
2	0.0	1.3	22.3	0.0	0.0	0.0	0.6	5.1	29.3	2.2	1.0	0.2	0.0	0.0
3	0.0	28.2	5.8	0.1	0.0	0.1	0.1	0.3	34.5	5.0	4.0	0.4	0.1	0.0
4	0.0	4.4	41.4	0.2	0.0	0.0	0.4	3.2	49.5	2.3	1.7	0.5	0.3	0.0
5	0.9	7.3	10.6	1.4	0.0	0.0	1.3	0.9	22.5	3.1	5.9	0.6	0.0	0.0
6	0.3	6.1	10.6	0.9	0.0	0.0	0.0	1.5	19.5	5.2	8.1	0.6	0.0	0.0
7	0.0	6.7	21.7	0.0	0.0	0.0	0.0	1.7	30.0	4.7	2.9	0.4	0.0	0.0
8	0.8	45.1	5.2	0.0	0.0	0.0	0.0	1.0	52.1	3.1	8.1	0.5	0.5	0.0
Avg	0.3	17.9	16.4	0.4	0.0	0.0	0.3	2.2	37.4	3.9	4.0	0.4	0.1	0.0
Min	0.0	1.3	5.2	0.0	0.0	0.0	0.0	0.3	19.5	2.2	0.6	0.2	0.0	0.0
Max	0.9	45.1	41.4	1.4	0.0	0.1	1.3	5.1	61.6	5.3	8.1	0.6	0.5	0.0

Mine/Seam with band no.	Ld	Fl	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI
Sharda													
1	0.3	0.0	0.0	0.0	0.0	8.2	0.3	0.7	21.0	2.1	7.4	9.5	40.9
2	0.8	0.0	0.9	0.0	0.0	7.7	2.8	1.5	29.3	7.2	1.5	16.2	58.3
3	0.5	0.0	0.4	0.0	0.0	12.0	0.2	1.0	10.8	14.4	2.9	9.0	38.3
4	0.8	0.0	1.3	0.0	0.0	12.6	0.0	0.3	8.1	10.6	4.6	8.5	32.1
5	0.2	0.0	1.0	0.0	0.0	13.0	0.1	1.4	10.4	6.1	9.1	10.9	38.0
6	0.3	0.2	1.6	0.0	0.0	15.9	0.4	0.9	10.0	3.7	2.9	17.1	34.9
7	0.6	0.0	2.5	0.3	0.0	22.0	0.3	0.7	9.2	4.0	4.6	5.8	24.6
8	0.5	0.0	0.6	0.0	0.0	8.1	0.2	0.8	31.5	6.2	2.6	10.3	51.5
Avg	0.5	0.0	1.0	0.0	0.0	12.4	0.5	0.9	16.3	6.8	4.4	10.9	39.8
Min	0.2	0.0	0.0	0.0	0.0	7.7	0.0	0.3	8.1	2.1	1.5	5.8	24.6
Max	0.8	0.2	2.5	0.3	0.0	22.0	2.8	1.5	31.5	14.4	9.1	17.1	58.3
Dhanpuri													
1	0.0	0.0	0.0	0.0	0.0	15.3	0.2	1.3	3.0	41.6	9.9	13.8	69.9
2	0.0	0.0	0.0	0.0	0.0	2.7	0.3	0.8	20.2	12.6	3.8	8.2	46.0
3	0.5	0.0	1.1	0.0	0.0	3.8	0.0	0.2	26.7	10.0	2.8	8.8	48.6
4	2.6	0.0	0.1	0.0	0.0	7.9	1.4	3.0	5.1	2.7	1.6	14.4	28.1
5	0.3	0.2	0.5	0.0	0.0	18.2	0.3	1.1	1.7	5.7	4.6	34.4	47.9
Avg	0.7	0.0	0.3	0.0	0.0	9.6	0.4	1.3	11.4	14.5	4.5	15.9	48.1
Min	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.2	1.7	2.7	1.6	8.2	28.1
Max	2.6	0.2	1.1	0.0	0.0	18.2	1.4	3.0	26.7	41.6	9.9	34.4	69.9
Rajendra													
1	0.7	0.0	1.6	0.0	0.0	20.3	1.4	1.0	8.5	17.3	4.8	9.6	42.6
2	1.2	0.0	0.4	0.0	0.0	26.2	0.2	2.2	9.5	11.6	5.0	4.9	33.3
3	1.1	0.0	2.1	0.0	0.0	16.3	0.1	0.0	1.7	7.6	0.1	3.9	13.6
4	0.4	0.0	0.2	0.4	0.0	16.4	0.1	0.3	4.6	25.3	5.7	9.0	45.0

Mine/Seam with band no.	Ld	Fl	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI
5	0.5	0.0	1.4	0.0	0.0	5.8	0.0	0.2	26.4	10.4	3.8	6.7	47.5
Avg	0.8	0.0	1.2	0.1	0.0	17.0	0.4	0.8	10.2	14.4	3.9	6.8	36.4
Min	0.4	0.0	0.2	0.0	0.0	5.8	0.0	0.0	1.7	7.6	0.1	3.9	13.6
Max	1.2	0.0	2.1	0.4	0.0	26.2	1.4	2.2	26.4	25.3	5.7	9.6	47.5
Khairaha VI seam													
1	0.2	0.1	0.7	0.0	0.0	7.6	0.0	0.1	2.6	10.0	3.2	5.7	21.6
2	0.0	0.2	0.6	0.0	0.0	10.1	0.3	1.4	5.8	13.6	1.6	8.7	31.3
3	0.7	0.0	1.9	0.0	0.0	19.7	0.2	0.0	3.9	6.7	0.2	3.0	14.0
4	0.0	0.1	0.6	0.0	0.0	9.9	0.0	1.2	14.5	21.5	0.9	13.2	51.4
5	0.4	0.0	1.3	0.0	0.0	6.8	0.1	0.4	37.4	13.5	3.5	7.9	62.9
Avg	0.3	0.1	1.0	0.0	0.0	10.8	0.1	0.6	12.8	13.1	1.9	7.7	36.2
Min	0.0	0.0	0.6	0.0	0.0	6.8	0.0	0.0	2.6	6.7	0.2	3.0	14.0
Max	0.7	0.2	1.9	0.0	0.0	19.7	0.3	1.4	37.4	21.5	3.5	13.2	62.9
Khairaha VII seam													
1	0.5	0.0	1.5	0.0	0.0	10.8	0.6	2.0	3.5	28.4	2.6	12.4	49.5
2	1.2	0.0	0.3	0.2	0.0	17.6	1.1	2.4	7.7	27.0	2.7	21.7	62.7
3	0.4	0.0	0.8	0.0	0.0	10.8	1.3	2.0	9.8	14.8	0.8	15.8	44.5
4	0.9	0.0	1.4	0.0	0.0	9.7	0.3	0.9	24.5	7.4	4.9	8.0	45.9
5	0.5	0.8	0.5	0.0	0.0	9.6	0.1	2.3	16.8	8.4	4.9	13.8	46.3
Avg	0.7	0.2	0.9	0.0	0.0	11.7	0.7	1.9	12.5	17.2	3.2	14.3	49.8
Min	0.4	0.0	0.3	0.0	0.0	9.6	0.1	0.9	3.5	7.4	0.8	8.0	44.5
Max	1.2	0.8	1.5	0.2	0.0	17.6	1.3	2.4	24.5	28.4	4.9	21.7	62.7
Damini VI seam													
1st site													
1	0.6	0.0	0.3	0.0	0.0	11.5	0.0	0.6	3.5	29.0	5.2	10.5	48.8
2	2.4	0.0	0.0	0.0	0.0	7.5	0.4	2.0	2.8	4.2	1.5	2.8	13.6

Mine/Seam with band no.	Ld	Fl	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI
3	1.2	0.0	0.2	0.0	0.0	11.3	0.8	4.2	8.3	7.4	2.9	24.2	47.8
Avg	1.4	0.0	0.2	0.0	0.0	10.1	0.4	2.3	4.8	13.5	3.2	12.5	36.7
Min	0.6	0.0	0.0	0.0	0.0	7.5	0.0	0.6	2.8	4.2	1.5	2.8	13.6
Max	2.4	0.0	0.3	0.0	0.0	11.5	0.8	4.2	8.3	29.0	5.2	24.2	48.8
Damini VI seam													
2nd site													
1	0.3	0.1	0.5	0.0	0.0	12.9	0.8	3.8	9.0	11.7	3.6	28.6	57.6
2	2.0	0.0	0.0	0.0	0.0	12.0	1.1	1.7	5.6	12.3	5.6	5.8	32.0
3	1.8	0.0	0.0	0.0	0.0	14.6	0.6	3.7	4.2	8.3	4.7	25.8	47.4
Avg	1.4	0.0	0.2	0.0	0.0	13.2	0.8	3.1	6.3	10.8	4.6	20.1	45.6
Min	0.3	0.0	0.0	0.0	0.0	12.0	0.6	1.7	4.2	8.3	3.6	5.8	32.0
Max	2.0	0.1	0.5	0.0	0.0	14.6	1.1	3.8	9.0	12.3	5.6	28.6	57.6
Damini V													
1	1.1	0.0	0.0	0.0	0.0	7.0	0.5	4.6	1.8	15.6	3.6	54.2	80.2
2	0.7	0.0	1.0	0.0	0.0	18.8	0.3	1.7	7.3	19.2	4.4	13.0	45.9
3	0.0	0.1	0.8	0.0	0.0	6.5	0.8	2.4	8.0	8.5	8.2	12.1	40.0
4	0.6	0.0	0.8	0.0	0.0	13.7	0.4	3.6	12.2	6.1	3.4	21.9	47.7
Avg	0.6	0.0	0.7	0.0	0.0	11.5	0.5	3.1	7.3	12.4	4.9	25.3	53.5
Min	0.0	0.0	0.0	0.0	0.0	6.5	0.3	1.7	1.8	6.1	3.4	12.1	40.0
Max	1.1	0.1	1.0	0.0	0.0	18.8	0.8	4.6	12.2	19.2	8.2	54.2	80.2
Bangwar													
1	0.7	0.0	0.0	0.0	0.0	16.4	0.1	0.2	24.9	8.1	8.6	4.1	46.0
2	1.2	0.0	2.3	0.0	0.0	14.1	0.4	1.7	20.7	9.7	2.2	18.1	52.8
3	0.0	0.0	0.9	0.0	0.0	9.1	0.7	3.5	8.5	6.5	2.0	15.2	36.4
4	0.7	0.0	1.0	0.0	0.0	8.6	0.3	1.3	8.4	31.8	2.8	8.8	53.4
Avg	0.6	0.0	1.0	0.0	0.0	12.1	0.4	1.7	15.6	14.0	3.9	11.5	47.1
Min	0.0	0.0	0.0	0.0	0.0	8.6	0.1	0.2	8.4	6.5	2.0	4.1	36.4

Mine/Seam with band no.	Ld	Fl	Ed	Bi	P	SL	Mi	Ma	Sf	Fu	Se	Id	SI
Max	1.2	0.0	2.3	0.0	0.0	16.4	0.7	3.5	24.9	31.8	8.6	18.1	53.4
Amalai													
1	0.3	0.0	0.9	0.0	0.0	7.5	0.0	0.0	2.3	16.3	3.8	8.6	30.9
2	1.1	0.0	0.1	0.0	0.0	4.6	1.6	3.0	25.4	5.1	2.8	28.2	66.2
3	0.7	0.2	0.4	0.0	0.0	10.7	0.2	3.2	18.6	6.1	2.9	23.7	54.8
4	0.7	0.0	0.1	0.0	0.0	5.7	0.6	5.8	14.6	2.3	1.2	20.2	44.8
5	0.0	0.3	0.6	0.0	0.0	10.6	0.5	4.4	7.3	35.0	10.1	9.7	66.9
6	0.0	0.0	0.0	0.0	0.0	13.9	0.0	3.2	9.0	36.3	3.5	14.6	66.6
7	0.8	0.0	0.3	0.0	0.0	9.2	0.3	0.6	9.4	29.7	1.5	19.3	60.8
8	1.4	0.0	0.5	0.0	0.0	14.1	0.0	0.3	5.4	15.7	1.5	11.0	33.8
Avg	0.6	0.1	0.4	0.0	0.0	9.5	0.4	2.6	11.5	18.3	3.4	16.9	53.1
Min	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	2.3	2.3	1.2	8.6	30.9
Max	1.4	0.3	0.9	0.0	0.0	14.1	1.6	5.8	25.4	36.3	10.1	28.2	66.9

Where Tl- Telinite, Ct- Collotelinite, Vt- Vitrodetrinite, Cd- Collodetrinite, Cp- Corpogelinite, G- Gelinite, DV- Dark Vitrinite, PD-Pseudovitrinite, SV- Sum of Vitrinite, Sp- Sporinite, Ct- Cutinite, Rs- Resinite, Al- Alginite, Sb- Suberinite, Ld- Liptodetrinite, Fl- Fluorinite, Ed- Exsudatinitite, Bi- Bituminite, P- Pollen, SL- Sum of Liptinite, Mi- Micrinite, Ma- Macrinite, Sf- Semifusinite, Fu- Fusinite, Se- Secretinite, Id- Inertodetrinite, SI- Sum of Inertinite, Arg- Argillaceous, Car- Carbonate, Py- Pyrite, SMM- Sum of Mineral matter.

4.6.3 Variation and qualitative distribution of microlithotype and carbominerite in Sohagpur coals

As discussed in the previous section, the qualitative distribution of macerals and mineral matter has been presented. In this section, the qualitative vertical distribution of microlithotypes and carbominerite is described, and their vertical seam profiles are illustrated in Figure 4.10. Variations in microlithotype assemblages provide important insights into peat preservation, maceral reworking, and mineral matter influx during coal seam development.

The Sharda coal seam exhibits a dominance of monomaceral microlithotypes in the upper part of the seam profile, indicating relatively uniform maceral composition and minimal degradation during peat accumulation. In contrast, the middle and lower bands are enriched in bimaceral microlithotypes, reflecting increased maceral mixing and reworking. These bimaceral-rich bands are also associated with a higher proportion of carbominerite, suggesting enhanced mineral matter influx during these depositional phases (Figure 4.10(a)).

The Dhanpuri coal seam profile shows that the top band contains more than 50% monomaceral microlithotypes. Moving downward toward the middle of the seam, the concentration of monomaceral microlithotypes further increases, accompanied by a corresponding decrease in bimaceral and trimaceral microlithotypes, indicating improved preservation of organic matter. However, from the middle to the bottom of the seam, a progressive increase in carbominerite content is observed, suggesting a higher influx of mineral matter in the lower bands, likely due to increased clastic sediment input during peat formation (Figure 4.10(b)).

In the Rajendra coal seam, the vertical profile is characterized by an abundance of monomaceral microlithotypes in the top band, followed by a sudden decrease in monomaceral content and a corresponding increase in bimaceral and trimaceral microlithotypes. This alternating pattern continues toward the bottom of the seam, indicating cyclical changes in peat accumulation conditions, with repeated phases of maceral reworking and variable degradation intensity (Figure 4.10(c)).

The Khairaha Seam VI displays a consistent dominance of monomaceral microlithotypes across all bands, accounting for approximately 60% of the total microlithotype assemblage. This uniformity suggests stable depositional conditions with minimal maceral degradation or reworking throughout seam development (Figure 4.10(d)).

In Khairaha Seam VII, the middle band is marked by a relatively high abundance of carbominerite compared to the upper and lower bands, indicating a significant influx of mineral matter during this stage of peat accumulation. In contrast, the upper and lower portions of the seam show increased monomaceral content, suggesting relatively lower degrees of maceral degradation and improved organic matter preservation during those periods (Figure 4.10(e)).

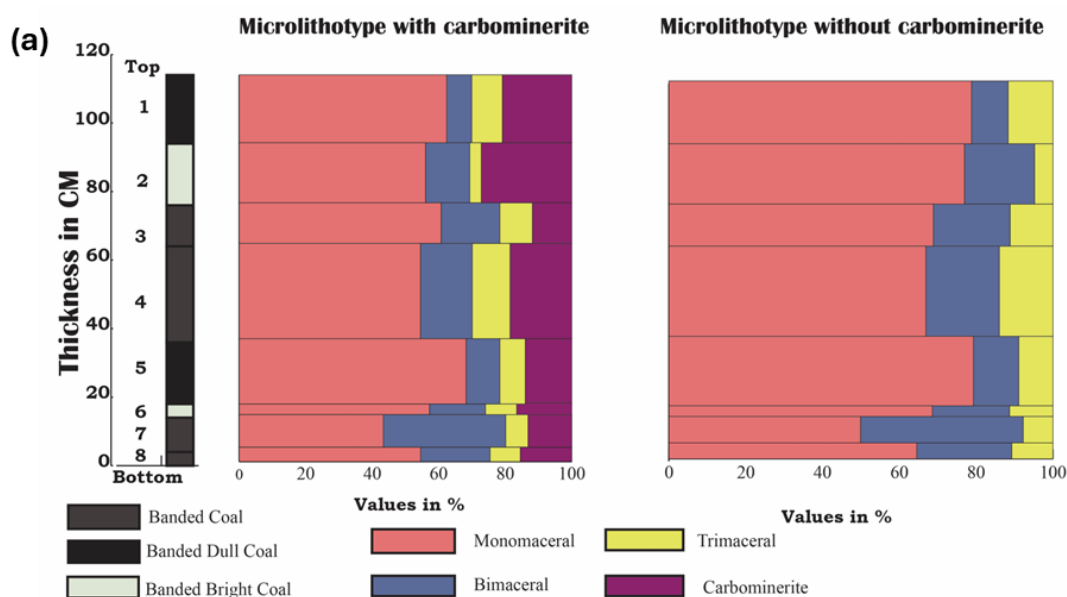
The Damini Seam VI, at both studied sites, is dominated by dull coal lithotypes and characterized by a high abundance of carbominerite and a comparatively lower proportion of microlithotypes. This reflects substantial input of mineral matter and greater maceral degradation. However, the uppermost bands at both sites show an increased abundance of monomaceral microlithotypes, suggesting that peat degradation was less intense during the initial stages of seam formation (Figure 4.10(f)).

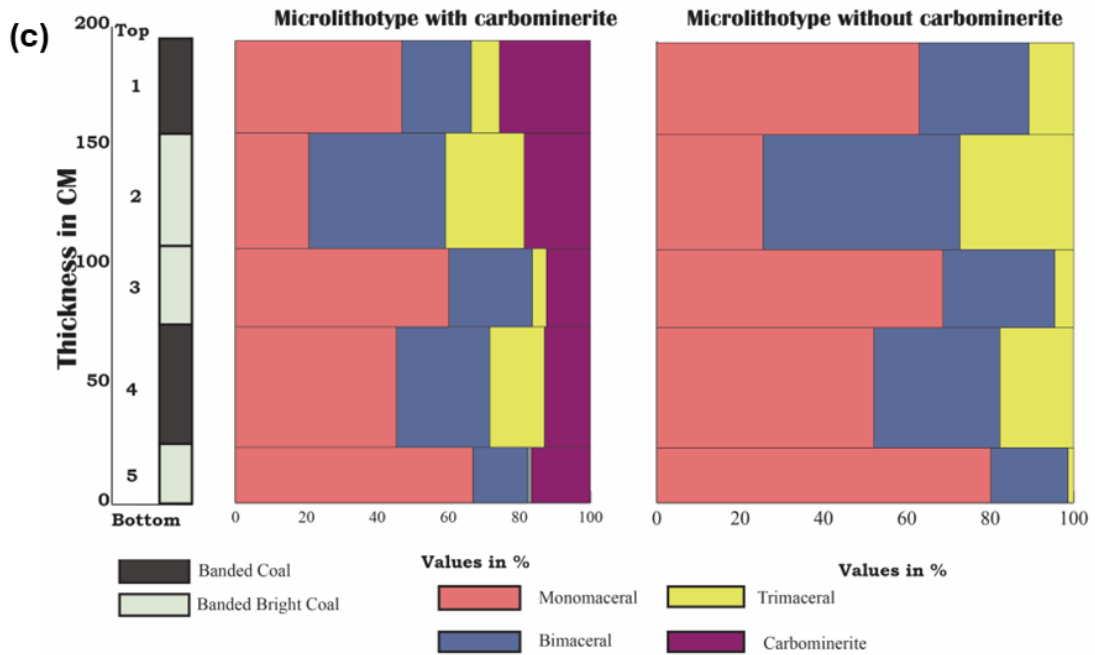
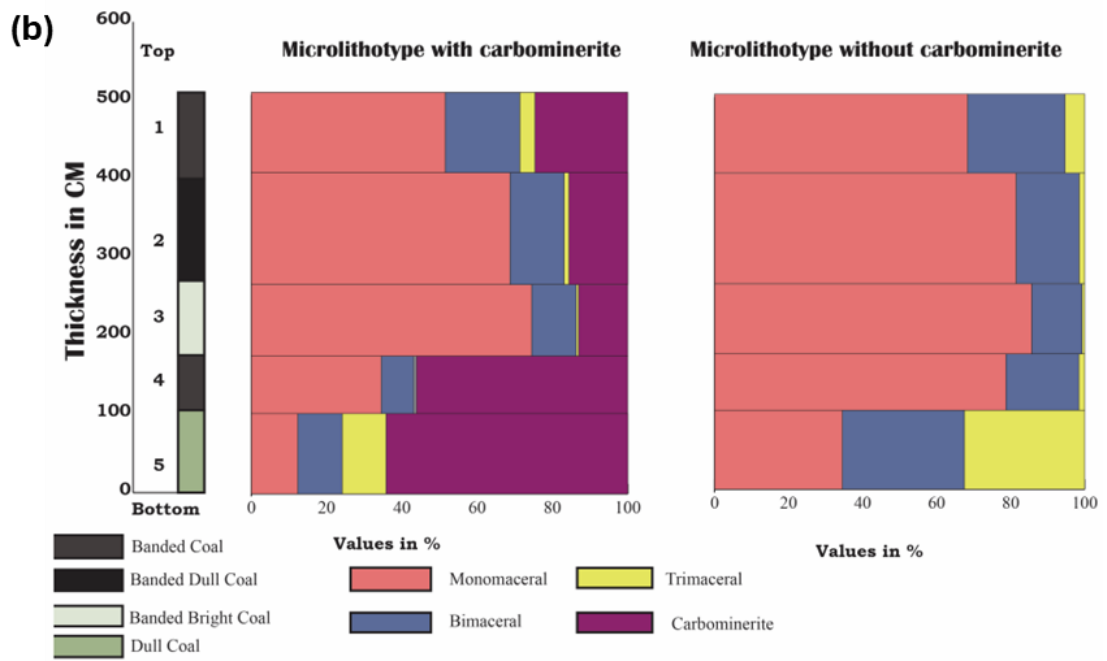
In the Damini Seam V, the top band exhibits a high proportion of carbominerite, indicating enhanced mineral matter influx during early peat accumulation. With

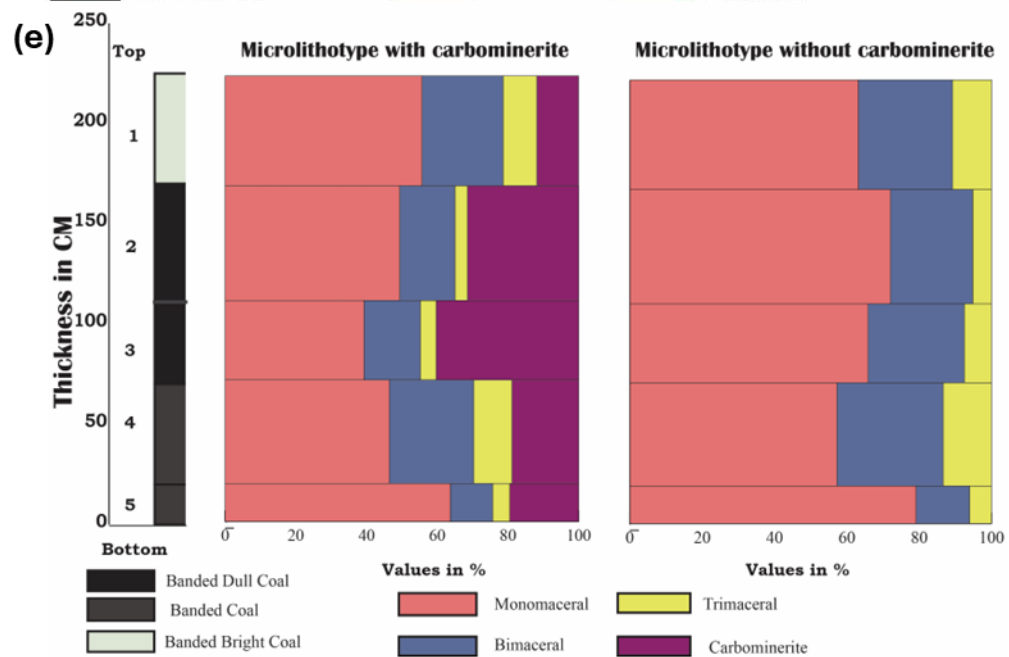
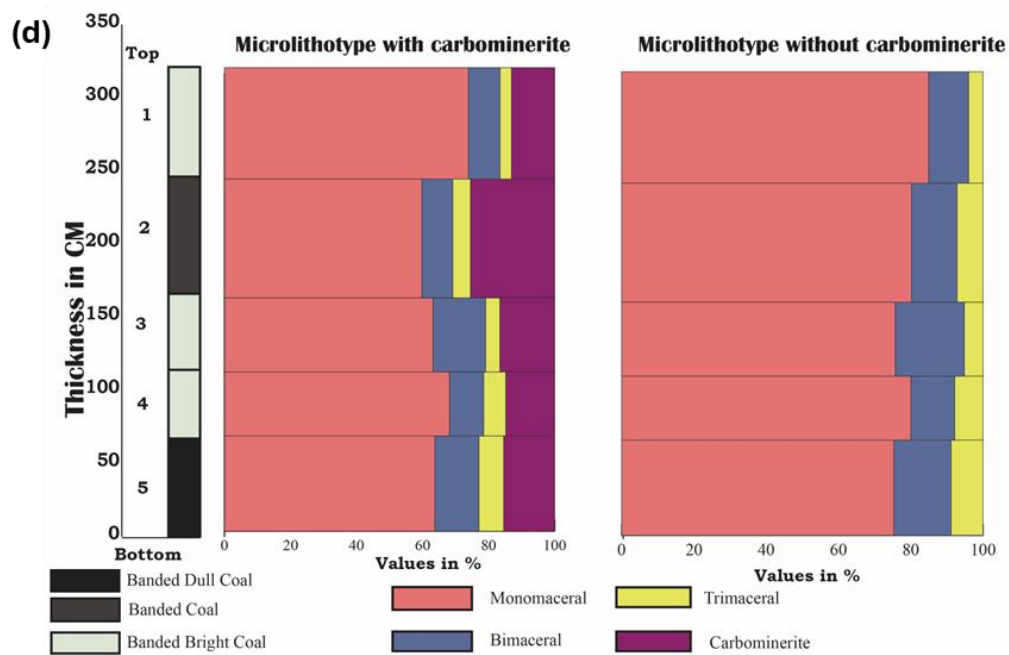
increasing depth, the middle band shows a dominance of monomaceral microlithotypes, reflecting a period of reduced degradation and more stable peat-forming conditions (Figure 4.10(g)).

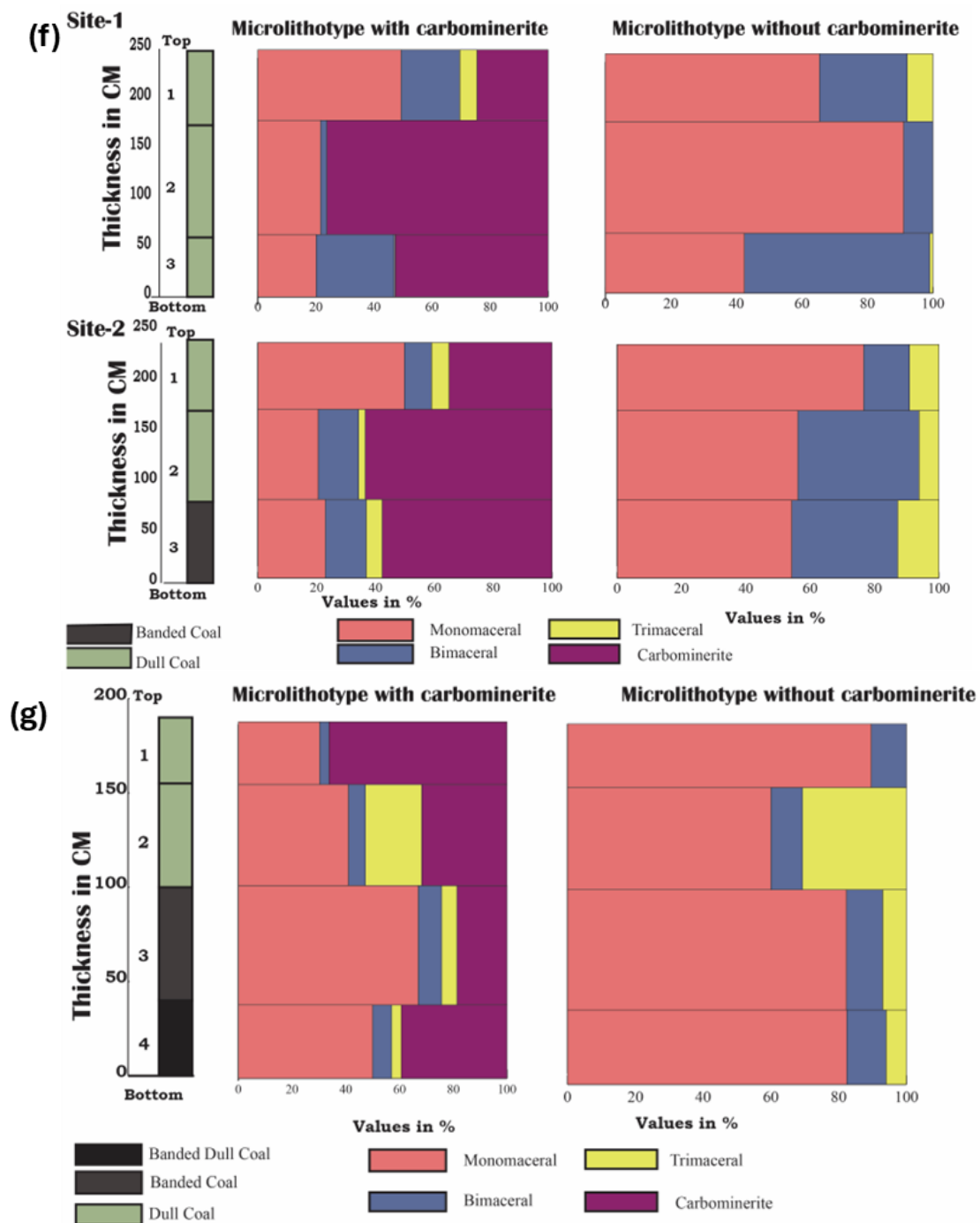
The Bangwar coal seam is characterized by the dominance of monomaceral microlithotypes throughout the vertical profile compared to other microlithotype groups. The middle band shows a particularly low abundance of trimaceral microlithotypes, suggesting limited maceral reworking and minimal degradation during this phase of peat accumulation (Figure 4.10(h)).

In the Amalai coal seam, the top band shows a high abundance of trimaceral microlithotypes, indicating intense maceral reworking and higher degrees of degradation. Toward the middle section of the seam, monomaceral microlithotypes become dominant, suggesting improved preservation conditions. In the lower section of the seam, an increase in bimaceral and trimaceral microlithotypes is again observed, confirming renewed phases of maceral degradation and reworking during later stages of seam development (Figure 4.10(i)).









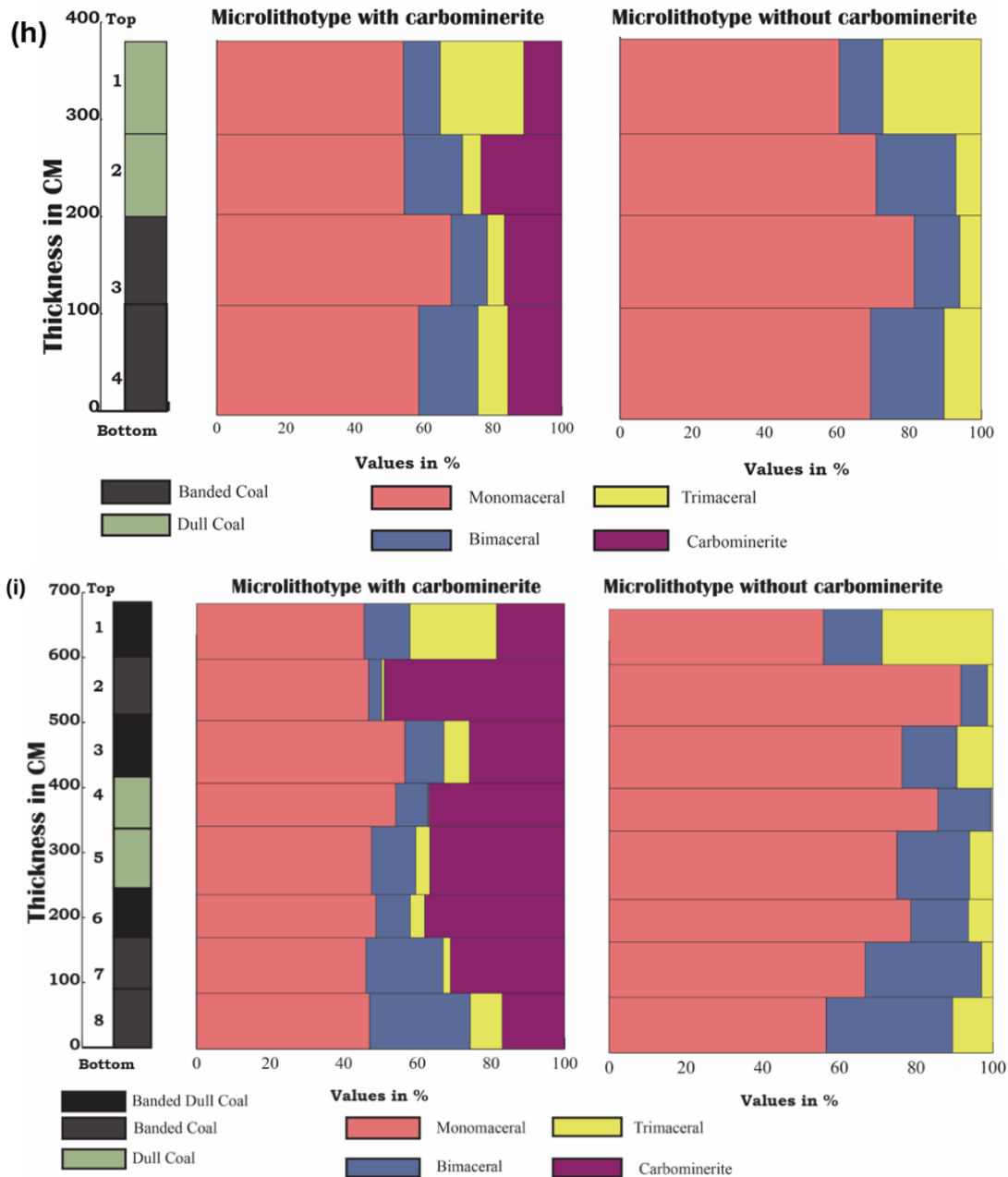


Figure 4.10 Vertical profile of coal seams with variation in microlithotype with carbominerite and microlithotype without carbominerite in Sohagpur coals (a) Sharda, (b) Dhanpuri, (c) Rajendra, (d) Khairaha Seam VI, (e) Khairaha Seam VII (f) Damini Seam VI, (g) Damini Seam V, (h) Bangwar, and (i) Amalai coal mine.

4.6.4 Quantitative distribution of microlithotype and carbominerite in Sohagpur coals

The microlithotype composition of the studied coal seams, as determined by the identification of monomaceral, bimaceral, trimaceral and carbominerite types, shows significant spatial variability across the different mining blocks. The Sharda mine records monomaceral with an average of 57.12% (ranges from 43.35 to 68.22%), bimaceral with

an average of 17.33% (ranges from 7.53 to 36.78%), trimaceral with an average of 8.36% (ranges from 3.48 to 11.38%) and carbominerite with an average of 17.20% (ranges from 11.83 to 27.22%). The Dhanpuri mine records monomaceral with an average of 48.31% (ranges from 12.34 to 74.47%), bimaceral with an average of 13.28% (ranges from 8.62 to 19.80%), trimaceral with an average of 3.65% (ranges from 0.63 to 11.62%) and carbominerite with an average of 34.76% (ranges from 13.08 to 64.25%). The Rajendra mine records monomaceral with an average of 47.99% (ranges from 20.70 to 66.89%), bimaceral with an average of 24.66% (ranges from 15.44 to 38.48%), trimaceral with an average of 10.11% (ranges from 1.12 to 22.16%) and carbominerite with an average of 17.23% (ranges from 12.39 to 25.59%). The Khairaha VI mine records monomaceral with an average of 65.71% (ranges from 59.75 to 73.84%), bimaceral with an average of 11.73% (ranges from 9.38 to 15.92%), trimaceral with an average of 5.47% (ranges from 3.49 to 7.47%) and carbominerite with an average of 17.09% (ranges from 13.08 to 25.50%). The Khairaha VII mine records monomaceral with an average of 50.93% (ranges from 39.33 to 63.72%), bimaceral with an average of 18.05% (ranges from 11.95 to 23.81%), trimaceral with an average of 6.66% (ranges from 3.54 to 10.86%) and carbominerite with an average of 24.37% (ranges from 11.81 to 40.29%). The Damini VI (first site) records monomaceral with an average of 30.36% (ranges from 20.10 to 49.36%), bimaceral with an average of 16.38% (ranges from 2.13 to 26.79%), trimaceral with an average of 2.15% (ranges from 0.00 to 5.96%) and carbominerite with an average of 51.11% (ranges from 24.47 to 76.24%). The Damini VI (second site) records monomaceral with an average of 31.09% (ranges from 20.51 to 49.83%), bimaceral with an average of 12.31% (ranges from 9.24 to 13.92%), trimaceral with an average of 4.53% (ranges from 2.25 to 5.94%) and carbominerite with an average of 52.07% (ranges from 34.98 to 63.48%). The Damini V mine records monomaceral with an average of 47.05%

(ranges from 30.27 to 66.97%), bimaceral with an average of 6.40% (ranges from 3.51 to 8.71%), trimaceral with an average of 7.58% (ranges from 0.00 to 20.96%) and carbominerite with an average of 38.97% (ranges from 18.62 to 66.22%). The Bangwar mine records monomaceral with an average of 58.66% (ranges from 54.00 to 67.88%), bimaceral with an average of 13.84% (ranges from 10.52 to 17.19%), trimaceral with an average of 10.83% (ranges from 4.97 to 24.25%) and carbominerite with an average of 16.67% (ranges from 11.00 to 23.42%). The Amalai mine records monomaceral with an average of 49.03% (ranges from 45.53 to 56.60%), bimaceral with an average of 13.11% (ranges from 3.53 to 27.36%), trimaceral with an average of 6.26% (ranges from 0.36 to 23.53%) and carbominerite with an average of 31.60% (ranges from 16.95 to 48.97%). Tables 4.13 and 4.14 show the microlithotype with carbominerite and microlithotype on carbominerite-free basis values for the Sohagpur coals, respectively.

Table 4.13 Occurrence and distribution of microlithotype with carbominerite (vol.%) of Sohagpur coals.

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	CI	VV	VI	Ve	DI
Sharda											
1	35.7	0.2	26.5	62.4	0.9	0.7	0.0	3.9	1.7	0.0	0.4
2	16.8	0.6	38.6	56.0	1.0	0.0	0.0	4.4	7.3	0.0	0.6
3	38.2	0.0	22.5	60.7	3.4	0.0	0.0	11.2	2.2	0.0	0.9
4	31.5	0.0	23.0	54.5	4.2	0.6	0.0	3.8	4.2	0.0	2.8
5	43.3	0.0	24.9	68.2	1.8	0.0	0.0	4.0	3.3	0.0	1.0
6	33.8	0.5	23.0	57.2	6.1	0.3	0.0	6.6	3.3	0.0	0.5
7	37.6	1.3	4.4	43.4	16.3	2.6	0.0	11.8	6.1	0.0	0.0
8	20.4	0.3	33.9	54.6	4.4	0.7	0.0	6.6	4.7	0.0	3.9
Avg	32.2	0.4	24.6	57.1	4.7	0.6	0.0	6.5	4.1	0.0	1.3
Min	16.8	0.0	4.4	43.4	0.9	0.0	0.0	3.8	1.7	0.0	0.0
Max	43.3	1.3	38.6	68.2	16.3	2.6	0.0	11.8	7.3	0.0	3.9
Dhanpuri											
1	4.2	0.7	46.6	51.5	1.3	0.3	0.0	3.4	2.2	0.0	10.1
2	41.1	0.0	27.7	68.7	0.4	0.0	0.0	9.5	4.5	0.0	0.0
3	38.4	0.0	36.1	74.5	0.8	0.0	0.0	7.2	3.6	0.0	0.2
4	24.0	0.5	10.0	34.5	1.2	0.0	0.0	4.9	2.3	0.0	0.2
5	5.1	0.4	6.9	12.3	1.1	0.4	0.0	4.0	2.2	0.0	3.6
Avg	22.6	0.3	25.5	48.3	1.0	0.1	0.0	5.8	3.0	0.0	2.8
Min	4.2	0.0	6.9	12.3	0.4	0.0	0.0	3.4	2.2	0.0	0.0
Max	41.1	0.7	46.6	74.5	1.3	0.4	0.0	9.5	4.5	0.0	10.1
Rajendra											
1	15.7	0.7	30.5	46.9	2.4	1.7	0.0	2.4	1.3	0.2	9.9

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	CI	VV	VI	Ve	DI
2	6.4	0.6	13.7	20.7	8.5	2.0	2.3	7.0	2.3	0.3	12.5
3	53.1	0.5	6.5	60.1	22.1	0.4	0.0	0.7	0.2	0.0	0.2
4	20.7	0.6	24.1	45.3	3.4	0.4	0.0	5.3	4.7	0.0	10.3
5	32.9	0.0	34.0	66.9	2.5	0.2	0.0	7.4	4.9	0.0	0.5
Avg	25.8	0.5	21.8	48.0	7.8	1.0	0.5	4.6	2.7	0.1	6.7
Min	6.4	0.0	6.5	20.7	2.4	0.2	0.0	0.7	0.2	0.0	0.2
Max	53.1	0.7	34.0	66.9	22.1	2.0	2.3	7.4	4.9	0.3	12.5
Khairaha VI seam											
1	57.3	0.9	15.7	73.8	6.7	0.3	0.0	0.3	2.0	0.0	0.3
2	44.9	0.4	14.5	59.8	2.8	0.3	0.0	0.0	4.6	1.4	0.4
3	57.6	0.2	5.4	63.2	13.0	0.7	0.0	0.5	1.7	0.0	0.0
4	22.1	0.0	46.0	68.2	4.5	0.6	0.0	3.3	1.0	0.0	1.0
5	17.3	0.5	45.9	63.7	6.7	0.8	0.0	3.6	1.8	0.0	0.5
Avg	39.8	0.4	25.5	65.7	6.7	0.5	0.0	1.5	2.2	0.3	0.4
Min	17.3	0.0	5.4	59.8	2.8	0.3	0.0	0.0	1.0	0.0	0.0
Max	57.6	0.9	46.0	73.8	13.0	0.8	0.0	3.6	4.6	1.4	1.0
Khairaha VII seam											
1	29.8	0.0	25.9	55.7	1.6	0.0	0.0	5.9	5.9	0.0	9.3
2	10.9	1.2	37.3	49.4	1.8	0.2	0.0	2.7	0.6	0.0	8.9
3	15.4	0.3	23.6	39.3	1.1	0.0	0.0	4.0	2.7	0.0	7.5
4	22.3	0.8	23.4	46.5	9.0	5.9	0.0	4.0	2.3	0.0	2.7
5	35.1	0.4	28.2	63.7	1.9	0.0	0.0	5.5	3.8	0.0	0.7
Avg	22.7	0.5	27.7	50.9	3.1	1.2	0.0	4.4	3.1	0.0	5.8
Min	10.9	0.0	23.4	39.3	1.1	0.0	0.0	2.7	0.6	0.0	0.7
Max	35.1	1.2	37.3	63.7	9.0	5.9	0.0	5.9	5.9	0.0	9.3
Damini VI seam 1st site											
1	9.6	0.6	39.2	49.4	0.6	0.0	0.0	5.1	3.0	0.0	10.6

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	CI	VV	VI	Ve	DI
2	6.4	0.7	14.5	21.6	1.4	0.7	0.0	0.0	0.0	0.0	0.0
3	1.4	0.5	18.2	20.1	2.9	0.2	0.2	8.4	5.3	0.2	9.1
Avg	5.8	0.6	24.0	30.4	1.6	0.3	0.1	4.5	2.8	0.1	6.6
Min	1.4	0.5	14.5	20.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Max	9.6	0.7	39.2	49.4	2.9	0.7	0.2	8.4	5.3	0.2	10.6
Damini VI seam 2nd site											
1	6.1	2.5	41.3	49.8	0.5	0.0	0.0	5.0	2.0	0.0	1.8
2	5.1	0.6	14.9	20.5	3.1	1.4	0.0	4.5	3.1	0.0	1.4
3	4.4	0.0	18.6	22.9	1.6	0.5	0.0	1.0	4.6	0.0	5.4
Avg	5.2	1.0	24.9	31.1	1.7	0.6	0.0	3.5	3.2	0.0	2.9
Min	4.4	0.0	14.9	20.5	0.5	0.0	0.0	1.0	2.0	0.0	1.4
Max	6.1	2.5	41.3	49.8	3.1	1.4	0.0	5.0	4.6	0.0	5.4
Damini V											
1	7.0	1.6	21.6	30.3	0.5	0.0	0.0	1.6	0.5	0.0	0.8
2	14.4	0.0	26.5	41.0	1.7	0.0	0.0	1.5	3.1	0.0	0.0
3	43.7	0.2	23.1	67.0	1.5	0.0	0.0	4.8	2.3	0.0	0.2
4	19.6	0.0	30.5	50.0	0.7	0.0	0.0	2.5	0.9	0.0	2.7
Avg	21.2	0.4	25.4	47.1	1.1	0.0	0.0	2.6	1.7	0.0	0.9
Min	7.0	0.0	21.6	30.3	0.5	0.0	0.0	1.5	0.5	0.0	0.0
Max	43.7	1.6	30.5	67.0	1.7	0.0	0.0	4.8	3.1	0.0	2.7
Bangwar											
1	16.8	0.8	36.5	54.0	5.8	0.8	0.0	0.8	0.3	0.0	3.0
2	18.2	0.4	35.7	54.3	7.1	1.3	0.0	5.2	1.5	0.0	1.5
3	56.8	0.0	11.1	67.9	5.0	0.0	0.0	4.4	1.0	0.0	0.2
4	20.3	0.2	38.0	58.5	1.2	0.2	0.1	5.0	3.5	0.0	6.6
Avg	28.0	0.3	30.3	58.7	4.7	0.6	0.0	3.9	1.5	0.0	2.8
Min	16.8	0.0	11.1	54.0	1.2	0.0	0.0	0.8	0.3	0.0	0.2

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	CI	VV	VI	Ve	DI
Max	56.8	0.8	38.0	67.9	7.1	1.3	0.1	5.2	3.5	0.0	6.6
Amalai											
1	33.3	0.0	12.2	45.5	2.2	0.2	0.0	4.4	3.9	0.4	0.9
2	1.8	0.3	44.7	46.8	0.2	0.2	0.0	0.9	0.3	0.0	2.1
3	20.1	0.5	35.9	56.6	1.1	0.0	0.0	5.4	3.0	0.0	1.1
4	3.9	0.7	49.5	54.1	2.5	0.0	0.0	3.6	0.4	0.0	2.3
5	6.0	0.6	40.9	47.5	1.5	0.4	0.0	1.7	2.1	0.0	4.7
6	2.8	0.0	45.9	48.7	2.5	0.6	0.0	0.9	1.1	0.0	3.4
7	4.4	0.6	40.9	46.0	1.2	0.0	0.0	5.4	2.2	0.0	11.3
8	32.2	1.0	13.8	47.0	17.0	1.0	0.0	4.4	1.9	0.0	2.7
Avg	13.1	0.5	35.5	49.0	3.5	0.3	0.0	3.3	1.9	0.1	3.6
Min	1.8	0.0	12.2	45.5	0.2	0.0	0.0	0.9	0.3	0.0	0.9
Max	33.3	1.0	49.5	56.6	17.0	1.0	0.0	5.4	3.9	0.4	11.3

Mine/Seam with band no.	DL	De	TB	VL	CD	DC	TT	Cg	Ca	Cp	Cm	TC
Sharda												
1	0.0	0.0	7.5	0.9	2.6	5.8	9.3	18.5	0.9	0.7	0.9	20.9
2	0.0	0.0	13.3	0.3	2.2	1.0	3.5	20.3	5.4	0.6	1.0	27.2
3	0.0	0.0	17.6	2.2	2.9	4.7	9.8	10.0	0.9	0.9	0.0	11.8
4	0.0	0.0	15.6	4.4	2.4	4.6	11.4	18.2	0.0	0.4	0.0	18.6
5	0.1	0.0	10.1	2.6	2.1	3.0	7.7	12.1	1.6	0.1	0.1	14.0
6	0.0	0.0	16.8	2.8	2.3	4.4	9.4	12.4	3.3	0.3	0.5	16.6
7	0.0	0.0	36.8	1.0	2.1	3.6	6.7	11.2	2.0	0.0	0.0	13.1
8	0.5	0.0	20.9	0.5	3.2	5.4	9.1	11.8	3.2	0.5	0.0	15.5
Avg	0.1	0.0	17.3	1.8	2.5	4.1	8.4	14.3	2.2	0.4	0.3	17.2

Mine/Seam with band no.	DL	De	TB	VL	CD	DC	TT	Cg	Ca	Cp	Cm	TC
Min	0.0	0.0	7.5	0.3	2.1	1.0	3.5	10.0	0.0	0.0	0.0	11.8
Max	0.5	0.0	36.8	4.4	3.2	5.8	11.4	20.3	5.4	0.9	1.0	27.2
Dhanpuri												
1	2.5	0.0	19.8	0.2	1.7	2.2	4.0	23.2	0.3	0.3	0.8	24.7
2	0.0	0.0	14.4	0.1	0.6	0.6	1.3	11.7	1.0	2.9	0.0	15.6
3	0.0	0.0	11.8	0.0	0.2	0.4	0.6	9.1	0.6	3.4	0.0	13.1
4	0.0	0.0	8.6	0.2	0.0	0.5	0.7	40.3	13.3	1.9	0.7	56.2
5	0.5	0.0	11.8	1.5	4.9	5.3	11.6	55.9	6.7	1.3	0.4	64.3
Avg	0.6	0.0	13.3	0.4	1.5	1.8	3.7	28.0	4.4	2.0	0.4	34.8
Min	0.0	0.0	8.6	0.0	0.0	0.4	0.6	9.1	0.3	0.3	0.0	13.1
Max	2.5	0.0	19.8	1.5	4.9	5.3	11.6	55.9	13.3	3.4	0.8	64.3
Rajendra												
1	1.7	0.0	19.6	2.2	1.7	4.1	8.0	20.7	4.5	0.4	0.0	25.6
2	3.5	0.0	38.5	5.3	2.6	14.3	22.2	16.0	2.3	0.3	0.0	18.7
3	0.0	0.0	23.5	0.4	0.7	2.9	4.0	8.3	3.6	0.5	0.0	12.4
4	2.2	0.0	26.3	0.4	6.7	8.3	15.4	8.5	3.4	1.0	0.0	13.0
5	0.0	0.0	15.4	0.0	0.5	0.7	1.1	14.8	1.6	0.2	0.0	16.6
Avg	1.5	0.0	24.7	1.6	2.4	6.0	10.1	13.6	3.1	0.5	0.0	17.2
Min	0.0	0.0	15.4	0.0	0.5	0.7	1.1	8.3	1.6	0.2	0.0	12.4
Max	3.5	0.0	38.5	5.3	6.7	14.3	22.2	20.7	4.5	1.0	0.0	25.6
Khairaha VI seam												
1	0.0	0.0	9.6	0.3	0.9	2.3	3.5	11.1	1.2	0.6	0.3	13.1
2	0.0	0.0	9.4	1.6	0.9	2.9	5.4	22.4	2.8	0.3	0.1	25.5
3	0.0	0.0	15.9	0.0	0.5	3.8	4.3	16.6	0.0	0.0	0.0	16.6
4	0.0	0.0	10.3	2.4	1.4	2.8	6.7	13.2	1.2	0.0	0.4	14.8
5	0.0	0.0	13.4	0.8	2.3	4.4	7.5	11.9	2.8	0.5	0.3	15.5

Mine/Seam with band no.	DL	De	TB	VL	CD	DC	TT	Cg	Ca	Cp	Cm	TC
Avg	0.0	0.0	11.7	1.0	1.2	3.3	5.5	15.0	1.6	0.3	0.2	17.1
Min	0.0	0.0	9.4	0.0	0.5	2.3	3.5	11.1	0.0	0.0	0.0	13.1
Max	0.0	0.0	15.9	2.4	2.3	4.4	7.5	22.4	2.8	0.6	0.4	25.5
Khairaha VII seam												
1	0.3	0.0	23.0	0.4	4.2	5.0	9.5	11.8	0.0	0.0	0.0	11.8
2	1.6	0.0	15.6	0.3	1.9	1.3	3.5	29.9	1.2	0.3	0.0	31.4
3	0.5	0.0	15.9	0.3	2.1	2.1	4.5	40.3	0.0	0.0	0.0	40.3
4	0.0	0.0	23.8	0.4	4.2	6.3	10.9	16.6	0.8	0.2	1.3	18.9
5	0.0	0.0	12.0	0.4	1.5	3.0	4.9	13.9	3.1	1.5	1.0	19.5
Avg	0.5	0.0	18.1	0.4	2.8	3.5	6.7	22.5	1.0	0.4	0.5	24.4
Min	0.0	0.0	12.0	0.3	1.5	1.3	3.5	11.8	0.0	0.0	0.0	11.8
Max	1.6	0.0	23.8	0.4	4.2	6.3	10.9	40.3	3.1	1.5	1.3	40.3
Damini VI seam 1st site												
1	0.9	0.0	20.2	0.4	2.8	2.8	6.0	20.9	3.0	0.6	0.0	24.5
2	0.0	0.0	2.1	0.0	0.0	0.0	0.0	75.2	0.0	1.1	0.0	76.2
3	0.5	0.0	26.8	0.0	0.5	0.0	0.5	50.7	0.0	1.9	0.0	52.6
Avg	0.4	0.0	16.4	0.1	1.1	0.9	2.2	48.9	1.0	1.2	0.0	51.1
Min	0.0	0.0	2.1	0.0	0.0	0.0	0.0	20.9	0.0	0.6	0.0	24.5
Max	0.9	0.0	26.8	0.4	2.8	2.8	6.0	75.2	3.0	1.9	0.0	76.2
Damini VI seam 2nd site												
1	0.0	0.0	9.2	3.0	2.2	0.8	5.9	28.6	5.0	1.2	0.3	35.0
2	0.3	0.0	13.8	0.3	0.8	1.1	2.3	61.5	0.0	0.8	1.1	63.5
3	0.8	0.0	13.9	1.6	3.1	0.8	5.4	55.9	0.5	1.3	0.0	57.7
Avg	0.4	0.0	12.3	1.6	2.0	0.9	4.5	48.7	1.8	1.1	0.5	52.1
Min	0.0	0.0	9.2	0.3	0.8	0.8	2.3	28.6	0.0	0.8	0.0	35.0

Mine/Seam with band no.	DL	De	TB	VL	CD	DC	TT	Cg	Ca	Cp	Cm	TC
Max	0.8	0.0	13.9	3.0	3.1	1.1	5.9	61.5	5.0	1.3	1.1	63.5
Damini V												
1	0.0	0.0	3.5	0.0	0.0	0.0	0.0	60.0	5.7	0.5	0.0	66.2
2	0.0	0.0	6.4	4.4	6.5	10.0	21.0	30.4	0.0	1.4	0.0	31.7
3	0.0	0.0	8.7	0.3	2.1	3.3	5.7	14.7	3.3	0.2	0.5	18.6
4	0.2	0.0	7.1	0.9	2.5	0.2	3.6	32.5	4.3	0.7	1.8	39.3
Avg	0.1	0.0	6.4	1.4	2.8	3.4	7.6	34.4	3.3	0.7	0.6	39.0
Min	0.0	0.0	3.5	0.0	0.0	0.0	0.0	14.7	0.0	0.2	0.0	18.6
Max	0.2	0.0	8.7	4.4	6.5	10.0	21.0	60.0	5.7	1.4	1.8	66.2
Bangwar												
1	0.3	0.0	10.8	4.3	11.5	8.5	24.3	9.3	1.3	0.5	0.0	11.0
2	0.4	0.0	16.9	1.7	0.6	3.2	5.4	17.5	4.3	0.7	0.9	23.4
3	0.0	0.0	10.5	1.2	1.5	2.3	5.0	13.8	2.5	0.0	0.4	16.6
4	0.6	0.0	17.2	0.7	2.5	5.5	8.7	14.4	1.3	0.0	0.0	15.6
Avg	0.3	0.0	13.8	2.0	4.0	4.9	10.8	13.7	2.3	0.3	0.3	16.7
Min	0.0	0.0	10.5	0.7	0.6	2.3	5.0	9.3	1.3	0.0	0.0	11.0
Max	0.6	0.0	17.2	4.3	11.5	8.5	24.3	17.5	4.3	0.7	0.9	23.4
Amalai												
1	0.0	0.4	12.4	0.7	8.3	14.6	23.5	18.5	0.0	0.0	0.0	18.5
2	0.0	0.0	3.5	0.2	0.2	0.4	0.7	32.1	6.9	6.9	3.1	49.0
3	0.0	0.0	10.6	2.5	1.5	3.0	6.9	18.1	4.9	2.0	0.8	25.9
4	0.0	0.0	8.7	0.0	0.0	0.4	0.4	27.8	6.8	1.4	0.9	36.8
5	1.5	0.0	12.0	0.9	1.3	1.7	3.9	33.6	2.8	0.2	0.0	36.6
6	0.9	0.0	9.3	0.6	2.0	1.4	3.9	35.5	0.0	2.5	0.0	38.0
7	0.8	0.0	21.0	0.2	1.2	0.6	2.0	21.2	8.7	1.2	0.0	31.1
8	0.5	0.0	27.4	0.5	3.2	5.1	8.7	9.9	5.8	0.7	0.5	17.0

Mine/Seam with band no.	DL	De	TB	VL	CD	DC	TT	Cg	Ca	Cp	Cm	TC
Avg	0.5	0.1	13.1	0.7	2.2	3.4	6.3	24.6	4.5	1.9	0.7	31.6
Min	0.0	0.0	3.5	0.0	0.0	0.4	0.4	9.9	0.0	0.0	0.0	17.0
Max	1.5	0.4	27.4	2.5	8.3	14.6	23.5	35.5	8.7	6.9	3.1	49.0

Table 4.14 Occurrence and distribution of microlithotype (vol.%) on carbominerite free basis for Sohagpur coals.

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	Cl	VV	VI	Ve	DI	DL	De	TB	VL	CD	DC	TT
Sharda																		
1	45.1	0.3	33.4	78.8	1.1	0.8	0.0	4.9	2.2	0.0	0.5	0.0	0.0	9.5	1.1	3.3	7.3	11.7
2	23.0	0.9	53.0	77.0	1.3	0.0	0.0	6.1	10.0	0.0	0.9	0.0	0.0	18.3	0.4	3.0	1.3	4.8
3	43.3	0.0	25.6	68.9	3.8	0.0	0.0	12.7	2.5	0.0	1.0	0.0	0.0	20.0	2.5	3.3	5.3	11.1
4	38.7	0.0	28.2	66.9	5.2	0.7	0.0	4.7	5.2	0.0	3.4	0.0	0.0	19.1	5.4	2.9	5.6	14.0
5	50.3	0.0	29.0	79.3	2.1	0.0	0.0	4.6	3.8	0.0	1.1	0.2	0.0	11.8	3.0	2.4	3.5	8.9
6	40.5	0.6	27.6	68.6	7.3	0.4	0.0	7.9	4.0	0.0	0.6	0.0	0.0	20.1	3.3	2.8	5.2	11.3
7	43.3	1.5	5.1	49.9	18.7	3.0	0.0	13.6	7.0	0.0	0.0	0.0	0.0	42.3	1.1	2.5	4.2	7.8
8	24.1	0.3	40.1	64.5	5.2	0.9	0.0	7.9	5.5	0.0	4.7	0.6	0.0	24.7	0.6	3.8	6.4	10.8
Avg	38.6	0.4	30.3	69.2	5.6	0.7	0.0	7.8	5.0	0.0	1.5	0.1	0.0	20.7	2.2	3.0	4.9	10.0
Min	23.0	0.0	5.1	49.9	1.1	0.0	0.0	4.6	2.2	0.0	0.0	0.0	0.0	9.5	0.4	2.4	1.3	4.8
Max	50.3	1.5	53.0	79.3	18.7	3.0	0.0	13.6	10.0	0.0	4.7	0.6	0.0	42.3	5.4	3.8	7.3	14.0
Dhanpuri																		
1	5.6	0.9	61.9	68.4	1.8	0.5	0.0	4.5	2.9	0.0	13.4	3.3	0.0	26.3	0.2	2.2	2.9	5.4
2	48.7	0.0	32.8	81.5	0.5	0.0	0.0	11.3	5.3	0.0	0.0	0.0	0.0	17.1	0.2	0.7	0.7	1.5
3	44.2	0.0	41.5	85.7	1.0	0.0	0.0	8.3	4.1	0.0	0.2	0.0	0.0	13.6	0.0	0.2	0.5	0.7
4	54.8	1.1	22.9	78.7	2.7	0.0	0.0	11.2	5.3	0.0	0.5	0.0	0.0	19.7	0.5	0.0	1.1	1.6
5	14.2	1.0	19.3	34.5	3.1	1.0	0.0	11.2	6.1	0.0	10.2	1.5	0.0	33.0	4.1	13.7	14.7	32.5

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	CI	VV	VI	Ve	DI	DL	De	TB	VL	CD	DC	TT
Avg	33.5	0.6	35.7	69.8	1.8	0.3	0.0	9.3	4.8	0.0	4.9	1.0	0.0	21.9	1.0	3.4	4.0	8.3
Min	5.6	0.0	19.3	34.5	0.5	0.0	0.0	4.5	2.9	0.0	0.0	0.0	0.0	13.6	0.0	0.0	0.5	0.7
Max	54.8	1.1	61.9	85.7	3.1	1.0	0.0	11.3	6.1	0.0	13.4	3.3	0.0	33.0	4.1	13.7	14.7	32.5
Rajendra																		
1	21.1	0.9	41.0	63.0	3.2	2.3	0.0	3.2	1.7	0.3	13.3	2.3	0.0	26.3	2.9	2.3	5.5	10.7
2	7.9	0.7	16.9	25.5	10.4	2.5	2.9	8.6	2.9	0.4	15.4	4.3	0.0	47.3	6.5	3.2	17.6	27.2
3	60.7	0.6	7.4	68.7	25.2	0.4	0.0	0.8	0.2	0.0	0.2	0.0	0.0	26.8	0.4	0.8	3.3	4.5
4	23.7	0.7	27.7	52.1	4.0	0.5	0.0	6.1	5.4	0.0	11.9	2.6	0.0	30.2	0.5	7.7	9.5	17.7
5	39.4	0.0	40.8	80.2	3.0	0.3	0.0	8.9	5.9	0.0	0.5	0.0	0.0	18.5	0.0	0.5	0.8	1.3
Avg	30.6	0.6	26.7	57.9	9.1	1.2	0.6	5.5	3.2	0.1	8.3	1.8	0.0	29.8	2.0	2.9	7.3	12.3
Min	7.9	0.0	7.4	25.5	3.0	0.3	0.0	0.8	0.2	0.0	0.2	0.0	0.0	18.5	0.0	0.5	0.8	1.3
Max	60.7	0.9	41.0	80.2	25.2	2.5	2.9	8.9	5.9	0.4	15.4	4.3	0.0	47.3	6.5	7.7	17.6	27.2
Khairaha VI seam																		
1	65.9	1.0	18.1	85.0	7.7	0.3	0.0	0.3	2.3	0.0	0.3	0.0	0.0	11.0	0.3	1.0	2.7	4.0
2	60.2	0.5	19.5	80.2	3.7	0.3	0.0	0.0	6.2	1.9	0.5	0.0	0.0	12.6	2.2	1.2	3.9	7.2
3	69.1	0.2	6.4	75.7	15.6	0.8	0.0	0.6	2.1	0.0	0.0	0.0	0.0	19.1	0.0	0.6	4.6	5.2
4	26.0	0.0	54.1	80.0	5.2	0.7	0.0	3.8	1.2	0.0	1.2	0.0	0.0	12.1	2.9	1.7	3.3	7.9
5	20.4	0.6	54.3	75.3	7.9	0.9	0.0	4.3	2.1	0.0	0.6	0.0	0.0	15.9	0.9	2.7	5.2	8.8
Avg	48.3	0.5	30.5	79.2	8.0	0.6	0.0	1.8	2.8	0.4	0.5	0.0	0.0	14.1	1.3	1.4	3.9	6.6
Min	20.4	0.0	6.4	75.3	3.7	0.3	0.0	0.0	1.2	0.0	0.0	0.0	0.0	11.0	0.0	0.6	2.7	4.0
Max	69.1	1.0	54.3	85.0	15.6	0.9	0.0	4.3	6.2	1.9	1.2	0.0	0.0	19.1	2.9	2.7	5.2	8.8
Khairaha VII seam																		
1	33.8	0.0	29.4	63.2	1.8	0.0	0.0	6.7	6.7	0.0	10.5	0.3	0.0	26.0	0.5	4.7	5.6	10.8
2	15.9	1.7	54.4	72.0	2.6	0.2	0.0	3.9	0.9	0.0	12.9	2.4	0.0	22.8	0.4	2.8	1.9	5.2
3	25.8	0.5	39.5	65.9	1.9	0.0	0.0	6.7	4.6	0.0	12.6	0.8	0.0	26.6	0.5	3.5	3.5	7.5
4	27.5	0.9	28.9	57.3	11.0	7.3	0.0	4.9	2.8	0.0	3.3	0.0	0.0	29.3	0.5	5.2	7.8	13.4
5	43.6	0.6	35.0	79.1	2.4	0.0	0.0	6.8	4.8	0.0	0.9	0.0	0.0	14.8	0.6	1.8	3.7	6.0

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	CI	VV	VI	Ve	DI	DL	De	TB	VL	CD	DC	TT
Avg	29.3	0.8	37.4	67.5	3.9	1.5	0.0	5.8	3.9	0.0	8.1	0.7	0.0	23.9	0.5	3.6	4.5	8.6
Min	15.9	0.0	28.9	57.3	1.8	0.0	0.0	3.9	0.9	0.0	0.9	0.0	0.0	14.8	0.4	1.8	1.9	5.2
Max	43.6	1.7	54.4	79.1	11.0	7.3	0.0	6.8	6.7	0.0	12.9	2.4	0.0	29.3	0.6	5.2	7.8	13.4
Damini VI seam 1st site																		
1	12.7	0.9	51.8	65.4	0.9	0.0	0.0	6.8	3.9	0.0	14.1	1.1	0.0	26.8	0.6	3.7	3.7	7.9
2	26.9	3.0	61.2	91.0	6.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0	0.0	0.0	0.0
3	3.0	1.0	38.4	42.4	6.1	0.5	0.5	17.7	11.1	0.5	19.2	1.0	0.0	56.6	0.0	1.0	0.0	1.0
Avg	14.2	1.6	50.5	66.3	4.3	1.2	0.2	8.2	5.0	0.2	11.1	0.7	0.0	30.8	0.2	1.6	1.2	3.0
Min	3.0	0.9	38.4	42.4	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0	0.0	0.0	0.0
Max	26.9	3.0	61.2	91.0	6.1	3.0	0.5	17.7	11.1	0.5	19.2	1.1	0.0	56.6	0.6	3.7	3.7	7.9
Damini VI seam 2nd site																		
1	9.4	3.8	63.5	76.7	0.8	0.0	0.0	7.6	3.1	0.0	2.8	0.0	0.0	14.2	4.6	3.3	1.3	9.1
2	13.9	1.5	40.8	56.2	8.5	3.9	0.0	12.3	8.5	0.0	3.9	0.8	0.0	37.7	0.8	2.3	3.1	6.2
3	10.4	0.0	43.9	54.3	3.7	1.2	0.0	2.4	11.0	0.0	12.8	1.8	0.0	32.9	3.7	7.3	1.8	12.8
Avg	11.2	1.8	49.4	62.4	4.3	1.7	0.0	7.5	7.5	0.0	6.5	0.9	0.0	28.3	3.0	4.3	2.1	9.4
Min	9.4	0.0	40.8	54.3	0.8	0.0	0.0	2.4	3.1	0.0	2.8	0.0	0.0	14.2	0.8	2.3	1.3	6.2
Max	13.9	3.8	63.5	76.7	8.5	3.9	0.0	12.3	11.0	0.0	12.8	1.8	0.0	37.7	4.6	7.3	3.1	12.8
Damini V																		
1	20.8	4.8	64.0	89.6	1.6	0.0	0.0	4.8	1.6	0.0	2.4	0.0	0.0	10.4	0.0	0.0	0.0	0.0
2	21.1	0.0	38.9	60.0	2.5	0.0	0.0	2.3	4.5	0.0	0.0	0.0	0.0	9.3	6.5	9.6	14.7	30.7
3	53.7	0.2	28.4	82.3	1.9	0.0	0.0	5.9	2.8	0.0	0.2	0.0	0.0	10.7	0.4	2.6	4.1	7.0
4	32.2	0.0	50.2	82.4	1.1	0.0	0.0	4.1	1.5	0.0	4.5	0.4	0.0	11.6	1.5	4.1	0.4	6.0
Avg	32.0	1.3	45.4	78.6	1.8	0.0	0.0	4.3	2.6	0.0	1.8	0.1	0.0	10.5	2.1	4.1	4.8	10.9
Min	20.8	0.0	28.4	60.0	1.1	0.0	0.0	2.3	1.5	0.0	0.0	0.0	0.0	9.3	0.0	0.0	0.0	0.0
Max	53.7	4.8	64.0	89.6	2.5	0.0	0.0	5.9	4.5	0.0	4.5	0.4	0.0	11.6	6.5	9.6	14.7	30.7
Bangwar																		

Mine/Seam with band no.	Vi	Li	In	TM	CV	CL	Cl	VV	VI	Ve	DI	DL	De	TB	VL	CD	DC	TT
1	18.8	0.8	41.0	60.7	6.5	0.8	0.0	0.8	0.3	0.0	3.4	0.3	0.0	12.1	4.8	12.9	9.6	27.3
2	23.8	0.5	46.6	70.9	9.2	1.7	0.0	6.8	1.9	0.0	1.9	0.5	0.0	22.1	2.2	0.7	4.1	7.0
3	68.1	0.0	13.3	81.4	6.0	0.0	0.0	5.3	1.2	0.0	0.2	0.0	0.0	12.6	1.4	1.8	2.8	6.0
4	24.1	0.3	45.0	69.3	1.4	0.3	0.1	6.0	4.1	0.0	7.8	0.8	0.0	20.4	0.9	3.0	6.5	10.3
Avg	33.7	0.4	36.5	70.6	5.8	0.7	0.0	4.7	1.9	0.0	3.3	0.4	0.0	16.8	2.3	4.6	5.7	12.6
Min	18.8	0.0	13.3	60.7	1.4	0.0	0.0	0.8	0.3	0.0	0.2	0.0	0.0	12.1	0.9	0.7	2.8	6.0
Max	68.1	0.8	46.6	81.4	9.2	1.7	0.1	6.8	4.1	0.0	7.8	0.8	0.0	22.1	4.8	12.9	9.6	27.3
Amalai																		
1	40.9	0.0	15.0	55.9	2.7	0.3	0.0	5.4	4.8	0.5	1.1	0.0	0.5	15.2	0.8	10.2	17.9	28.9
2	3.5	0.6	87.6	91.6	0.3	0.3	0.0	1.7	0.6	0.0	4.0	0.0	0.0	6.9	0.3	0.3	0.9	1.4
3	27.2	0.7	48.4	76.3	1.5	0.0	0.0	7.3	4.0	0.0	1.5	0.0	0.0	14.3	3.3	2.0	4.0	9.4
4	6.2	1.1	78.3	85.6	3.9	0.0	0.0	5.6	0.6	0.0	3.7	0.0	0.0	13.8	0.0	0.0	0.6	0.6
5	9.5	1.0	64.5	75.0	2.4	0.7	0.0	2.7	3.4	0.0	7.4	2.4	0.0	18.9	1.4	2.0	2.7	6.1
6	4.6	0.0	74.1	78.6	4.1	0.9	0.0	1.4	1.8	0.0	5.5	1.4	0.0	15.0	0.9	3.2	2.3	6.4
7	6.4	0.9	59.4	66.7	1.8	0.0	0.0	7.9	3.2	0.0	16.4	1.2	0.0	30.4	0.3	1.8	0.9	2.9
8	38.8	1.2	16.6	56.6	20.4	1.2	0.0	5.3	2.3	0.0	3.2	0.6	0.0	32.9	0.6	3.8	6.1	10.5
Avg	17.1	0.7	55.5	73.3	4.6	0.4	0.0	4.7	2.6	0.1	5.3	0.7	0.1	18.4	0.9	2.9	4.4	8.3
Min	3.5	0.0	15.0	55.9	0.3	0.0	0.0	1.4	0.6	0.0	1.1	0.0	0.0	6.9	0.0	0.0	0.6	0.6
Max	40.9	1.2	87.6	91.6	20.4	1.2	0.0	7.9	4.8	0.5	16.4	2.4	0.5	32.9	3.3	10.2	17.9	28.9

Where Vi- Vitrite, Li- Liptite, In- Inertite, TM- Total Monomaceral, CV- Clarite V, CL- Clarite L, Cl- Clarite, VV- Vitrinertite V, VI- Vitrinertite I, Ve- Vitrinertite, DI- Durite I, DL- Durite L, De- Durite, TB- Total Bimaceral, VL- Vitrnerto Liptite, CD- Claro Durite, DC- Duroclarite, TT- Total Trimaceral, Cg- Carbargilite, Ca- Carbankerite, Cp- Carbopyrite, Cm- Carbopolymnerite, TC- Total Carbominerite.

4.7 Geochemical study of coals from Sohagpur coalfield

Coal's geochemical characterization is challenging due to the variability introduced by different peat-forming plant assemblages and coalification pathways. Nevertheless, understanding the geochemical characteristics of coal is essential for evaluating this important energy resource (Gupta, 2007; Dai et al., 2020). Coal exhibits variable elemental concentrations due to the physical, chemical, and microbiological transformations that occur during the coalification process. Chemical analyses provide critical information about the genetic composition and quality of coal, including its rank and grade.

Geochemical characterization is fundamental to understanding the compositional, mineralogical, and molecular attributes of geological materials and their associated formation and alteration processes (Kishor et al., 2025c). A comprehensive evaluation requires for integration of multiple analytical techniques capable of examining both organic and inorganic components. In this study, proximate analysis, ultimate analysis, X-ray diffraction (XRD), X-ray fluorescence (XRF), and Fourier transform infrared spectroscopy (FT-IR) were employed to provide a detailed and systematic assessment of the samples' geochemical properties.

Proximate analysis was used to determine moisture content, volatile matter, ash yield, and fixed carbon, providing essential information on the physicochemical behaviour and classification of the coals. Ultimate analysis provided elemental composition data, including carbon, hydrogen, nitrogen, sulfur, and oxygen, which are critical for understanding characteristics of organic matter and geochemical maturity. Mineralogical composition and crystalline phase identification were determined by XRD analysis, while XRF quantified major, minor, and trace elemental concentrations, enabling interpretation

of elemental distribution and geochemical variations. FT-IR spectroscopy complemented these techniques by identifying functional groups and molecular structures, thereby enhancing the understanding of chemical bonding and mineral–organic associations.

The primary objective of this study is to integrate physicochemical, elemental, mineralogical, and spectroscopic data to achieve a comprehensive geochemical interpretation of the samples. The scope of the research is confined to laboratory-based analyses using standardized techniques, focusing on bulk composition and structural characteristics within the analytical limits of the methods employed. The significance of this study lies in its contribution to geochemical research by providing a holistic analytical framework that enhances understanding of material composition, geochemical processes, and potential applications, and by deciphering the coal-forming depositional environments as well as the unconventional resources present in coal (Kishor et al., 2023a; 2025c).

In this study, for the geochemical analysis, various analytical techniques including proximate analysis, ultimate analysis, XRD, XRF, and FT-IR, were used.

4.7.1 Proximate analysis

Proximate analysis of coal is a standard laboratory procedure used to evaluate the fundamental physical and chemical characteristics of coal that influence its behaviour during handling and combustion. It provides a rapid assessment of coal quality by determining four main constituents: moisture, volatile matter, ash, and fixed carbon.

Moisture content represents the amount of water present in coal, both inherent and surface moisture. High moisture reduces the effective heating value of coal and increases transportation and handling costs. Volatile matter refers to the gaseous products released when coal is heated in the absence of air. It plays a significant role in ignition, flame

stability, and combustion efficiency. Coals with higher volatile matter are generally a low rank coals.

Ash content is the incombustible mineral residue left after complete combustion of coal. It affects boiler efficiency, slagging, fouling, and disposal requirements. High ash content lowers the calorific value of coal and can cause operational problems in furnaces and boilers. Fixed carbon is the solid combustible material that remains after moisture and volatile matter are removed. It represents the portion of coal that burns in the solid state and contributes significantly to sustained heat release.

The proximate analysis is widely used in the quality assessment of coal for industrial applications. The 4 key components of proximate analysis are moisture (M), volatile matter (V.M.), ash yield (A) and fixed carbon (F.C.). This analysis was performed following the Indian Standard (IS 1350; 1984)

Moisture- The water content of coal can exist in several ways, including as films on the coal particles surface, within capillaries, combined with organic molecules, and as a component of the minerals crystal structure. Coal's moisture content is the amount of water it contains. In the coals of the Sohagpur coalfield, the moisture content ranges from 3.04 % to 15.1 %, with an average value of 8.92 %.

Volatile matter- Volatile matter is the term used to describe the organic coal components that are released at high temperatures under vacuum conditions, ignoring moisture content. These coal's volatile matter has an average of 24.00% and ranges from 15.45% to 30.00%. Volatile matter on a dry ash-free basis is also used to predict coal rank.

Ash yield- The ash of coal is a non-combustible inorganic residue that remains in the crucible when coal is burned. It represents the bulk of the mineral matter present in coal in various forms. The ash of coal is also an important factor in the utilization of coal

across different sectors. Ash yield for these coals ranges from 7.13% to 52.84% with an average value of 19.54%. The high ash yield value in a few coals suggests that these coals have a high amount of mineral matter, while the average value 19.54% falls within the range of Gondwana coals.

Fixed Carbon- Fixed carbon is the fraction of coal after the complete removal of moisture, volatile matter and ash during proximate analysis, and it represents the carbon available for sustained combustion and heat generation. It is a key indicator of coal quality, as higher fixed carbon content leads to higher calorific value, more stable combustion, and better fuel efficiency, making such coal suitable for industrial boilers, thermal power plants, and furnaces. It is especially important in metallurgical applications, where high fixed carbon coal is used for coke production in blast furnaces, serving as both a fuel and a reducing agent, and it also plays a vital role in coal gasification and carbonization processes for producing industrial gases. The F.C. of these coals ranges from the 26.00% to 60.78% with an average value of 47.55%.

4.4.1.1 Variation and qualitative distribution of Proximate constituents in Sohagpur coals

The qualitative distribution of proximate analysis parameters of Sohagpur coals, along with their vertical seam profiles, is illustrated in Figure 4.11. Variations in moisture content, ash yield, volatile matter, and fixed carbon across the seam profiles reflect changes in coal lithotype, maceral composition, and mineral matter influx during peat accumulation and subsequent coalification.

In the Sharda coal mine, the coal seam shows a relatively high moisture content in the banded bright coal, which constitutes the third band from the bottom of the seam. Ash yield is comparatively high in the middle and lower bands, indicating increased mineral matter influx during these depositional phases. The distribution of volatile matter shows

an inverse relationship with ash yield, with higher volatile matter concentrations occurring in bands with lower mineral matter content. Fixed carbon content is higher in the upper part of the seam, followed by a sudden decrease, and then increases again within the banded bright coal near the bottom of the seam, as shown in Figure 4.11(a).

Seam of Dhanpuri coal mine exhibits a gradual increase in moisture content toward the bottom of the seam. The lower portion of the seam shows a higher ash yield, suggesting enhanced detrital and clastic influx during the later stages of peat deposition. Correspondingly, both volatile matter and fixed carbon contents decrease in the lower bands, reflecting dilution of organic matter by mineral constituents (Figure 4.11(b)).

At the Rajendra coal mine, the seam profile shows an overall increase in moisture content toward the bottom. The banded coal layer exhibits relatively higher ash yield, indicating localized enrichment in mineral matter. Volatile matter content is higher in banded bright coal, reflecting better preservation of reactive organic components. Fixed carbon content is comparatively high in both the uppermost and lowermost bands of the seam, suggesting variability in coalification and organic matter concentration across the seam profile (Figure 4.11(c)).

The Khairaha Seam VI profile shows lower moisture content in the bottom bands, accompanied by higher ash yield. Volatile matter and fixed carbon contents are lowest in the bottom band of the seam, indicating significant mineral matter dilution and comparatively poorer organic matter concentration in this interval (Figure 4.11(d)).

In Khairaha Seam VII, the upper and lower bands display higher moisture content, whereas the middle band shows comparatively lower moisture. Ash yield is highest in the middle band, corresponding to increased mineral matter input. Both volatile matter and

fixed carbon contents are lower in the middle band, consistent with its higher ash yield and dull coal character (Figure 4.11(e)).

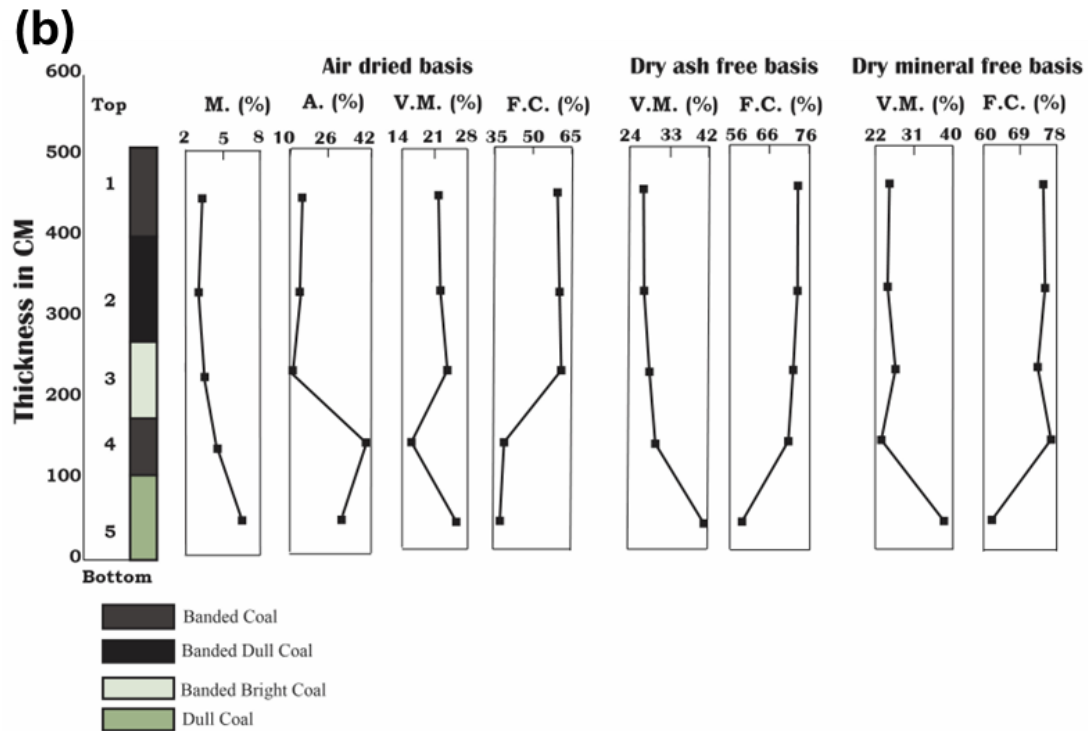
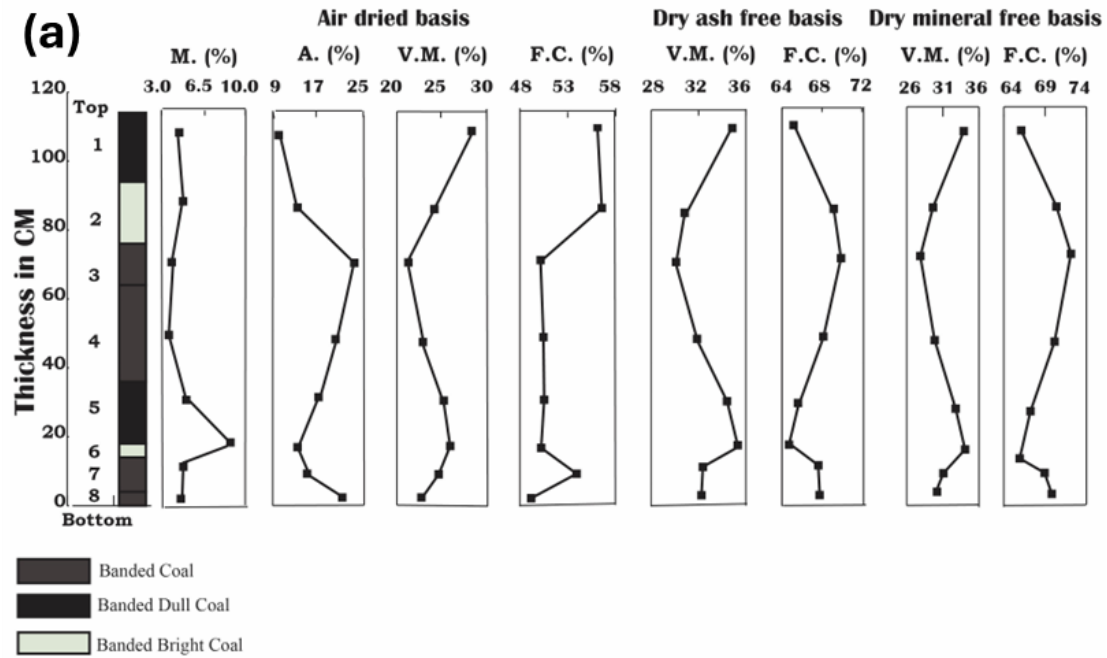
The Damini Seam VI shows site-specific variations. At the first site, a slight decrease in moisture content is observed in the middle band, accompanied by an increase in ash yield. Volatile matter and fixed carbon contents are correspondingly lower in this band. At the second site, moisture content decreases progressively toward the bottom of the seam, while ash yield increases. Volatile matter and fixed carbon contents decrease with depth, reflecting increased mineral matter concentration in the lower seam sections (Figure 4.11(f)).

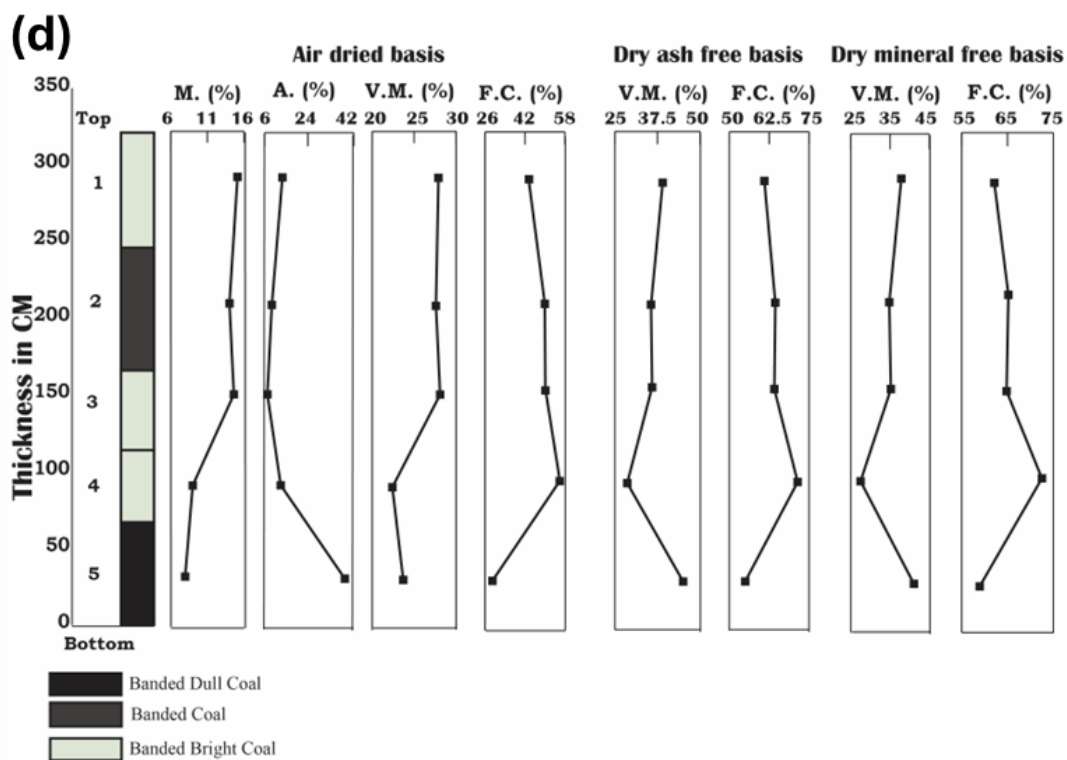
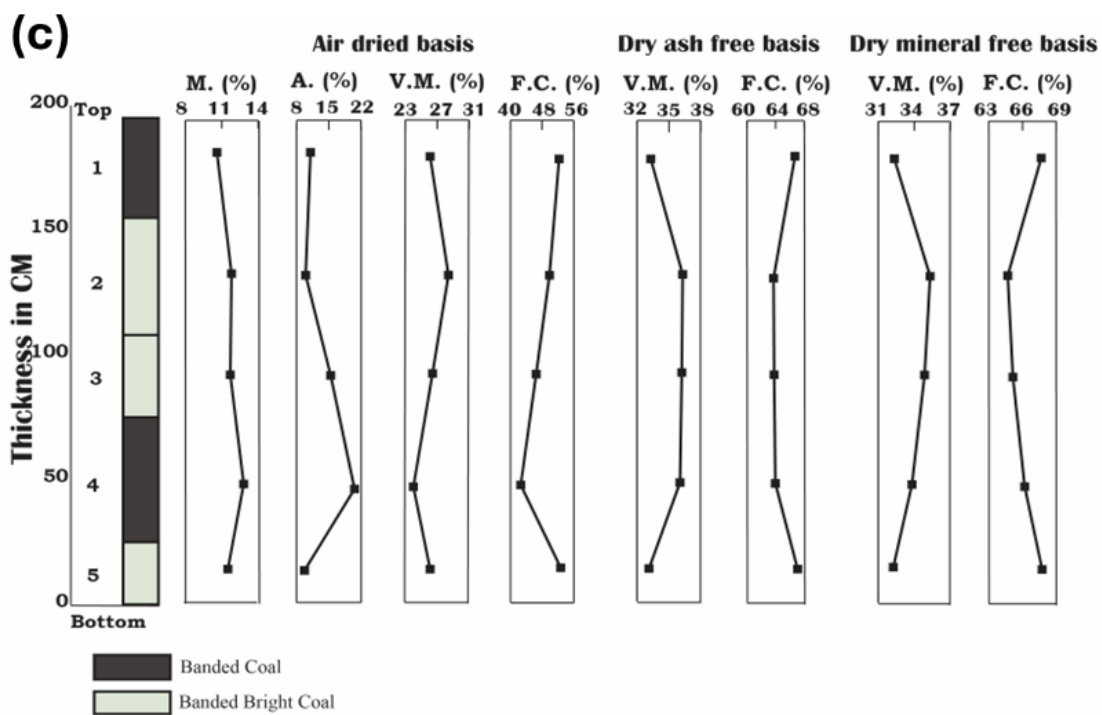
In the Damini Seam V, an increase in moisture content is observed in the middle band, while ash yield decreases in the same interval. Volatile matter and fixed carbon contents exhibit trends similar to moisture content throughout the seam profile, indicating a close relationship between organic matter preservation and moisture retention in this seam (Figure 4.11(g)).

The Bangwar coal mine seam shows relatively low moisture content in the upper band, followed by a sudden increase and subsequent decrease toward the bottom of the seam. Ash yield is higher in the upper band, suggesting an early-stage influx of mineral matter. Volatile matter and fixed carbon contents display a zigzag pattern of decrease and increase throughout the seam profile, reflecting fluctuating depositional conditions and variable organic matter preservation (Figure 4.11(h)).

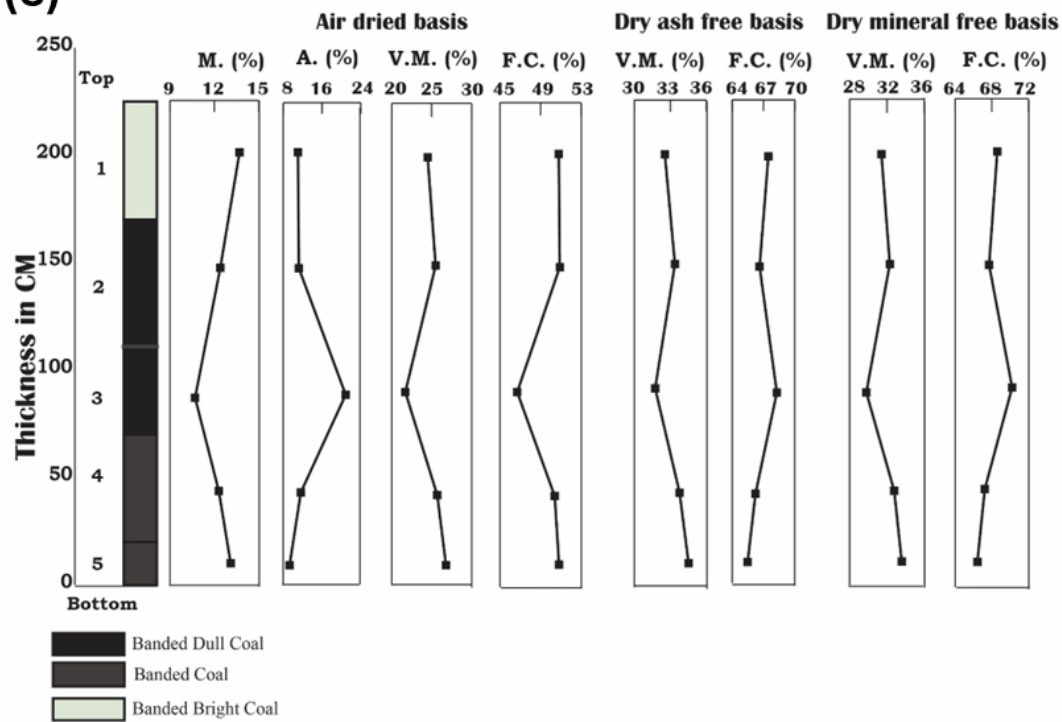
The Amalai coal mine seam exhibits lower moisture content in the middle band, with higher moisture content in the upper and lower bands. The middle band, characterized by dull coal, shows the highest ash yield, indicating a pronounced influx of mineral matter. This same band also displays lower volatile matter and fixed carbon contents, reflecting

dilution of organic matter by inorganic constituents and a sudden increase in ash yield due to enhanced detrital input, as shown in Figure 4.11(i).

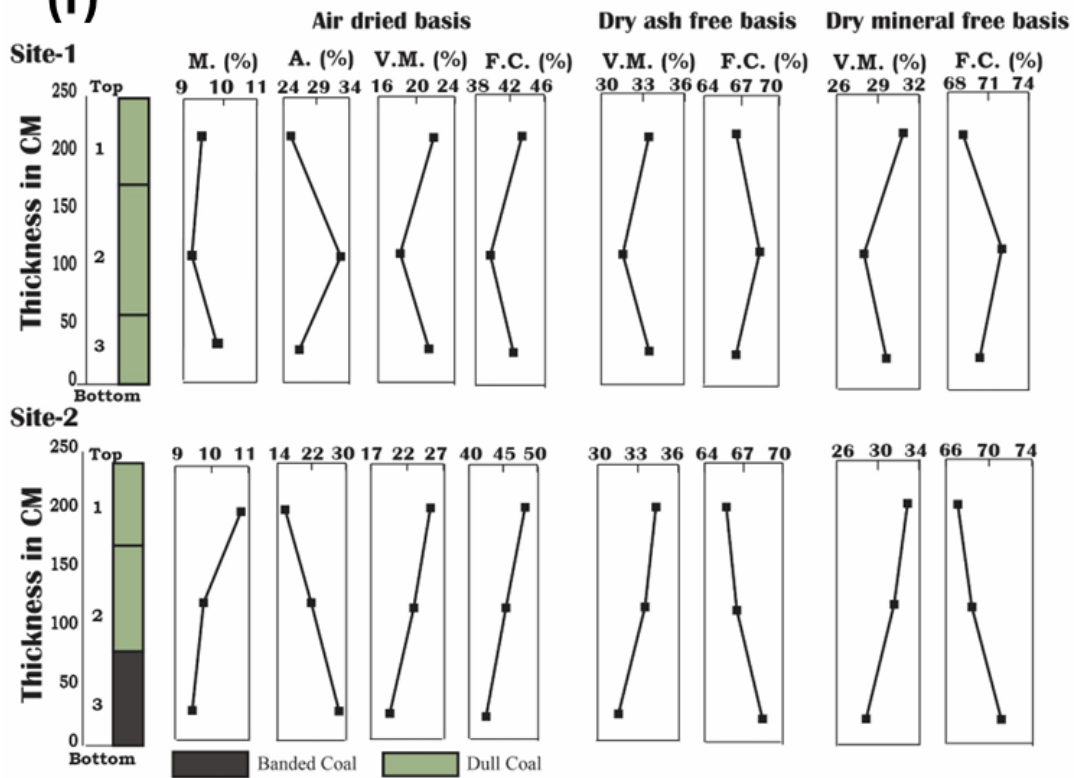


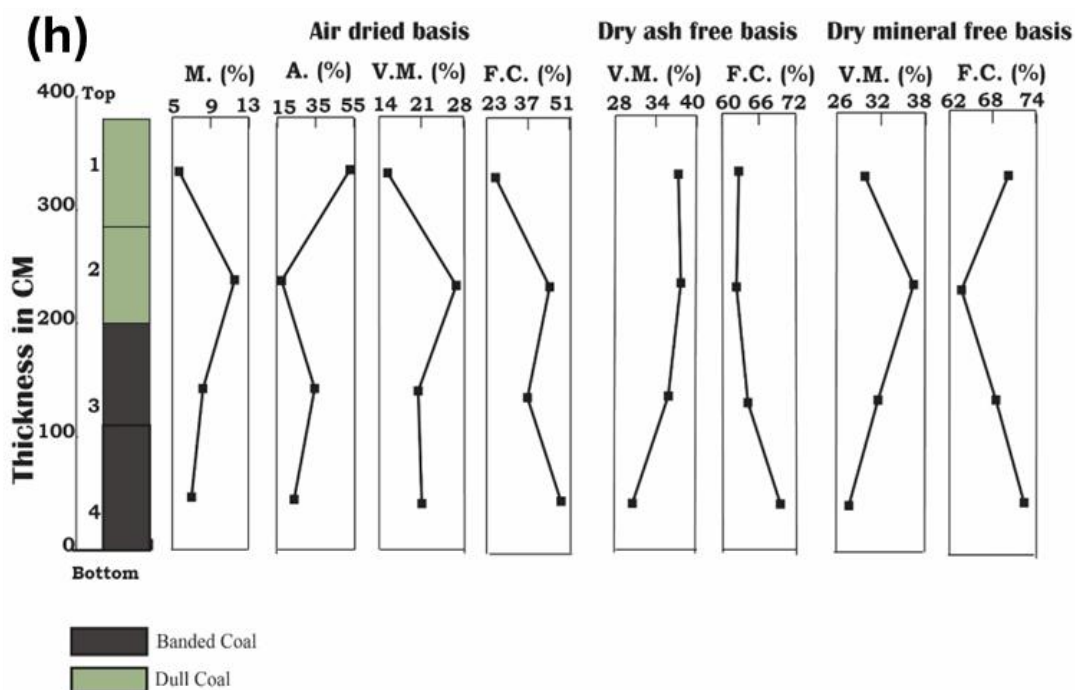
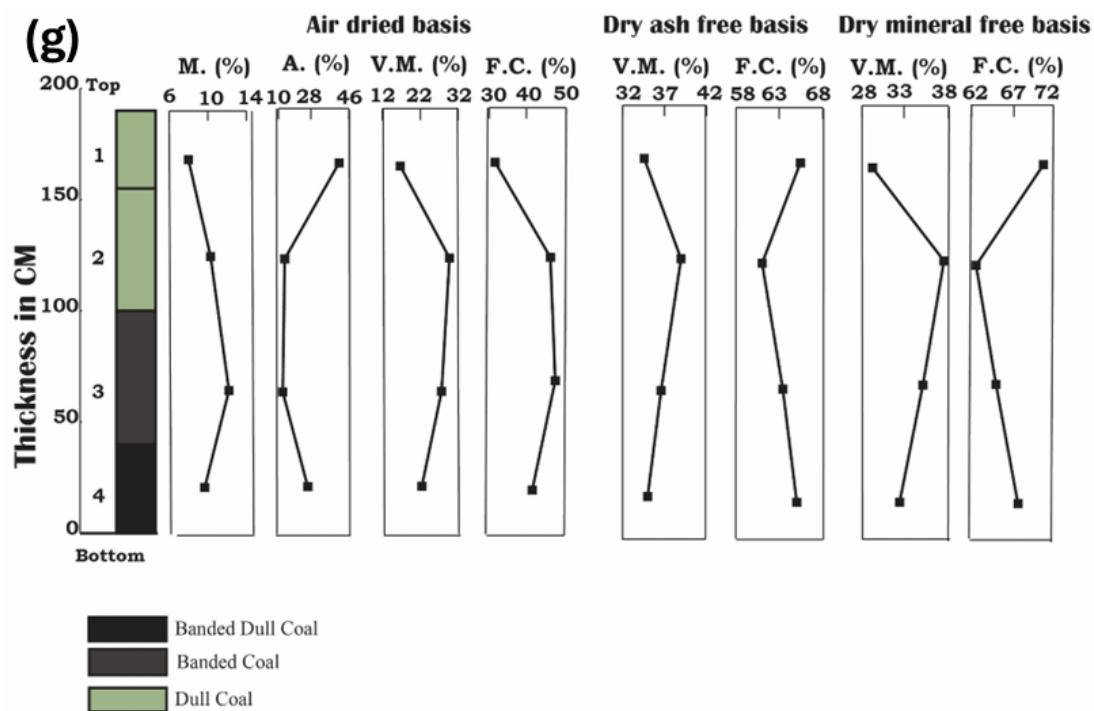


(e)



(f)





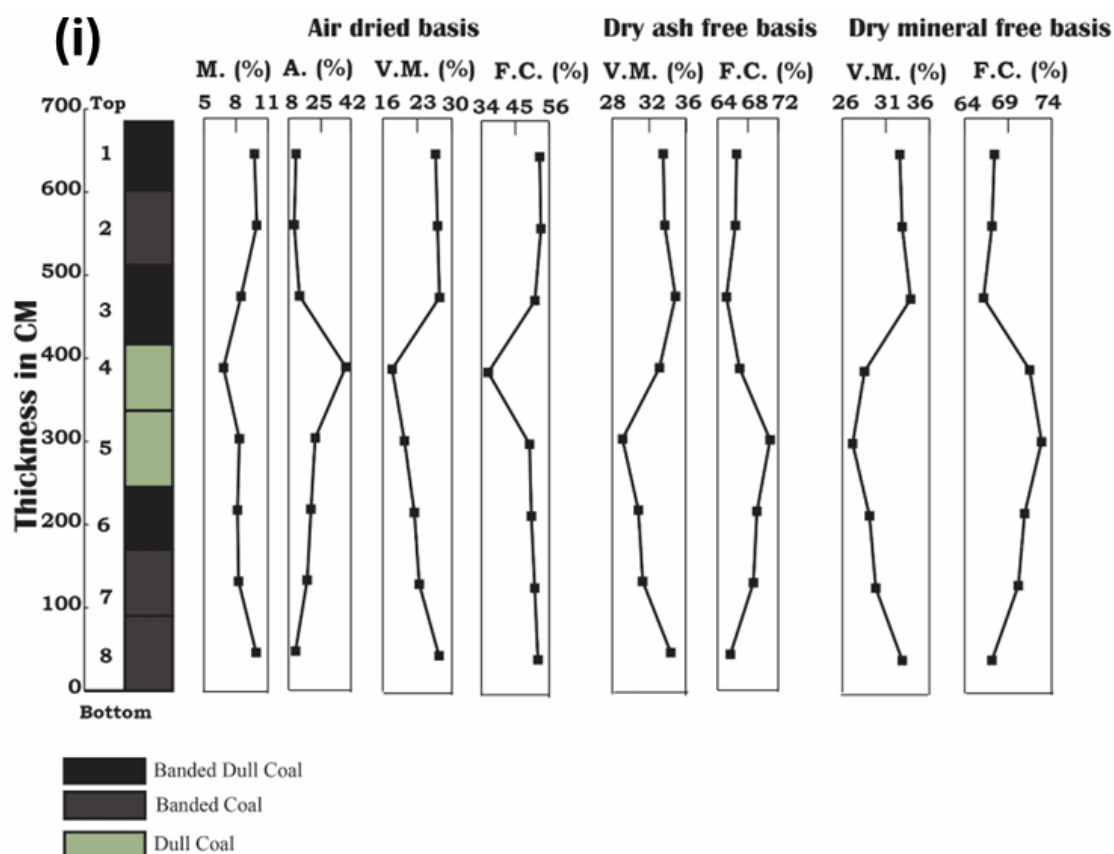


Figure 4.11 Vertical profile of coal seams with variation in proximate constituents (a) Sharda, (b) Dhanpuri, (c) Rajendra, (d) Khairaha Seam VI, (e) Khairaha Seam VII, (f) Damini Seam VI, (g) Damini Seam V, (h) Bangwar, and (i) Amalai coal mine.

4.7.1.2 Quantitative distribution of Proximate constituents in Sohagpur coals

In this present study, the pillar sampling technique was followed across all coal mines/seams. The coal samples were subjected to proximate analysis to see the variation in the distribution of these constituents within the seam profile from top to bottom. Table 4.15 also shows the values of proximate constituents from all coal seams/mines.

The Sharda coal records moisture with an average of 5.31% (ranges from 3.74% to 9.28%), ash with an average of 17.10% (ranges from 9.12% to 24.20%), volatile matter on air-dried basis with an average of 25.44% (ranges from 21.60% to 30.00%) and fixed carbon with an average of 52.15% (ranges from 49.18% to 56.56%). On a dry ash-free basis, volatile matter averages 32.74% (ranges from 30.10% to 35.30%) and fixed carbon averages 67.26% (ranges from 64.70% to 69.90%). On a dry mineral matter-free basis,

volatile matter averages 31.17% (ranges from 27.87% to 34.08%) and fixed carbon averages 68.83% (ranges from 65.92% to 72.13%). The Dhanpuri coal records moisture with an average of 4.18% (ranges from 3.04% to 6.50%), ash with an average of 22.76% (ranges from 12.00% to 40.80%), volatile matter with an average of 21.86% (ranges from 16.00% to 25.60%) and fixed carbon with an average of 51.20% (ranges from 37.00% to 60.78%). On a dry ash-free basis, volatile matter averages 30.41% (ranges from 26.85% to 40.89%) and fixed carbon averages 69.59% (ranges from 59.11% to 73.15%). On a dry mineral matter-free basis, volatile matter averages 27.63% (ranges from 23.39% to 37.94%) and fixed carbon averages 72.37% (ranges from 62.06% to 76.61%). The Rajendra coal records moisture with an average of 11.68% (ranges from 10.60% to 12.80%), ash with an average of 13.33% (ranges from 9.69% to 20.60%), volatile matter (ADB) with an average of 26.20% (ranges from 24.00% to 28.40%) and fixed carbon with an average of 48.79% (ranges from 42.60% to 52.71%). On a dry ash-free basis, volatile matter averages 34.99% (ranges from 33.12% to 36.29%) and fixed carbon averages 65.01% (ranges from 63.71% to 66.88%). On a dry mineral matter-free basis, volatile matter averages 33.71% (ranges from 32.25% to 35.31%) and fixed carbon averages 66.29% (ranges from 64.69% to 67.75%). The Khairaha VI seam records moisture with an average of 12.13% (ranges from 7.96% to 15.10%), ash with an average of 16.22% (ranges from 7.13% to 39.40%), volatile matter (ADB) with an average of 25.94% (ranges from 22.40% to 28.10%) and fixed carbon with an average of 45.71% (ranges from 28.94% to 55.91%). On a dry ash-free basis, volatile matter averages 36.83% (ranges from 28.60% to 45.02%) and fixed carbon averages 63.17% (ranges from 54.98% to 71.40%). On a dry mineral matter-free basis, volatile matter averages 35.29% (ranges from 27.49% to 41.07%) and fixed carbon averages 64.71% (ranges from 58.93% to 72.51%). The Khairaha VII seam records moisture with an average of 12.44% (ranges

from 10.70% to 13.70%), ash with an average of 12.79% (ranges from 9.27% to 20.90%), volatile matter with an average of 24.84% (ranges from 21.70% to 26.80%) and fixed carbon with an average of 49.93% (ranges from 46.70% to 50.90%). On dry ash-free basis, volatile matter averages 33.19% (ranges from 31.73% to 34.52%) and fixed carbon averages 66.81% (ranges from 65.48% to 68.27%). On a dry mineral matter-free basis, volatile matter averages 31.97% (ranges from 29.78% to 33.58%) and fixed carbon averages 68.03% (ranges from 66.42% to 70.22%). The Damini VI seam (first site) records moisture with an average of 9.62% (ranges from 9.30% to 9.90%), ash with an average of 28.07% (ranges from 25.10% to 32.70%), volatile matter (ADB) with an average of 20.47% (ranges from 18.30% to 21.80%) and fixed carbon with an average of 41.83% (ranges from 39.70% to 43.40%). On a dry ash-free basis, volatile matter averages 32.80% (ranges from 31.55% to 33.44%) and fixed carbon averages 67.20% (ranges from 66.56% to 68.45%). On a dry mineral matter-free basis, volatile matter averages 29.50% (ranges from 27.99% to 30.87%) and fixed carbon averages 70.50% (ranges from 69.13% to 72.01%). The Damini VI seam (second site) records moisture with an average of 10.02% (ranges from 9.47% to 10.80%), ash with an average of 22.03% (ranges from 15.80% to 28.40%), volatile matter with an average of 22.57% (ranges from 19.60% to 25.20%) and fixed carbon with an average of 45.37% (ranges from 42.50% to 48.20%). On dry ash-free basis, volatile matter averages 33.13% (ranges from 31.55% to 34.33%) and fixed carbon averages 66.87% (ranges from 65.67% to 68.45%). On a dry mineral matter-free basis, volatile matter averages 31.12% (ranges from 28.86% to 32.90%) and fixed carbon averages 68.88% (ranges from 67.10% to 71.14%). The Damini V coal records moisture with an average of 10.05% (ranges from 8.00% to 12.20%), ash with an average of 23.98% (ranges from 12.40% to 43.70%), volatile matter with an average of 24.10% (ranges from 16.70% to 29.70%) and fixed carbon with an

average of 41.88% (ranges from 31.60% to 47.80%). On a dry ash-free basis, volatile matter averages 36.29% (ranges from 34.58% to 38.98%) and fixed carbon averages 63.71% (ranges from 61.02% to 65.42%). On a dry mineral matter-free basis, volatile matter averages 33.70% (ranges from 29.26% to 37.79%) and fixed carbon averages 66.30% (ranges from 62.21% to 70.74%). The Bangwar coal records moisture with an average of 8.10% (ranges from 5.71% to 11.50%), ash with an average of 32.11% (ranges from 17.30% to 52.84%), volatile matter with an average of 20.96% (ranges from 15.45% to 26.80%) and fixed carbon with an average of 38.80% (ranges from 26.00% to 48.10%). On a dry ash-free basis, volatile matter averages 35.30% (ranges from 30.49% to 37.64%) and fixed carbon averages 64.70% (ranges from 62.36% to 69.51%). On a dry mineral matter-free basis, volatile matter averages 31.33% (ranges from 27.62% to 36.35%) and fixed carbon averages 68.67% (ranges from 63.65% to 72.38%). The Amalai coal records moisture with an average of 8.70% (ranges from 6.83% to 9.95%), ash with an average of 17.50% (ranges from 9.56% to 39.10%), volatile matter with an average of 24.10% (ranges from 17.90% to 27.50%) and fixed carbon with an average of 49.71% (ranges from 36.17% to 53.39%). On a dry ash-free basis, volatile matter averages 32.59% (ranges from 29.11% to 34.84%) and fixed carbon averages 67.41% (ranges from 65.16% to 70.89%). On a dry mineral matter-free basis, volatile matter averages 30.85% (ranges from 27.17% to 33.83%) and fixed carbon averages 69.15% (ranges from 66.17% to 72.83%).

Table 4.15 Proximate constituents (wt.%) of coal seams from Sohagpur coalfield.

Mine/Seam with Band no.	Proximate constituents							
	Air-dried basis				dry ash-free basis		dry mineral free basis	
	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %
Sharda								
1	4.76	9.12	30	56.12	34.84	65.16	33.9	66.1
2	5.14	13.1	25.2	56.56	30.82	69.18	29.63	70.37
3	4.03	24.2	21.6	50.17	30.1	69.9	27.87	72.13
4	3.74	22.2	23.6	50.46	31.87	68.13	29.86	70.14
5	5.46	17.5	26.5	50.54	34.4	65.6	32.77	67.23
6	9.28	13.1	27.4	50.22	35.3	64.7	34.08	65.92
7	5.17	15.1	25.8	53.93	32.36	67.64	31.07	68.93
8	4.92	22.5	23.4	49.18	32.24	67.76	30.19	69.81
Avg	5.31	17.1	25.44	52.15	32.74	67.26	31.17	68.83
Min	3.74	9.12	21.6	49.18	30.1	64.7	27.87	65.92
Max	9.28	24.2	30	56.56	35.3	69.9	34.08	72.13
Dhanpuri								
1	3.32	15.5	21.8	59.38	26.85	73.15	25.3	74.7
2	3.04	14.6	22.2	60.16	26.95	73.05	24.86	75.14
3	3.52	12	23.7	60.78	28.05	71.95	26.69	73.31
4	4.54	40.8	16	38.66	29.27	70.73	23.39	76.61
5	6.5	30.9	25.6	37	40.89	59.11	37.94	62.06
Avg	4.18	22.76	21.86	51.2	30.41	69.59	27.63	72.37

Mine/Seam with Band no.	Proximate constituents							
	Air-dried basis				dry ash-free basis		dry mineral free basis	
	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %
Min	3.04	12	16	37	26.85	59.11	23.39	62.06
Max	6.5	40.8	25.6	60.78	40.89	73.15	37.94	76.61
Rajendra								
1	10.6	11	26.1	52.3	33.29	66.71	32.33	67.67
2	11.8	9.94	28.4	49.86	36.29	63.71	35.31	64.69
3	11.7	15.4	26.4	46.5	36.21	63.79	34.85	65.15
4	12.8	20.6	24	42.6	36.04	63.96	33.8	66.2
5	11.5	9.69	26.1	52.71	33.12	66.88	32.25	67.75
Avg	11.68	13.33	26.2	48.79	34.99	65.01	33.71	66.29
Min	10.6	9.69	24	42.6	33.12	63.71	32.25	64.69
Max	12.8	20.6	28.4	52.71	36.29	66.88	35.31	67.75
Khairaha VI seam								
1	15.1	13.4	27.9	43.6	39.02	60.98	37.87	62.13
2	14	8.45	27.6	49.95	35.59	64.41	34.8	65.2
3	14.6	7.13	28.1	50.17	35.9	64.1	35.2	64.8
4	8.99	12.7	22.4	55.91	28.6	71.4	27.49	72.51
5	7.96	39.4	23.7	28.94	45.02	54.98	41.07	58.93
Avg	12.13	16.22	25.94	45.71	36.83	63.17	35.29	64.71
Min	7.96	7.13	22.4	28.94	28.6	54.98	27.49	58.93
Max	15.1	39.4	28.1	55.91	45.02	71.4	41.07	72.51
Khairaha VII seam								
1	13.7	11	24.5	50.8	32.54	67.46	31.4	68.6

Mine/Seam with Band no.	Proximate constituents							
	Air-dried basis				dry ash-free basis		dry mineral free basis	
	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %
2	12.4	11.2	25.5	50.9	33.38	66.62	32.3	67.7
3	10.7	20.9	21.7	46.7	31.73	68.27	29.78	70.22
4	12.3	11.6	25.7	50.4	33.77	66.23	32.77	67.23
5	13.1	9.27	26.8	50.83	34.52	65.48	33.58	66.42
Avg	12.44	12.79	24.84	49.93	33.19	66.81	31.97	68.03
Min	10.7	9.27	21.7	46.7	31.73	65.48	29.78	66.42
Max	13.7	20.9	26.8	50.9	34.52	68.27	33.58	70.22
Damini VI seam 1st site								
1	9.66	25.1	21.8	43.4	33.42	66.58	30.87	69.13
2	9.3	32.7	18.3	39.7	31.55	68.45	27.99	72.01
3	9.9	26.4	21.3	42.4	33.44	66.56	29.63	70.37
Avg	9.62	28.07	20.47	41.83	32.8	67.2	29.5	70.5
Min	9.3	25.1	18.3	39.7	31.55	66.56	27.99	69.13
Max	9.9	32.7	21.8	43.4	33.44	68.45	30.87	72.01
Damini VI seam 2nd site								
1	10.8	15.8	25.2	48.2	34.33	65.67	32.9	67.1
2	9.78	21.9	22.9	45.4	33.52	66.48	31.59	68.41
3	9.47	28.4	19.6	42.5	31.55	68.45	28.86	71.14
Avg	10.02	22.03	22.57	45.37	33.13	66.87	31.12	68.88
Min	9.47	15.8	19.6	42.5	31.55	65.67	28.86	67.1
Max	10.8	28.4	25.2	48.2	34.33	68.45	32.9	71.14
Damini V								

Mine/Seam with Band no.	Proximate constituents							
	Air-dried basis				dry ash-free basis		dry mineral free basis	
	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %
1	8	43.7	16.7	31.6	34.58	65.42	29.26	70.74
2	10.3	13.5	29.7	46.5	38.98	61.02	37.79	62.21
3	12.2	12.4	27.6	47.8	36.6	63.4	35.27	64.73
4	9.69	26.3	22.4	41.6	34.99	65.01	32.49	67.51
Avg	10.05	23.98	24.1	41.88	36.29	63.71	33.7	66.3
Min	8	12.4	16.7	31.6	34.58	61.02	29.26	62.21
Max	12.2	43.7	29.7	47.8	38.98	65.42	37.79	70.74
Bangwar								
1	5.71	52.84	15.45	26	37.27	62.73	29.8	70.2
2	11.5	17.3	26.8	44.3	37.64	62.36	36.35	63.65
3	8.2	34.5	20.5	36.8	35.78	64.22	31.55	68.45
4	7	23.8	21.1	48.1	30.49	69.51	27.62	72.38
Avg	8.1	32.11	20.96	38.8	35.3	64.7	31.33	68.67
Min	5.71	17.3	15.45	26	30.49	62.36	27.62	63.65
Max	11.5	52.84	26.8	48.1	37.64	69.51	36.35	72.38
Amalai								
1	9.73	10.6	26.7	52.97	33.51	66.49	32.58	67.42
2	9.95	9.56	27.1	53.39	33.67	66.33	32.86	67.14
3	8.47	12.6	27.5	51.43	34.84	65.16	33.83	66.17
4	6.83	39.1	17.9	36.17	33.11	66.89	28.54	71.46
5	8.32	21.6	20.4	49.68	29.11	70.89	27.17	72.83
6	8.14	19.2	22.4	50.26	30.83	69.17	29.11	70.89

Mine/Seam with Band no.	Proximate constituents							
	Air-dried basis				dry ash-free basis		dry mineral free basis	
	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %	Volatile Matter %	Fixed Carbon %
7	8.24	17	23.4	51.36	31.3	68.7	29.83	70.17
8	9.89	10.3	27.4	52.41	34.33	65.67	32.87	67.13
Avg	8.7	17.5	24.1	49.71	32.59	67.41	30.85	69.15
Min	6.83	9.56	17.9	36.17	29.11	65.16	27.17	66.17
Max	9.95	39.1	27.5	53.39	34.84	70.89	33.83	72.83

4.7.2 Ultimate analysis

Coal remains one of the most important fossil fuels worldwide, serving as a primary energy source for power generation, metallurgical processes, and various industrial applications. Its efficiency and suitability for these purposes, however, depend largely on its chemical composition. Coal is a complex mixture of organic matter, minerals, moisture, and volatile compounds, and understanding its chemical properties is essential for efficient, safe, and environmentally responsible utilization (Ryemshak et al., 2016). Among the analytical methods employed, ultimate analysis plays a pivotal role by providing detailed information about the elemental composition of coal (White and Whittingham 1983; Ryemshak et al., 2016).

Ultimate analysis refers to the quantitative determination of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). While proximate analysis measures moisture, ash, volatile matter, and fixed carbon, ultimate analysis delves deeper into the elemental makeup, which directly influences energy content and combustion characteristics (White and Whittingham 1983).

The significance of ultimate analysis extends across energy and environmental domains. From an energy perspective, high carbon and hydrogen content indicate a higher calorific value, which is crucial for power generation and metallurgical processes (Gupta 2007). Economically, ultimate analysis aids in selecting the most appropriate coal type for industrial operations, preventing operational problems such as slagging, fouling, and inefficient combustion (Gupta 2007; Bakri et al., 2022).

An ultimate analysis of the Sohagpur coals has been carried out to determine the essential elements present in coal samples. In this analysis, the elemental wt.% of carbon, hydrogen, nitrogen, and sulfur was determined. The results of carbon, hydrogen, nitrogen, and

sulphur have been obtained from the ultimate analyser, while for oxygen wt.%, we must subtract the total from 100. The determination of these elements is essential because carbon and hydrogen aid in evaluating the rank and stage of coalification (Chelgani et al., 2010). They are also helpful in determining the suitability of coal for hydrogenation and gasification purposes (Gupta 2007; Rahman et al., 2020; Bakri et al., 2022).

Carbon- The carbon content of the Sohagpur coal samples, expressed on a dry ash-free (daf) basis, ranges from 62.99% to 85.97%, with an average value of 80.48%. Carbon is the principal constituent of coal and serves as a key indicator of coal rank and maturity. The relatively high average carbon content suggests that the Sohagpur coals predominantly fall within the medium rank category. Variations in carbon content are strongly influenced by the maceral composition and banding characteristics of the coal. Petrographic observations indicate that bright bands, which are rich in vitrinite macerals, exhibit significantly higher carbon concentrations compared to dull bands, which are generally enriched in inertinite and mineral matter. This heterogeneity reflects differences in the original plant material, degree of coalification, and depositional conditions.

Hydrogen- Hydrogen content in the Sohagpur coals varies from 2.93% to 6.52%, with an average value of 4.54% on a dry ash-free basis. Hydrogen in coal is primarily associated with volatile matter and hydrocarbon structures. Higher hydrogen values typically indicate the presence of aliphatic compounds and a relatively lower degree of aromatic condensation. The observed range suggests moderate variability in coalification processes and organic matter composition. Coals with higher hydrogen content are generally characterized by enhanced combustibility and higher volatile yields, whereas lower hydrogen values may reflect increased aromaticity and thermal maturity.

Sulphur- The sulphur content of Sohagpur coals on a dry ash-free basis ranges between 0.34% and 3.80%, with an average value of 1.02%. Sulphur in coal occurs in organic, pyritic, and sulphate forms, and its concentration is largely governed by depositional environment and post-depositional geochemical conditions. The relatively low average sulphur content suggests that most of the coals were deposited under freshwater or low-sulphate conditions, which is favourable from both environmental and industrial perspectives. However, localized enrichment of sulphur may indicate intermittent marine influence or reducing conditions that promoted sulphur fixation.

Nitrogen- Nitrogen content in the Sohagpur coal samples ranges from 1.26% to 2.44%, with an average of 1.70% on a dry ash-free basis. Nitrogen is primarily incorporated into coal as part of heterocyclic organic compounds derived from original plant proteins and other nitrogen-bearing biomolecules. The relatively narrow range of nitrogen content indicates a consistent type of vegetal input and limited alteration during coalification. Nitrogen content generally shows little variation with coal rank, but it plays an important role in the formation of nitrogen oxides (NO_x) during combustion.

Oxygen- The oxygen content of Sohagpur coals, calculated on a dry ash-free basis, varies widely from 6.71% to 32.15%, with an average value of 12.27%. Oxygen is mainly present in functional groups such as hydroxyl, carboxyl, and carbonyl structures. Higher oxygen content is typically associated with lower-rank coals and greater degrees of oxidation or weathering. The wide variation observed suggests differences in coal rank, extent of biochemical degradation, and post-depositional oxidation. Lower oxygen values correspond to higher carbon content and greater coal maturity, whereas elevated oxygen content indicates less advanced coalification and a lower calorific value.

4.7.2.1 Variation and qualitative distribution of Ultimate constituents in coal seams of Sohagpur coalfield

The qualitative vertical distribution of ultimate analysis parameters for Sohagpur coals is illustrated in Figure 4.12. Variations in elemental composition across seam profiles reflect differences in coal lithotype, degree of organic matter preservation, and post-depositional geochemical processes.

In the Sharda coal mine, the banded dull coal exhibits relatively lower carbon content compared to the banded bright coal, while the bottom section shows the highest carbon percentage. This reflects enhanced organic matter concentration and better preservation in banded bright coal, which is typically enriched in vitrinite macerals. Hydrogen content shows only minor variation throughout the seam, although slightly lower values in the bottom section suggest a relatively greater aromaticity of organic matter. Sulphur content displays a zigzag pattern, being higher in the top section, decreasing downward, and increasing again within the banded dull coal. This variability likely reflects fluctuating sulphur incorporation during peat accumulation, influenced by changes in microbial activity and mineral matter input. Nitrogen content shows minimal variation, consistent with its association with stable organic constituents. Oxygen content is higher in dull coal bands, indicating increased oxidation concentration in these intervals (Figure 4.12(a)).

The Dhanpuri coal mine seam shows a progressive decrease in carbon content toward the bottom band, which is dominated by dull coal. This decline is attributed to increased mineral matter and poorer preservation of organic matter. In contrast, hydrogen content is relatively higher in the bottom band, suggesting a greater proportion of hydrogen-rich functional groups, possibly related to lower coalification or increased moisture retention. Sulphur content exhibits a zigzag pattern, reflecting variable depositional conditions and sulphur fixation during peat accumulation. Nitrogen content remains relatively constant

throughout the seam, whereas oxygen content is elevated in the bottom dull coal bands, consistent with increased oxidation presence (Figure 4.12(b)).

In the Rajendra coal mine, the middle band shows a lower carbon percentage, whereas the upper and lower sections exhibit higher carbon content. This distribution suggests that the middle band experienced greater degradation or influx of mineral matter, thereby reducing organic carbon concentration. Hydrogen content decreases slightly with depth, reflecting progressive coalification. Sulphur content increases toward the banded coal of the bottom section, possibly due to enhanced sulphide mineral formation or greater incorporation of sulphur under reducing conditions. Nitrogen content is also higher in the banded coal of the lower section, reflecting better preservation of nitrogen-bearing organic compounds. Oxygen content is lowest in the top band and highest in the middle section, indicating increased oxidation association in the middle band (Figure 4.12(c)).

For Khairaha Seam VI, carbon content increases in the middle section where banded bright coal occurs, reflecting enhanced preservation of organic matter. Hydrogen content is lowest in this band, indicating relatively greater aromaticity, whereas the highest hydrogen values in the bottom band suggest lower rank characteristics or increased moisture influence. Sulphur content is also higher in the bottom band, possibly due to sulphur enrichment during late-stage peat accumulation. Nitrogen content generally decreases upward but increases in the banded dull coal of the bottom band, indicating localized enrichment of nitrogen-bearing compounds. Oxygen content decreases toward the middle band and then increases toward the bottom, making the top and bottom bands relatively oxygen-rich, consistent with increased oxidation in these intervals (Figure 4.12(d)).

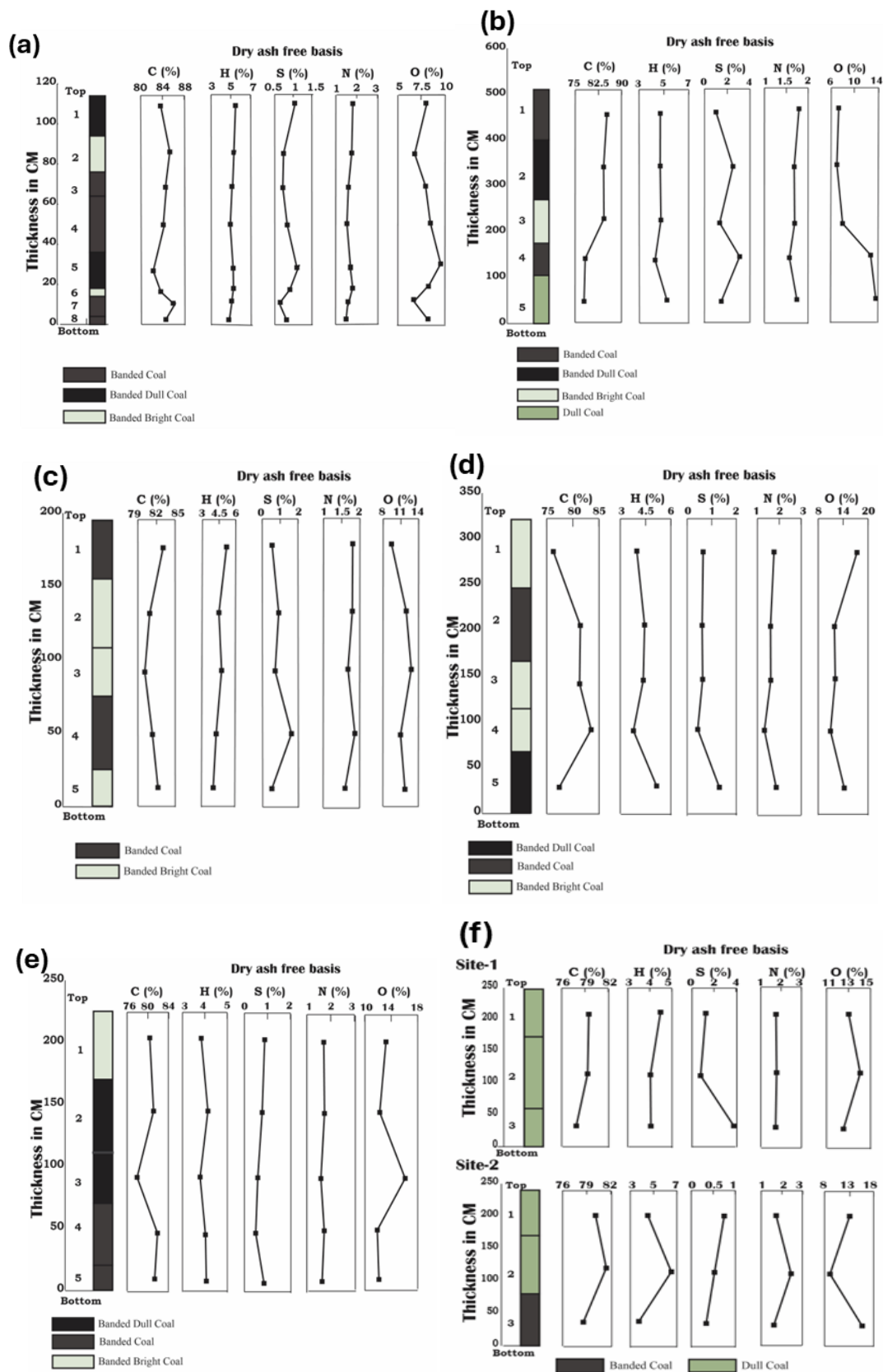
In Khairaha Seam VII, a sudden decrease in carbon content is observed in the banded dull coal of the middle section, reflecting increased mineral matter dilution and oxidation. Hydrogen and sulphur contents follow a similar decreasing trend, suggesting reduced preservation of organic matter in this interval. Nitrogen content remains nearly constant throughout the seam, indicating limited sensitivity to depositional changes. Oxygen content reaches its maximum in the middle band, confirming enhanced oxidation and higher inorganic matter content in the dull coal interval (Figure 4.12(e)).

The Damini Seam VI shows site-specific variations. At the first site, both carbon and hydrogen contents decrease with depth, indicating progressive enrichment in mineral matter or degradation of organic matter. A sudden increase in sulphur content in the basal section suggests localized sulphur fixation under reducing conditions. Nitrogen content remains relatively constant, while oxygen content is highest in the middle band, reflecting increased oxidation. At the second site, carbon and hydrogen contents are highest in the middle section, indicating improved preservation of organic matter during that depositional phase. Sulphur content decreases with depth, while nitrogen content peaks in the middle band. Oxygen content is lowest in the middle section, consistent with reduced oxidation and better peat preservation (Figure 4.12(f)).

In the Damini Seam V, carbon, hydrogen, and sulphur contents increase upward toward the middle band and then decrease toward the bottom. This suggests optimal peat preservation and reduced input of mineral matter during middle-stage seam development. In contrast, nitrogen and oxygen contents decrease toward the middle band and increase toward the top and bottom sections, reflecting greater oxidation influence at the seam boundaries (Figure 4.12(g)).

The Bangwar coal mine seam shows the highest carbon content in the bottom banded coal and the lowest in the middle dull coal band, reflecting variations in organic matter concentration and oxidation. Hydrogen content exhibits a zigzag pattern, with higher values at the top, decreasing in the middle, increasing again, and finally decreasing toward the bottom, indicating fluctuating coalification and preservation conditions. Sulphur content is higher in the middle and bottom sections, suggesting enhanced sulphur incorporation during these phases. Oxygen content is highest in the dull coal band, reflecting increased oxidation (Figure 4.12(h)).

The Amalai coal mine seam shows a sudden drop in carbon content within the dull coal band, accompanied by similarly low hydrogen content, indicating significant organic matter degradation. Sulphur content is higher in the lower section of the seam, likely due to sulphur enrichment under reducing conditions. Nitrogen content shows minimal variation throughout the seam, while oxygen content is highest in the middle dull coal band, confirming enhanced oxidation during that depositional phase (Figure 4.12(i)).



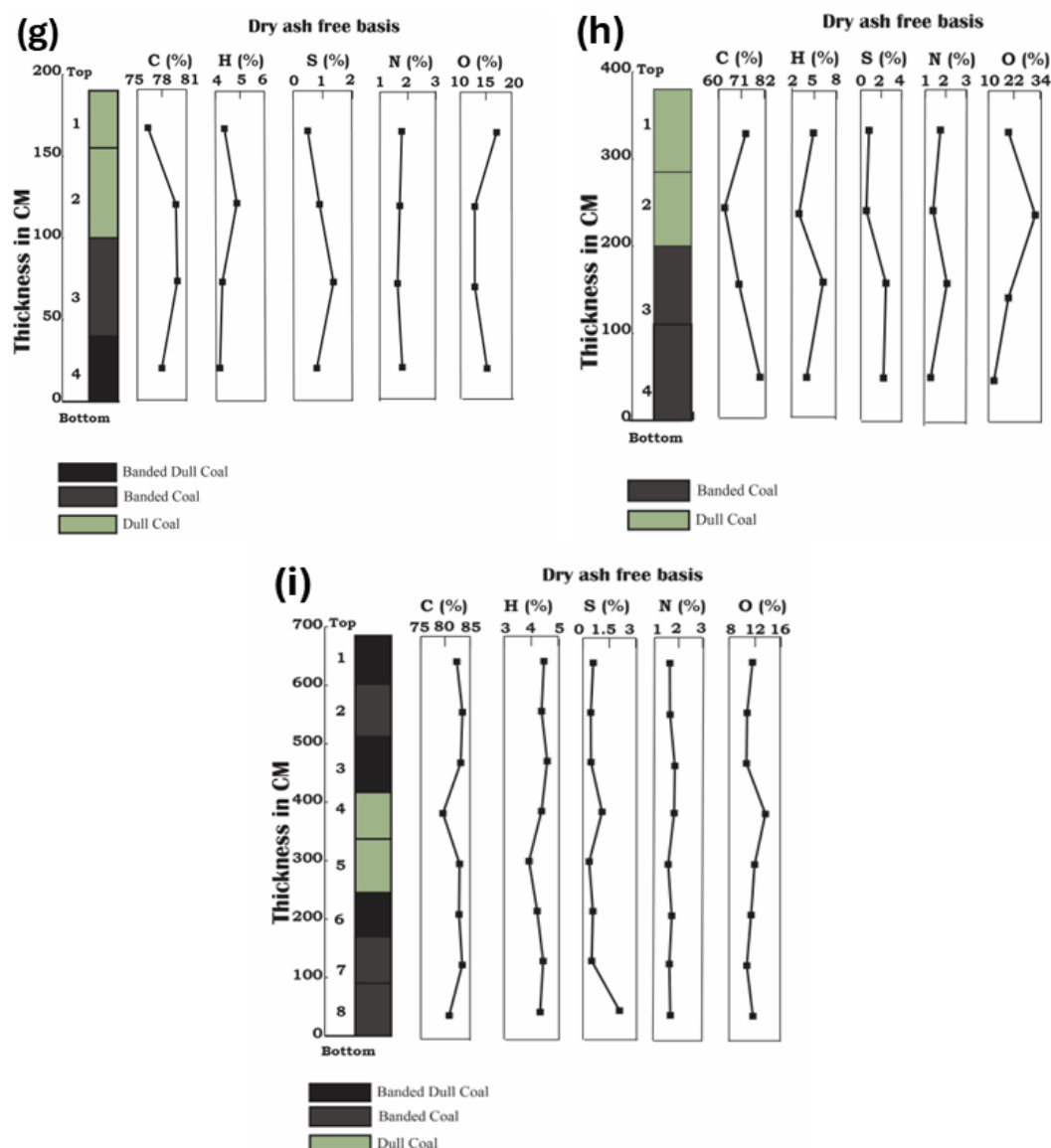


Figure 4.12 Vertical profile of coal seams with variation in ultimate constituents on dry ash free basis (a) Sharda, (b) Dhanpuri, (c) Rajendra, (d) Khairaha Seam VI, (e) Khairaha Seam VII, (f) Damini Seam VI, (g) Damini Seam V, (h) Bangwar, and (i) Amalai coal mine.

4.7.2.2 Quantitative distribution of Ultimate constituents in coal seams of Sohagpur coalfield

For the distribution of ultimate constituents of Sohagpur coalfield, band-wise data are presented in tabular form and in vertical profiles for C%, H%, S%, N%, and O% (Table 4.16). As coal is highly heterogeneous in character and a mixture of organic and inorganic constituents, the variation in its ultimate constituents is affected by several factors ranging from composition to syn and post depositional activity.

The Sharda coal sample records carbon with an average of 84.29% (ranges from 82.32% to 85.97%), hydrogen with an average of 5.16% (ranges from 4.80% to 5.48%), sulphur with an average of 0.85% (ranges from 0.65% to 1.10%), nitrogen with an average of 1.66% (ranges from 1.49% to 1.81%) and oxygen with an average of 8.03% (ranges from 6.71% to 9.63%). The Dhanpuri coal records carbon with an average of 81.93% (ranges from 77.83% to 85.21%), hydrogen with an average of 4.74% (ranges from 4.29% to 5.24%), sulphur with an average of 1.88% (ranges from 1.01% to 3.09%), nitrogen with an average of 1.69% (ranges from 1.57% to 1.79%) and oxygen with an average of 9.76% (ranges from 6.97% to 13.72%). The Rajendra coal records carbon with an average of 81.54% (ranges from 80.12% to 83.07%), hydrogen with an average of 4.51% (ranges from 3.96% to 5.17%), sulphur with an average of 0.87% (ranges from 0.54% to 1.63%), nitrogen with an average of 1.74% (ranges from 1.59% to 1.86%) and oxygen with an average of 11.34% (ranges from 9.41% to 12.76%). The Khairaha VI seam records carbon with an average of 79.99% (ranges from 76.27% to 83.51%), hydrogen with an average of 4.34% (ranges from 3.78% to 5.15%), sulphur with an average of 0.73% (ranges from 0.43% to 1.31%), nitrogen with an average of 1.63% (ranges from 1.32% to 1.86%) and oxygen with an average of 13.32% (ranges from 10.96% to 17.34%). The Khairaha VII seam records carbon with an average of 80.50% (ranges from 77.92% to 81.84%), hydrogen with an average of 3.97% (ranges from 3.79% to 4.14%), sulphur with an average of 0.71% (ranges from 0.49% to 0.88%), nitrogen with an average of 1.68% (ranges from 1.59% to 1.74%) and oxygen with an average of 13.13% (ranges from 11.90% to 16.11%). The Damini VI seam (first site) records carbon with an average of 78.91% (ranges from 77.88% to 79.49%), hydrogen with an average of 4.19% (ranges from 4.03% to 4.49%), sulphur with an average of 1.95% (ranges from 0.78% to 3.80%), nitrogen with an average of 1.75% (ranges from 1.73% to 1.78%) and oxygen with an average of

13.21% (ranges from 12.54% to 14.07%). The Damini VI seam (second site) records carbon with an average of 80.03% (ranges from 78.58% to 81.43%), hydrogen with an average of 4.92% (ranges from 3.74% to 6.52%), sulphur with an average of 0.54% (ranges from 0.34% to 0.75%), nitrogen with an average of 1.92% (ranges from 1.61% to 2.44%) and oxygen with an average of 12.59% (ranges from 9.08% to 15.73%). The Damini V coal records carbon with an average of 78.48% (ranges from 76.29% to 79.89%), hydrogen with an average of 4.42% (ranges from 4.18% to 4.87%), sulphur with an average of 0.89% (ranges from 0.49% to 1.36%), nitrogen with an average of 1.73% (ranges from 1.63% to 1.80%) and oxygen with an average of 14.49% (ranges from 12.82% to 17.07%). The Bangwar coal records carbon with an average of 71.47% (ranges from 62.99% to 79.94%), hydrogen with an average of 4.49% (ranges from 2.93% to 6.18%), sulphur with an average of 1.51% (ranges from 0.55% to 2.46%), nitrogen with an average of 1.61% (ranges from 1.26% to 2.06%) and oxygen with an average of 20.92% (ranges from 12.62% to 32.15%). The Amalai coal records carbon with an average of 81.67% (ranges from 79.12% to 82.77%), hydrogen with an average of 4.34% (ranges from 3.92% to 4.59%), sulphur with an average of 0.76% (ranges from 0.36% to 2.07%), nitrogen with an average of 1.68% (ranges from 1.56% to 1.84%) and oxygen with an average of 11.54% (ranges from 10.67% to 13.59%).

Table 4.16 Ultimate analysis (wt.%) of Sohagpur coals.

Mine/Seam with sample no.	Ultimate Constituents					Atomic Ratios	
	dry ash-free basis					Atomic H/C	Atomic O/C
	Carbon (%)	Hydrogen (%)	Sulphur (%)	Nitrogen (%)	Oxygen (%)		
Sharda							
1	83.63	5.48	1.04	1.81	8.04	0.79	0.07
2	85.36	5.32	0.74	1.76	6.82	0.75	0.06
3	84.56	5.12	0.72	1.6	8	0.73	0.07
4	84.16	4.96	0.84	1.53	8.52	0.71	0.08
5	82.32	5.25	1.1	1.7	9.63	0.77	0.09
6	83.7	5.28	0.91	1.8	8.31	0.76	0.07
7	85.97	5.09	0.65	1.58	6.71	0.71	0.06
8	84.64	4.8	0.82	1.49	8.26	0.68	0.07
Avg	84.29	5.16	0.85	1.66	8.03	0.74	0.07
Min	82.32	4.8	0.65	1.49	6.71	0.68	0.06
Max	85.97	5.48	1.1	1.81	9.63	0.79	0.09
Dhanpuri							
1	85.21	4.71	1.01	1.79	7.29	0.66	0.06
2	84.15	4.7	2.5	1.68	6.97	0.67	0.06
3	84.26	4.76	1.33	1.69	7.97	0.68	0.07
4	78.21	4.29	3.09	1.57	12.83	0.66	0.12
5	77.83	5.24	1.47	1.74	13.72	0.81	0.13
Avg	81.93	4.74	1.88	1.69	9.76	0.7	0.09
Min	77.83	4.29	1.01	1.57	6.97	0.66	0.06
Max	85.21	5.24	3.09	1.79	13.72	0.81	0.13
Rajendra							

Mine/Seam with sample no.	Ultimate Constituents					Atomic Ratios	
	dry ash-free basis					Atomic H/C	Atomic O/C
	Carbon (%)	Hydrogen (%)	Sulphur (%)	Nitrogen (%)	Oxygen (%)		
1	83.07	5.17	0.55	1.8	9.41	0.75	0.08
2	80.91	4.48	0.92	1.79	11.9	0.66	0.11
3	80.12	4.72	0.72	1.67	12.76	0.71	0.12
4	81.35	4.23	1.63	1.86	10.93	0.62	0.1
5	82.24	3.96	0.54	1.59	11.68	0.58	0.11
Avg	81.54	4.51	0.87	1.74	11.34	0.66	0.1
Min	80.12	3.96	0.54	1.59	9.41	0.58	0.08
Max	83.07	5.17	1.63	1.86	12.76	0.75	0.12
Khairaha VI seam							
1	76.27	3.98	0.65	1.76	17.34	0.63	0.17
2	81.44	4.44	0.61	1.6	11.91	0.65	0.11
3	81.3	4.36	0.63	1.61	12.1	0.64	0.11
4	83.51	3.78	0.43	1.32	10.96	0.54	0.1
5	77.41	5.15	1.31	1.86	14.27	0.8	0.14
Avg	79.99	4.34	0.73	1.63	13.32	0.65	0.13
Min	76.27	3.78	0.43	1.32	10.96	0.54	0.1
Max	83.51	5.15	1.31	1.86	17.34	0.8	0.17
Khairaha VII seam							
1	80.36	3.84	0.88	1.71	13.21	0.57	0.12
2	81.09	4.14	0.77	1.74	12.27	0.61	0.11
3	77.92	3.79	0.58	1.59	16.11	0.58	0.16
4	81.84	4.03	0.49	1.73	11.9	0.59	0.11
5	81.3	4.07	0.85	1.64	12.15	0.6	0.11

Mine/Seam with sample no.	Ultimate Constituents					Atomic Ratios	
	dry ash-free basis					Atomic H/C	Atomic O/C
Avg	Carbon (%)	Hydrogen (%)	Sulphur (%)	Nitrogen (%)	Oxygen (%)		
	80.5	3.97	0.71	1.68	13.13	0.59	0.12
Min	77.92	3.79	0.49	1.59	11.9	0.57	0.11
Max	81.84	4.14	0.88	1.74	16.11	0.61	0.16
Damini VI seam 1st site							
1	79.49	4.49	1.25	1.75	13.02	0.68	0.12
2	79.34	4.03	0.78	1.78	14.07	0.61	0.13
3	77.88	4.05	3.8	1.73	12.54	0.62	0.12
Avg	78.91	4.19	1.95	1.75	13.21	0.64	0.13
Min	77.88	4.03	0.78	1.73	12.54	0.61	0.12
Max	79.49	4.49	3.8	1.78	14.07	0.68	0.13
Damini VI seam 2nd site							
1	80.1	4.5	0.75	1.72	12.94	0.67	0.12
2	81.43	6.52	0.53	2.44	9.08	0.96	0.08
3	78.58	3.74	0.34	1.61	15.73	0.57	0.15
Avg	80.03	4.92	0.54	1.92	12.59	0.74	0.12
Min	78.58	3.74	0.34	1.61	9.08	0.57	0.08
Max	81.43	6.52	0.75	2.44	15.73	0.96	0.15
Damini V							
1	76.29	4.36	0.49	1.78	17.07	0.69	0.17
2	79.71	4.87	0.89	1.71	12.82	0.73	0.12
3	79.89	4.28	1.36	1.63	12.83	0.64	0.12
4	78	4.18	0.8	1.8	15.22	0.64	0.15
Avg	78.48	4.42	0.89	1.73	14.49	0.68	0.14

Mine/Seam with sample no.	Ultimate Constituents					Atomic Ratios	
	dry ash-free basis					Atomic H/C	Atomic O/C
Min	76.29	4.18	0.49	1.63	12.82	0.64	0.12
Max	79.89	4.87	1.36	1.8	17.07	0.73	0.17
Bangwar							
1	73.1	4.88	0.81	1.74	19.47	0.8	0.2
2	62.99	2.93	0.55	1.38	32.15	0.56	0.38
3	69.86	6.18	2.46	2.06	19.44	1.06	0.21
4	79.94	3.96	2.22	1.26	12.62	0.59	0.12
Avg	71.47	4.49	1.51	1.61	20.92	0.75	0.23
Min	62.99	2.93	0.55	1.26	12.62	0.56	0.12
Max	79.94	6.18	2.46	2.06	32.15	1.06	0.38
Amalai							
1	81.7	4.47	0.59	1.63	11.61	0.66	0.11
2	82.77	4.38	0.45	1.64	10.77	0.64	0.1
3	82.44	4.59	0.46	1.84	10.67	0.67	0.1
4	79.12	4.38	1.09	1.81	13.59	0.66	0.13
5	82.23	3.92	0.36	1.56	11.93	0.57	0.11
6	82.12	4.22	0.57	1.71	11.38	0.62	0.1
7	82.73	4.44	0.5	1.61	10.72	0.64	0.1
8	80.28	4.33	2.07	1.65	11.66	0.65	0.11
Avg	81.67	4.34	0.76	1.68	11.54	0.64	0.11
Min	79.12	3.92	0.36	1.56	10.67	0.57	0.1
Max	82.77	4.59	2.07	1.84	13.59	0.67	0.13

4.7.3 X-ray fluorescence (XRF) analysis

X-ray Fluorescence (XRF) analysis is a widely used analytical technique for determining the elemental and oxide composition of materials, including coal (Gupta 2007; Junussov et al., 2020; Revenko and Pashkova 2025). The method works by exposing a coal sample to high-energy X-rays, which cause atoms in the sample to emit secondary or fluorescent X-rays. Each element emits X-rays at characteristic energies, allowing both qualitative and quantitative identification of elements ranging from major constituents like silicon, aluminium, and iron to trace elements such as arsenic, lead, and mercury. XRF is a non-destructive, rapid, and multi-elemental technique, that require minimal sample preparation, making it highly suitable for coal analysis (Thorne et al., 1983; Bettinelli and Taina 1990; John 1990; Tiwari et al., 2014).

The primary objective of XRF analysis in coal is to accurately determine the chemical and mineralogical composition of coal samples. This includes identifying the major elements and oxides, assessing mineral matter, and detecting trace or hazardous elements that can influence the coal's industrial performance or environmental impact (Kierzek et al., 1990; Ward et al., 1990; Damdinsuren et al., 2024).

The importance of XRF in coal analysis lies in its speed, precision, and cost-effectiveness. XRF provides rapid, reliable, and reproducible results, often in just a few minutes (John 1990). It allows simultaneous detection of multiple elements over a wide concentration range, making it suitable for both major constituents and trace elements (John 1990; Ward et al., 1999). Furthermore, XRF is non-destructive, which is particularly valuable when working with limited or high-value samples.

X-ray Fluorescence (XRF) analysis is highly significant in understanding the depositional environment of coal because it provides rapid, quantitative data on the elemental

composition of coal and associated sediments (Zhang et al., 2014; Singh et al., 2021; Kumari et al., 2023; Wang et al., 2024). The distribution of major elements and oxides reveals the nature of mineral matter and the contribution of terrigenous or marine inputs. In contrast, trace elements (such as V, Cr, Ni, and Mo) reflect redox conditions and water chemistry during peat formation (Uzoegbu et al., 2020; Biswas et al., 2021; Li et al., 2022). Elemental ratios and enrichments can indicate paleoclimate variations, nutrient availability, and periodic environmental changes, and post-depositional alterations. By linking geochemical signatures to depositional processes, XRF helps reconstruct the paleoenvironment, identify sources of detrital material, and support coal correlation and basin analysis, making it an indispensable tool for interpreting the geological and environmental history of coal-forming settings (Kumar et al., 2023; Junussov and Mustapayeva 2024; Wang et al., 2024).

The major oxides in coal, such as SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , K_2O , and TiO_2 primarily originate from the mineral matter associated with coal, including clay minerals, quartz, feldspars, carbonates, sulfides, and oxides. These oxides may be derived from terrigenous or detrital sources (weathered rocks and transported sediments), carbonate minerals from marine or freshwater influence, authigenic formation during peat diagenesis, or minor contributions from volcanic ash or atmospheric dust (Ward 2002; Dai et al., 2020). Determining their concentration is crucial because they control the ash composition and behaviour during combustion, influence slagging and fouling in boilers, provide insights into coal quality and mineralogy, aid in reconstructing the depositional environment, and guide industrial applications such as power generation, cement production, or metallurgical processes (Huffman et al., 1990; Gupta 2007).

The XRF analysis was performed for the quantitative calculations (wt. %) of major oxides including SiO_2 , Al_2O_3 , Fe_2O_3 , MnO , CaO , MgO , K_2O , Na_2O , TiO_2 , and P_2O_5 . The XRF

analysis was also performed on the same band-wise classification used for the proximate and ultimate analysis. XRF analysis also provides the quantitative trace elemental data on parts per million concentrations (ppm) level.

4.7.3.1 Occurrence and distribution of major oxides in Sohagpur coalfield

The concentrations of various oxides across different sampling sites exhibit notable variations, reflecting the diverse geochemical characteristics of each band as shown in Table 4.17. The average concentration is also plotted in Figure 4.13. Among these, sulfur trioxide (SO_3) displays a broad range. An average of 1.06% (min 0.53%, max 12.40%) at Damini VI 2nd site, in stark contrast, the Damini VI 1st Site shows the highest average SO_3 content at 4.59%, with values ranging widely from 0.53% to a peak of 12.40%. This significant variability suggests localized enrichment or specific mineralogical conditions contributing to elevated SO_3 levels in the Damini area. Silicon dioxide (SiO_2), a major component often associated with silicate minerals, also exhibits considerable spatial variation. The highest average of SiO_2 concentration is observed at Bangwar, at 21.04%. Within this site, the minimum and maximum values recorded are 9.36% and 34.21%, respectively, indicating substantial heterogeneity in the silica content of the samples. Conversely, Khairaha VII exhibits the lowest SiO_2 content, average of just 4.72%. Here, the individual values vary narrowly, from 4.18% to 5.39%, suggesting a more uniform and silica-deficient composition in this region. Titanium dioxide (TiO_2), typically found in accessory minerals such as ilmenite and rutile, remains consistently low across all sampling sites. The highest average TiO_2 content is again observed at Bangwar, averages 0.69%, with values lies between 0.31% and 1.12%. Sharda, on the other hand, has the lowest TiO_2 average content of 0.37%, with ranging from 0.23% to 0.54%. These low concentrations align with expectations for titanium-bearing phases in these geological contexts. Aluminium oxide (Al_2O_3), an important indicator of clay minerals and

aluminosilicates, reaches its highest average at Bangwar with 10.30%. The range within this site extends from 4.87% up to 16.11%, highlighting significant mineralogical diversity. In contrast, Khairaha VII reports the lowest average for this oxide at 2.67%, with values ranging from 2.19% to 3.45%, reinforcing its relatively aluminous-poor composition. When examining ferrous oxide (FeO), the highest average concentration is found at Damini VI 1st Site, coming in at 4.27%. Individual measurements here range from 0.51% to 11.44%, indicating a broad distribution and possibly pointing to varying levels of iron-bearing minerals. On the other end of the spectrum, Khairaha VI presents the lowest FeO average of 0.54%, with a range from 0.25% to 1.44%. Manganese oxide (MnO) is uniformly low across all sampled sites. The highest average value is a mere 0.04%, observed at Damini VI 2nd Site. Even within this location, the range is minimal, from 0.03% to 0.05%. Many other sites report MnO level below 0.01%, indicating negligible MnO across the surveyed areas. Magnesium oxide (MgO), another significant component of mafic minerals, shows only slight variations. The highest average is recorded at Bangwar, at 0.30%, with individual sample values ranging from 0.13% to 0.41%. Dhanpuri reports the lowest average MgO content at 0.07%, with values narrowly fluctuating between 0.06% and 0.08%. Calcium oxide (CaO), often associated with carbonate and plagioclase content, displays more noticeable variation. Khairaha VI records the highest average CaO content at 1.49%, with range from 0.47% to 2.28%. The lowest concentrations are found at Dhanpuri, where the average is only 0.22%, and individual values range from 0.17% to 0.29%. Potassium oxide (K₂O), usually associated with feldspar and mica minerals, peaks at Bangwar with an average concentration of 0.50%. Within this site, K₂O ranges from 0.18% to 0.90%. At the other end of the spectrum, Khairaha VII shows the lowest K₂O average at just 0.03%, with recorded values ranging from 0.02% to 0.05%, suggesting a significant depletion of potassium-

bearing phases. Phosphorus pentoxide (P_2O_5) is present in trace amounts across all sites, typically ranging from 0.00% to 0.03%. Rajendra shows a slightly elevated average of 0.01%, although this remains within the generally negligible range. The uniformly low levels of P_2O_5 suggest minimal presence of phosphate minerals across the region. Sodium oxide (Na_2O) is either completely absent or present only in trace amounts (ranging from 0.00% to 0.01%) at all locations studied. This may reflect a paucity of sodium-rich minerals, such as albite, or could be due to leaching during weathering processes. Ferric oxide (Fe_2O_3) exhibits the widest range of variation among the oxides analyzed. The highest average concentration is observed at Damini VI 1st Site, where Fe_2O_3 averages 4.75%. The range at this site spans, from 0.56% up to 12.71%, indicating highly variable oxidized iron content, possibly linked to differential weathering or mineralization processes. In contrast, Khairaha VI has the lowest average (0.60%, min 0.28%, max 1.60%).

Table 4.17 Major oxides (wt.%) values of Sohagpur coals.

Mine/Seam with sample no.	SO ₃	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	K ₂ O	P ₂ O ₅	Na ₂ O	Fe ₂ O ₃
Sharda												
1	2.02	7.46	0.27	4.5	0.93	0.02	0.1	1.28	0.46	0.02	0	1.04
2	1.62	9.29	0.45	4.63	0.83	0.01	0.14	0.14	0.35	0.01	0	0.92
3	1.31	12.19	0.48	6.29	1.28	0.01	0.21	0.19	0.41	0	0	1.43
4	1.82	10.39	0.47	5.34	1.07	0.01	0.15	0.17	0.45	0	0	1.19
5	2.01	7.91	0.23	4.86	0.71	0	0.12	0.2	0.41	0	0	0.79
6	1.64	11.37	0.3	3.62	0.41	0.01	0.11	0.28	0.15	0	0	0.45
7	2.14	7.09	0.24	4.54	0.45	0	0.1	0.18	0.42	0	0	0.5
8	2.03	6.91	0.54	3.26	0.55	0.01	0.09	0.2	0.42	0	0	0.61
Avg	1.82	9.08	0.37	4.63	0.78	0.01	0.13	0.33	0.38	0	0	0.87
Min	1.31	6.91	0.23	3.26	0.41	0	0.09	0.14	0.15	0	0	0.45
Max	2.14	12.19	0.54	6.29	1.28	0.02	0.21	1.28	0.46	0.02	0	1.43
Dhanpuri												
1	1.75	8.57	0.34	2.94	1.11	0.01	0.08	0.2	0.13	0	0	1.23
2	2.4	6.31	0.32	3.13	2.46	0.02	0.07	0.22	0.13	0	0	2.74
3	2.79	5.96	0.43	2.82	1.89	0.05	0.08	0.29	0.19	0	0	2.1
4	2.67	18.7	0.66	6.92	2.51	0.04	0.07	0.17	0.29	0.01	0	2.79
5	1.56	14.95	0.82	7.31	0.98	0.01	0.06	0.23	0.39	0	0	1.09
Avg	2.23	10.9	0.51	4.62	1.79	0.02	0.07	0.22	0.22	0	0	1.99
Min	1.56	5.96	0.32	2.82	0.98	0.01	0.06	0.17	0.13	0	0	1.09
Max	2.79	18.7	0.82	7.31	2.51	0.05	0.08	0.29	0.39	0.01	0	2.79
Rajendra												

Mine/Seam with sample no.	SO ₃	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	K ₂ O	P ₂ O ₅	Na ₂ O	Fe ₂ O ₃
1	1.29	5.99	0.5	3.53	0.55	0.02	0.08	0.61	0.04	0.03	0	0.61
2	1.78	5.45	0.45	2.97	0.48	0.02	0.07	0.62	0.08	0	0	0.53
3	1.61	8.22	0.57	4.55	0.63	0.01	0.08	0.48	0.29	0	0	0.7
4	2.09	7.78	0.23	6	1.32	0.01	0.07	0.5	0.03	0	0	1.47
5	1.79	4.07	0.27	2.86	0.51	0.02	0.06	0.57	0.02	0	0	0.57
Avg	1.71	6.3	0.4	3.98	0.7	0.02	0.07	0.56	0.09	0.01	0	0.77
Min	1.29	4.07	0.23	2.86	0.48	0.01	0.06	0.48	0.02	0	0	0.53
Max	2.09	8.22	0.57	6	1.32	0.02	0.08	0.62	0.29	0.03	0	1.47
Khairaha VI seam												
1	1.39	6.26	0.44	3.87	0.26	0.01	0.09	1.88	0.18	0.01	0	0.29
2	1.42	5.03	0.25	3.21	0.25	0.01	0.09	1.61	0.09	0.01	0	0.28
3	1.75	4.32	0.26	2.48	0.27	0.01	0.09	1.21	0.14	0.01	0	0.3
4	1.88	14.21	0.6	7.36	1.44	0.02	0.18	0.47	0.5	0.01	0	1.6
5	1.13	6.46	0.35	3.79	0.48	0.01	0.13	2.28	0.17	0.01	0	0.53
Avg	1.51	7.26	0.38	4.14	0.54	0.01	0.11	1.49	0.21	0.01	0	0.6
Min	1.13	4.32	0.25	2.48	0.25	0.01	0.09	0.47	0.09	0.01	0	0.28
Max	1.88	14.21	0.6	7.36	1.44	0.02	0.18	2.28	0.5	0.01	0	1.6
Khairaha VII seam												
1	0.96	4.8	0.3	2.59	1.19	0.03	0.11	0.47	0.05	0.01	0.01	1.32
2	1.02	5.05	0.31	2.49	0.99	0.04	0.09	0.52	0.04	0	0	1.1
3	1.75	4.18	0.38	2.19	1.04	0.03	0.06	0.48	0.03	0	0	1.15
4	1.05	5.39	0.24	3.45	0.71	0.04	0.09	0.58	0.03	0	0	0.79
5	1.4	4.19	0.22	2.61	0.87	0.03	0.07	0.51	0.02	0	0	0.97
Avg	1.23	4.72	0.29	2.67	0.96	0.03	0.08	0.51	0.03	0	0	1.07
Min	0.96	4.18	0.22	2.19	0.71	0.03	0.06	0.47	0.02	0	0	0.79

Mine/Seam with sample no.	SO ₃	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	K ₂ O	P ₂ O ₅	Na ₂ O	Fe ₂ O ₃
Max	1.75	5.39	0.38	3.45	1.19	0.04	0.11	0.58	0.05	0.01	0.01	1.32
Damini VI seam 1st site												
1	0.85	6.06	0.26	3.43	0.88	0.03	0.11	0.71	0.04	0	0	0.98
2	0.53	16.48	1.11	4.75	0.51	0.03	0.11	0.93	0.1	0	0	0.56
3	12.4	11.17	0.63	4.3	11.44	0.03	0.13	0.77	0.06	0	0	12.71
Avg	4.59	11.24	0.67	4.16	4.27	0.03	0.11	0.8	0.07	0	0	4.75
Min	0.53	6.06	0.26	3.43	0.51	0.03	0.11	0.71	0.04	0	0	0.56
Max	12.4	16.48	1.11	4.75	11.44	0.03	0.13	0.93	0.1	0	0	12.71
Damini VI seam 2nd site												
1	1.89	7.08	0.4	3.54	1.83	0.03	0.12	0.68	0.04	0	0	2.04
2	0.63	12.08	0.93	3.77	0.9	0.05	0.13	0.91	0.1	0	0	1
3	0.67	15.64	1.05	4.27	0.54	0.03	0.1	0.87	0.1	0	0	0.59
Avg	1.06	11.6	0.79	3.86	1.09	0.04	0.12	0.82	0.08	0	0	1.21
Min	0.63	7.08	0.4	3.54	0.54	0.03	0.1	0.68	0.04	0	0	0.59
Max	1.89	15.64	1.05	4.27	1.83	0.05	0.13	0.91	0.1	0	0	2.04
Damini V												
1	1.02	17.97	1.38	7.11	1.6	0.02	0.15	0.7	0.38	0.02	0	1.78
2	2.68	13.58	0.85	5.3	1.68	0.02	0.05	0.92	0.12	0	0.01	1.87
3	1.79	4.23	0.17	2.83	1.03	0.08	0.08	0.98	0.03	0	0	1.14
4	2.82	10.86	0.61	4.82	0.64	0.04	0.16	1.57	0.05	0	0	0.71
Avg	2.08	11.66	0.75	5.01	1.24	0.04	0.11	1.04	0.15	0.01	0	1.37
Min	1.02	4.23	0.17	2.83	0.64	0.02	0.05	0.7	0.03	0	0	0.71
Max	2.82	17.97	1.38	7.11	1.68	0.08	0.16	1.57	0.38	0.02	0.01	1.87
Bangwar												
1	1.04	34.21	1.12	16.11	1.41	0.01	0.41	0.73	0.9	0.01	0	1.57

Mine/Seam with sample no.	SO ₃	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	K ₂ O	P ₂ O ₅	Na ₂ O	Fe ₂ O ₃
2	1.43	22.99	0.83	10.52	1.46	0.02	0.32	0.65	0.47	0	0	1.62
3	4.37	9.36	0.31	4.87	2.34	0.01	0.13	0.18	0.18	0.01	0	2.61
4	3.26	17.59	0.51	9.71	2	0.01	0.35	0.53	0.46	0.01	0	2.22
Avg	2.52	21.04	0.69	10.3	1.8	0.01	0.3	0.52	0.5	0.01	0	2
Min	1.04	9.36	0.31	4.87	1.41	0.01	0.13	0.18	0.18	0	0	1.57
Max	4.37	34.21	1.12	16.11	2.34	0.02	0.41	0.73	0.9	0.01	0	2.61
Amalai												
1	1.79	8.59	0.34	2.47	0.92	0.01	0.05	0.3	0.12	0	0	1.02
2	1.38	7.53	0.31	2.08	0.52	0.01	0.05	0.32	0.08	0	0	0.58
3	1.09	7.63	0.35	2.72	0.81	0.02	0.05	0.3	0.08	0	0	0.9
4	1.35	19.14	0.74	7.34	1.2	0.01	0.1	0.42	0.28	0.01	0	1.33
5	0.82	11.48	0.59	4.83	0.81	0.01	0.07	0.39	0.15	0	0.01	0.9
6	1.03	8.11	0.67	4.17	1.65	0.02	0.09	0.4	0.18	0.03	0	1.83
7	1.1	8.18	0.62	3.82	1.22	0.01	0.07	0.42	0.13	0.02	0	1.35
8	1.86	4.03	0.37	2.25	1.15	0.01	0.06	0.34	0.12	0.02	0	1.28
Avg	1.3	9.34	0.5	3.71	1.03	0.01	0.07	0.36	0.14	0.01	0	1.15
Min	0.82	4.03	0.31	2.08	0.52	0.01	0.05	0.3	0.08	0	0	0.58
Max	1.86	19.14	0.74	7.34	1.65	0.02	0.1	0.42	0.28	0.03	0.01	1.83

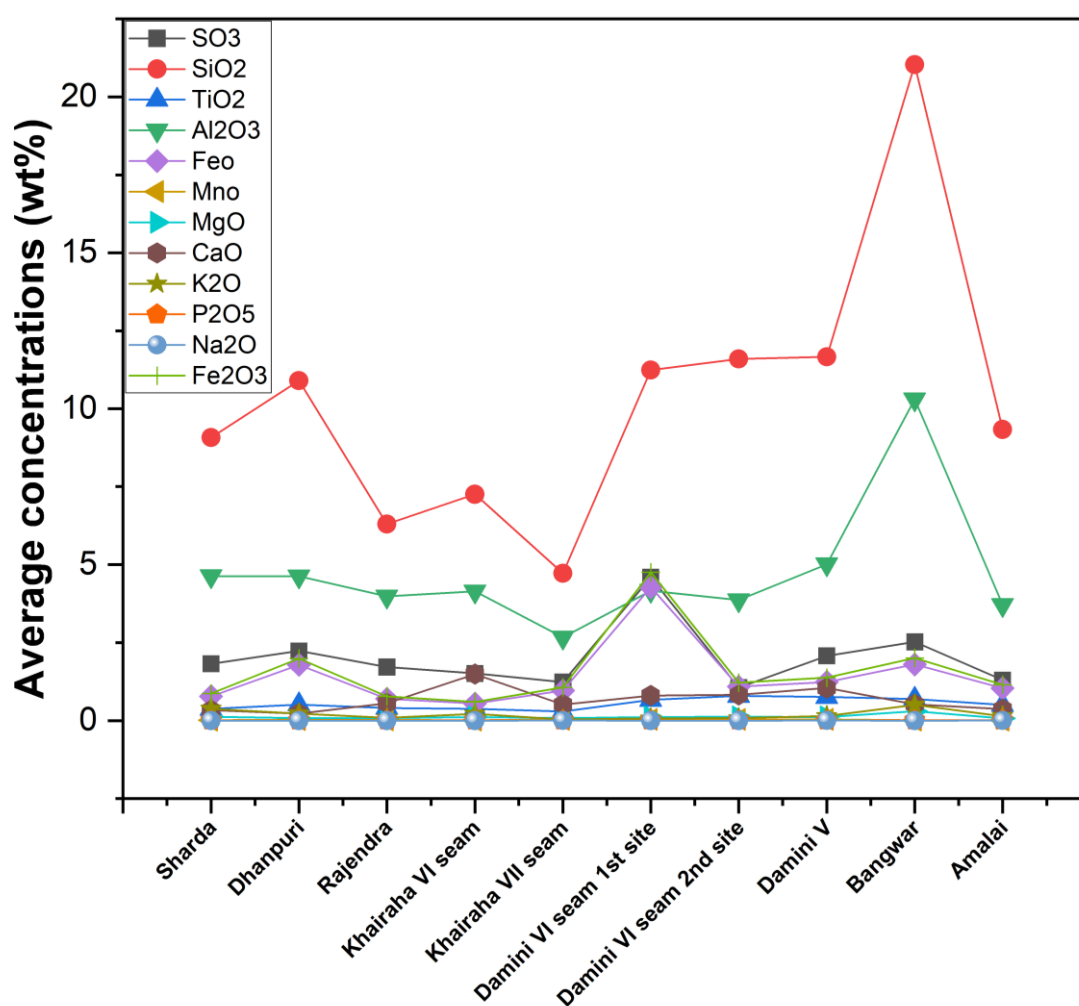


Figure 4.13 Average concentrations (wt.%) plotted for all major oxides with respect to coal seams/mine.

4.7.3.2 Occurrence and distribution of major and minor elements in Sohagpur coals

Coal is a heterogeneous sedimentary rock formed from the accumulation, burial, and transformation of plant materials under varying geological, chemical, and biological conditions over millions of years (Dai et al., 2020). The origin of coal involves complex processes of peat formation, diagenesis, and coalification, during which organic matter is progressively altered by increasing temperature and pressure (Dai et al., 2020). Along with organic constituents, coal contains inorganic matter derived from the original plant material, detrital mineral inputs, volcanic ash, and secondary mineralization. These inorganic components are commonly expressed as major and minor elements, ranging from >1 wt. % (major elements) and 1-0.1 wt. % (minor elements) such as silicon (Si),

aluminium (Al), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), titanium (Ti), and phosphorus (P), which are mainly associated with mineral phases including quartz, clay minerals, carbonates, sulfides, and oxides (Singh et al., 2021).

The measurement of major and minor elements in coal is of significant scientific and industrial importance. Major element composition provides valuable insights into the provenance of sediments, depositional environments, and post-depositional processes that influenced coal formation (Singh et al., 2021; Kumari et al., 2023). Variations in major element concentrations can reflect changes in source rocks, climatic conditions, and hydrological regimes during peat accumulation. From an industrial perspective, major elements strongly influence coal utilization behaviour, including combustion efficiency, ash yield, slagging and fouling tendencies, and environmental emissions (Huffman et al., 1990; Junussov and Mustapayeva 2024).

Major and minor element data contribute to geological interpretations and the reconstruction of paleoenvironmental and paleodepositional conditions. Additionally, the presence of major elements is also helpful for industrial utilization of coal samples.

Sharda mine shows moderate concentrations of major and minor elements. The average Si and Al contents are 4.07% and 2.34%, respectively, with Si ranging from 3.12% to 5.42% and Al from 1.67% to 3.15%. Iron (Fe) averages 0.59%, while Ca and Mg occur in relatively low amounts, averaging 0.23% and 0.07%, respectively. Potassium (K) and titanium (Ti) display moderate average values of 0.31% and 0.22%, suggesting the presence of feldspars and heavy minerals.

In Dhanpuri mine, Si and Al show higher variability, with Si ranging from 2.68% to 8.12% (average 4.82%) and Al from 1.44% to 3.62% (average 2.30%). Iron content is comparatively high, average of 1.36% and reaching 1.89%, indicating possible

enrichment of an iron-bearing minerals. Calcium and magnesium are present in minor amounts, while K and Ti exhibit moderate enrichment compared to Sharda.

Rajendra mine is characterized by relatively lower average Si (2.85%) and moderate Al (2.03%) contents. Iron remains low to moderate (average 0.53%). Calcium shows slightly higher average values (0.39%) than in several other mines, which may suggesting a greater contribution from carbonate minerals. Potassium and Mg are low, whereas Ti averages 0.24%.

The Khairaha VI seam exhibits moderate Si (3.25%) and Al (2.10%) contents, but notably high Ca concentrations, averaging 1.04% and reaching 1.59%. This suggests significant input of carbonate or Ca-bearing mineral. Iron varies widely from 0.19% to 1.09%. Potassium and Ti show moderate enrichment, particularly in maximum values.

In contrast, the Khairaha VII seam records lower overall major element contents. Average Si and Al are 2.15% and 1.38%, respectively, with relatively narrow ranges. Iron averages 0.73%, while Ca, Mg, and K remain consistently low, indicating limited mineral matter input and a more uniform depositional setting.

The Damini VI 1st site exhibits distinctive characteristics including elevated Fe content. Although the average Fe is 3.21%, it reaches a maximum value of 8.58%, indicating localized iron enrichment, possibly from pyrite or iron oxides. Si and Al average 4.93% and 2.06%, respectively. Calcium, Mg, and K are present in minor amounts, while Ti shows moderate variability.

At the Damini VI 2nd site, the average Si (5.16%) is slightly higher than at the 1st site, whereas average Fe content 0.83% is significantly lower. Calcium content remains moderate (average 0.57%), and Ti shows relatively higher average values (0.46%), suggesting differences in mineralogical composition between the two sites.

Damini V mine exhibits relatively high average Si (5.14%) and Al (2.50%) contents. Iron averages 0.94%, while Ca is comparatively enriched (average 0.72%, maximum 1.09%). Potassium and Ti show moderate concentrations, with Ti reaching a maximum of 0.80%, indicating a notable heavy mineral contribution.

The Bangwar mine displays the highest concentrations of most major elements among all studied samples. Average Si and Al contents are 9.04% and 4.92%, respectively, with maximum values of 14.45% for Si and 7.47% for Al. Iron averages 1.36%, while minor elements such as Mg (0.17%) and K (0.40%) are significantly higher than in other mines. These results suggest a strong detrital mineral influence and high ash-forming mineral content.

Amalai mine shows moderate major element concentrations, with average Si and Al values of 4.17% and 1.87%, respectively. Minor elements such as Fe average 0.79%, while Ca and Mg are low. Potassium and Ti occur in modest amounts, reflecting contribution of both silicate and accessory minerals.

Table 4.18 presents the concentrations of major elements (wt. %) in coal samples. These samples lack of Na due to the below detection limit of XRF instruments.

Table 4.18 Concentration of major and minor elements (wt.%) present in Sohagpur coals.

Mine/Seam with band no.	Elements in wt. %						
	Si	Al	Fe	Ca	Mg	K	Ti
Sharda							
1	3.35	2.28	0.71	0.89	0.05	0.37	0.16
2	4.17	2.35	0.63	0.09	0.08	0.28	0.26
3	5.42	3.15	0.97	0.13	0.12	0.33	0.28
4	4.64	2.69	0.81	0.12	0.08	0.36	0.27
5	3.56	2.47	0.54	0.14	0.07	0.33	0.14
6	5.10	1.83	0.31	0.20	0.06	0.12	0.17
7	3.20	2.32	0.34	0.13	0.06	0.34	0.14
8	3.12	1.67	0.42	0.14	0.05	0.34	0.32
Avg	4.07	2.34	0.59	0.23	0.07	0.31	0.22

Mine/Seam with band no.	Elements in wt. %						
	Si	Al	Fe	Ca	Mg	K	Ti
Min	3.12	1.67	0.31	0.09	0.05	0.12	0.14
Max	5.42	3.15	0.97	0.89	0.12	0.37	0.32
Dhanpuri							
1	3.86	1.50	0.84	0.14	0.04	0.10	0.20
2	2.84	1.59	1.87	0.15	0.04	0.10	0.19
3	2.68	1.44	1.44	0.20	0.05	0.15	0.25
4	8.12	3.37	1.89	0.12	0.04	0.23	0.38
5	6.60	3.62	0.74	0.16	0.03	0.31	0.47
Avg	4.82	2.30	1.36	0.15	0.04	0.18	0.30
Min	2.68	1.44	0.74	0.12	0.03	0.10	0.19
Max	8.12	3.62	1.89	0.20	0.05	0.31	0.47
Rajendra							
1	2.72	1.81	0.42	0.43	0.05	0.03	0.30
2	2.48	1.53	0.37	0.44	0.04	0.06	0.26
3	3.70	2.31	0.48	0.33	0.05	0.23	0.33
4	3.49	3.04	1.00	0.35	0.04	0.03	0.13
5	1.86	1.47	0.39	0.40	0.04	0.02	0.16
Avg	2.85	2.03	0.53	0.39	0.04	0.07	0.24
Min	1.86	1.47	0.37	0.33	0.04	0.02	0.13
Max	3.70	3.04	1.00	0.44	0.05	0.23	0.33
Khairaha VI seam							
1	2.83	1.97	0.20	1.31	0.05	0.14	0.26
2	2.29	1.65	0.19	1.13	0.05	0.07	0.15
3	1.97	1.28	0.21	0.85	0.05	0.11	0.15
4	6.26	3.64	1.09	0.32	0.09	0.40	0.35
5	2.92	1.94	0.37	1.59	0.07	0.14	0.21
Avg	3.25	2.10	0.41	1.04	0.06	0.17	0.22
Min	1.97	1.28	0.19	0.32	0.05	0.07	0.15
Max	6.26	3.64	1.09	1.59	0.09	0.40	0.35
Khairaha VII seam							
1	2.19	1.34	0.91	0.33	0.07	0.04	0.17
2	2.30	1.29	0.76	0.37	0.05	0.03	0.18
3	1.90	1.13	0.79	0.34	0.04	0.02	0.23
4	2.45	1.77	0.54	0.41	0.05	0.02	0.14
5	1.91	1.35	0.67	0.36	0.04	0.02	0.13
Avg	2.15	1.38	0.73	0.36	0.05	0.03	0.17
Min	1.90	1.13	0.54	0.33	0.04	0.02	0.13
Max	2.45	1.77	0.91	0.41	0.07	0.04	0.23
Damini VI seam 1st site							
1	2.75	1.76	0.67	0.50	0.06	0.03	0.15
2	7.28	2.36	0.38	0.64	0.06	0.08	0.65
3	4.75	2.06	8.58	0.51	0.07	0.05	0.36
Avg	4.93	2.06	3.21	0.55	0.06	0.05	0.38
Min	2.75	1.76	0.38	0.50	0.06	0.03	0.15

Mine/Seam with band no.	Elements in wt. %						
	Si	Al	Fe	Ca	Mg	K	Ti
Max	7.28	2.36	8.58	0.64	0.07	0.08	0.65
Damini VI seam 2nd site							
1	3.18	1.80	1.40	0.47	0.07	0.03	0.24
2	5.39	1.90	0.69	0.63	0.08	0.08	0.54
3	6.92	2.13	0.41	0.60	0.06	0.08	0.61
Avg	5.16	1.94	0.83	0.57	0.07	0.06	0.46
Min	3.18	1.80	0.41	0.47	0.06	0.03	0.24
Max	6.92	2.13	1.40	0.63	0.08	0.08	0.61
Damini V							
1	7.84	3.48	1.21	0.48	0.09	0.30	0.80
2	5.98	2.63	1.27	0.63	0.03	0.10	0.49
3	1.92	1.46	0.79	0.69	0.05	0.02	0.10
4	4.82	2.41	0.48	1.09	0.09	0.04	0.36
Avg	5.14	2.50	0.94	0.72	0.06	0.12	0.44
Min	1.92	1.46	0.48	0.48	0.03	0.02	0.10
Max	7.84	3.48	1.27	1.09	0.09	0.30	0.80
Bangwar							
1	14.45	7.47	1.07	0.50	0.22	0.71	0.65
2	9.93	5.06	1.10	0.44	0.18	0.37	0.48
3	4.15	2.43	1.77	0.13	0.08	0.14	0.18
4	7.64	4.71	1.51	0.36	0.19	0.36	0.29
Avg	9.04	4.92	1.36	0.36	0.17	0.40	0.40
Min	4.15	2.43	1.07	0.13	0.08	0.14	0.18
Max	14.45	7.47	1.77	0.50	0.22	0.71	0.65
Amalai							
1	3.87	1.26	0.70	0.21	0.03	0.10	0.20
2	3.41	1.07	0.40	0.22	0.03	0.06	0.18
3	3.46	1.39	0.62	0.21	0.03	0.07	0.21
4	8.36	3.59	0.91	0.29	0.06	0.22	0.43
5	5.13	2.44	0.62	0.27	0.04	0.11	0.34
6	3.64	2.12	1.26	0.28	0.05	0.15	0.39
7	3.68	1.95	0.93	0.29	0.04	0.10	0.36
8	1.84	1.16	0.88	0.24	0.03	0.10	0.22
Avg	4.17	1.87	0.79	0.25	0.04	0.11	0.29
Min	1.84	1.07	0.40	0.21	0.03	0.06	0.18
Max	8.36	3.59	1.26	0.29	0.06	0.22	0.43

4.7.3.3 Occurrence and distribution of trace elements in Sohagpur coals

Coal is not only a significant energy resource but also a valuable geological archive that preserves information about past environments. Among its constituents, trace elements

present in minor concentrations, typically less than 0.1% by weight, hold critical clues to the conditions under which the coal-forming peat accumulated and subsequently transformed into coal (Valkovic 1984; Swaine 2013). Understanding the origin, significance, and application of these elements is essential for reconstructing paleodepositional environments (Raask 1985; Finkelman 1999; Swaine 2013).

Trace elements in coal are derived from multiple sources. Primarily, they originate from the botanical precursors of coal, with different plant species selectively accumulating certain metals and elements. Secondary contributions come from detrital input, including fine-grained sediments, volcanic ash, and atmospheric dust that settled into the peat swamp (Valkovic 1984; Singh et al., 2021; Kumar et al., 2023). Additionally, diagenetic and post-depositional processes, such as groundwater migration and microbial activity, can modify the concentration and distribution of trace elements. The resulting geochemical signature thus represents an integrated record of both the organic and inorganic influences during coal formation (Li et al., 2013).

The geochemical composition of trace elements in coal is highly sensitive to environmental parameters, making them effective proxies for paleoenvironmental reconstruction. For instance, redox-sensitive elements such as vanadium (V), nickel (Ni), and molybdenum (Mo) provide insight into the degree of waterlogging and oxygen availability during peat accumulation. Elements like chromium (Cr) and cobalt (Co) can indicate marine influence or tidal incursion, while aluminium (Al), titanium (Ti), and zirconium (Zr) reflect the contribution of terrigenous clastic material (Gluskoter 1977; Querol et al., 1995; Finkelman 1999; Vejahati et al., 2010; Li et al., 2013; Kumari et al., 2023).

The primary objective of studying trace elements in coal is to reconstruct the paleodepositional environment in which the coal formed. This involves identifying the sources of organic matter and inorganic input, determining the redox and hydrological conditions, and assessing the influence of paleoclimate on peat accumulation.

The trace elemental concentrations of Cr, Co, V, Ni, Cu, Zn, Cd, As, Pb, Ga, Rb, Sr, Ba, Nb, U, Th, Mo, and Zr have been quantitatively examined at ppm level.

The elemental analysis across various sites reveals distinct spatial variations in trace elements concentrations (ppm). Chromium (Cr) is most enriched in Khairaha VI, where the maximum and average concentrations reach 443.20 ppm and 139.84 ppm, respectively, whereas Amalai shows the lowest maximum at 51.60 ppm. Cobalt (Co) peaks at Damini VI 1st Site with a maximum of 409.70 ppm and an average of 155.40 ppm, although data is unavailable for Sharda, Rajendra, Bangwar, and Damini V. Vanadium (V) mirrors chromium's distribution, with Khairaha VI recording the highest values (Max: 451.70 ppm; Avg: 140.00 ppm), and Bangwar being the most enriched outside Khairaha (Max: 183.60 ppm). Nickel (Ni) ranges from 11.90 ppm in Amalai to 135.60 ppm in Khairaha VI, where the average is also highest at 80.14 ppm. Copper (Cu) is most consistent in Bangwar (Avg: 38.03 ppm), with a maximum value of 64.30 ppm in Dhanpuri. Zinc (Zn) is elevated in Khairaha VI (Max: 265.70 ppm; Avg: 79.38 ppm) and lowest in Damini VI 2nd Site (Avg: 5.20 ppm). Cadmium (Cd) reaches 2.80 ppm in Dhanpuri but is not detected in Sharda, Rajendra, Bangwar, and Damini V. Arsenic (As) is notably high in Khairaha VI (Max: 21.30 ppm; Avg: 6.83 ppm), while absent in Bangwar. Lead (Pb) is highly concentrated in Damini VI 1st Site (Max: 222.70 ppm; Avg: 80.27 ppm), but Khairaha VI has the lowest average (6.00 ppm). Gallium (Ga) concentrations are highest in Bangwar (Max: 62.30 ppm; Avg: 29.80 ppm), with Rajendra also showing elevated levels (Avg: 21.30 ppm). Rubidium (Rb) peaks in Bangwar (66.20

ppm), whereas Rajendra maintains a consistent average of 17.90 ppm. Strontium (Sr) varies from 12.00 ppm in Bangwar to 73.30 ppm in Damini V, which also has the highest average (48.65 ppm). Barium (Ba) shows the greatest variability, with Amalai reporting a maximum of 937.00 ppm and an average of 199.96 ppm, while Sharda remains stable at 131.10 ppm. Niobium (Nb) is most concentrated in Damini V (Max: 31.60 ppm; Avg: 19.67 ppm), and least in Sharda (Avg: 9.08 ppm). Uranium (U) is highest in Khairaha VI (Max: 19.20 ppm; Avg: 9.60 ppm), though absent in many other sites. Thorium (Th) reaches a maximum of 45.90 ppm in Damini V, with high averages in Bangwar (15.58 ppm) and Damini VI 1st Site (13.23 ppm). Molybdenum (Mo) is significantly elevated only in Damini VI 1st Site (52.60 ppm), while Sharda exhibits consistently low levels (Avg: 0.30 ppm). Zirconium (Zr) is most abundant in Damini VI 2nd Site (Avg: 139.97 ppm), with a maximum of 240.60 ppm in Bangwar and the lowest minimum of 37.20 ppm in Khairaha VII, reflecting substantial variation in zirconium distribution across the sites as shown in Table 4.19.

Table 4.19 Trace elemental concentration (ppm) of Sohagpur coals.

Mine/Seam with sample no.	Cr	Co	V	Ni	Cu	Zn	Cd	As	Pb	Ga	Rb	Sr	Ba	Nb	U	Th	Mo	Zr
Sharda																		
1	161.5	--	100.9	49.6	22.9	18.5	--	1.3	7.7	6.9	12.4	47.7	131.1	7.6	--	7.2	--	56.8
2	52.6	--	60.7	36.2	26.5	--	--	--	7.9	9.9	10.3	32.4	--	11.8	--	--	--	69.9
3	79.1	--	62	44.4	39.8	18.3	--	--	25.5	14.6	12.4	39.6	--	7.9	--	15.4	--	85.6
4	56.4	--	60.7	41.4	27.4	10.5	--	--	9.7	10.3	13	36	--	9.5	--	--	--	74
5	52.1	--	36.3	33.3	17.5	--	--	--	7.5	12	9.8	33.6	--	--	--	--	--	42.8
6	35.2	--	30.8	25.9	15.7	--	--	--	--	8.3	4.6	20	--	--	--	--	--	50.6
7	86.6	--	54.8	41.2	20.9	17.6	--	--	5.8	12.8	10.3	32.7	--	7.1	--	--	--	44.1
8	168.2	--	112.1	55	36.7	55	--	0.8	18.4	9.1	11.8	31.9	--	10.6	--	16.9	0.3	83.3
Avg	86.46	--	64.79	40.88	25.93	23.98	--	1.05	11.79	10.4 9	10.58	34.2 4	131.1	9.08	--	13.1 7	0.3	63.39
Min	35.2	--	30.8	25.9	15.7	10.5	--	0.8	5.8	6.9	4.6	20	131.1	7.1	--	7.2	0.3	42.8
Max	168.2	--	112.1	55	39.8	55	--	1.3	25.5	14.6	13	47.7	131.1	11.8	--	16.9	0.3	85.6
Dhanpuri																		
1	32.6	45.2	32.8	21.8	17	11.9	0.5	1.8	6.9	7.6	5.7	14	14.7	6.5	0.7	6.7	7.4	65.7
2	36	98.2	34.3	25.2	24.1	38.1	0.3	0	14.3	11.4	6.4	15.4	16.3	7.3	0.8	5.6	28	56.2
3	48.7	77.1	31.2	28.9	31.1	19.1	1.5	0	16.1	12.4	10	22.3	23	8.2	0.7	4.6	12.9	81.2
4	175.6	85.9	48.3	24.8	27.6	34.3	0.1	0	28.5	11.5	14.6	14.4	36	18.8	3.6	21.7	0	261.3
5	98.5	45.3	83.3	39.9	64.3	48.7	2.8	1.3	29.3	16.6	23.2	20.2	49	16.6	3.5	21.8	0	154.5
Avg	78.28	70.34	45.98	28.12	32.82	30.42	1.04	0.6	19.0	11.9	11.98	17.2 6	27.8	11.4 8	1.8 6	12.0 8	9.66	123.7 8
Min	32.6	45.2	31.2	21.8	17	11.9	0.1	0	6.9	7.6	5.7	14	14.7	6.5	0.7	4.6	0	56.2
Max	175.6	98.2	83.3	39.9	64.3	48.7	2.8	1.8	29.3	16.6	23.2	22.3	49	18.8	3.6	21.8	28	261.3

Mine/Seam with sample no.	Cr	Co	V	Ni	Cu	Zn	Cd	As	Pb	Ga	Rb	Sr	Ba	Nb	U	Th	Mo	Zr
Rajendra																		
1	112.1	--	71.1	31.9	31.1	--	--	1	19.1	12.2	--	22.2	127.1	9.7	--	--	--	83.2
2	45.5	--	40.9	24.4	18.8	6.2	--	0.3	6.3	21.6	--	19.7	365.8	7.4	--	--	--	60.7
3	120.8	--	125.4	37.8	60.2	21.9	--	--	20.7	35	17.9	18.7	--	16.9	--	20.4	1.2	60.9
4	60.3	--	39.3	16.9	19.2	--	--	2	13.9	18.8	--	16.5	--	6.7	--	--	--	41.7
5	74.8	--	64.3	21.7	14.8	6.1	--	--	--	18.9	--	18.4	--	8.3	--	8	--	44.1
Avg	82.7	--	68.2	26.54	28.82	11.4	--	1.1	15	21.3	17.9	19.1	246.4	9.8	--	14.2	1.2	58.12
Min	45.5	--	39.3	16.9	14.8	6.1	--	0.3	6.3	12.2	17.9	16.5	127.1	6.7	--	8	1.2	41.7
Max	120.8	--	125.4	37.8	60.2	21.9	--	2	20.7	35	17.9	22.2	365.8	16.9	--	20.4	1.2	83.2
Khairaha VI seam																		
1	443.2	42.9	451.7	96.7	21.3	265.7	1.1	3	4.5	21.9	12.9	32.4	30.8	8.6	19. 2	4.7	8	92.3
2	80.6	42.7	50	50.3	16.7	37.4	1	0.9	3.8	28.5	5	33.5	14	4.6	14. 6	2.9	7.6	45.5
3	43.2	29.5	37.1	57.7	15.8	6.5	2.2	--	1.5	33.7	10.9	25.3	23	5.9	9.3	4.4	6.4	42.7
4	84.5	127.9	101.9	135.6	37.9	68.2	2.3	21.3	13.3	18.1	36.9	28.7	66.4	15.6	1.5	11.9	3.5	128.6
5	47.7	37.8	59.3	60.4	28.7	19.1	0.3	2.1	6.9	11.5	10.4	44.1	39.2	5.6	3.4	5.3	--	53.1
Avg	139.84	56.16	140	80.14	24.08	79.38	1.38	6.83	6	22.7	15.22	32.8	34.68	8.06	9.6	5.84	6.38	72.44
Min	43.2	29.5	37.1	50.3	15.8	6.5	0.3	0.9	1.5	11.5	5	25.3	14	4.6	1.5	2.9	3.5	42.7
Max	443.2	127.9	451.7	135.6	37.9	265.7	2.3	21.3	13.3	33.7	36.9	44.1	66.4	15.6	19. 2	11.9	8	128.6
Khairaha VII seam																		
1	87.7	48.2	96.7	33.3	27	3.2	1.6	--	10.3	13.3	1.1	22.2	280.9	10.1	2.4	5.6	--	65.4
2	76.9	48.5	70.8	27	23.6	4.5	2.3	0.8	7	9.7	1.3	21.2	29.8	6.7	0.9	5.9	--	61.2
3	36.9	47	28.9	35.4	20.1	3.9	0.4	--	7.6	13.4	0.7	18.5	15.9	8.1	2.6	4.2	--	60.6
4	25.6	33.5	19.6	26.1	17.1	2.6	1.8	0.5	4.2	8.3	0.6	19.8	24	5.8	1.4	5.5	--	44.1

Mine/Seam with sample no.	Cr	Co	V	Ni	Cu	Zn	Cd	As	Pb	Ga	Rb	Sr	Ba	Nb	U	Th	Mo	Zr
5	19.9	43	20.2	27.3	14.9	2.6	1.7	0.9	4.8	10.9	0.1	21.1	19.2	5.9	1.1	2.8	--	37.2
Avg	49.4	44.04	47.24	29.82	20.54	3.36	1.56	0.73	6.78	11.1	0.76	20.5	73.96	7.32	1.6	4.8	--	53.7
Min	19.9	33.5	19.6	26.1	14.9	2.6	0.4	0.5	4.2	8.3	0.1	18.5	15.9	5.8	0.9	2.8	--	37.2
Max	87.7	48.5	96.7	35.4	27	4.5	2.3	0.9	10.3	13.4	1.3	22.2	280.9	10.1	2.6	5.9	--	65.4
Damini VI seam 1st site																		
1	23.7	40.6	19.4	26.4	12.3	6.5	2	2.8	4.4	7.7	1.4	25.3	33.2	6.6	2	6.7	--	49.2
2	72.3	15.9	55.6	16.4	32.7	6.1	2.3	0.8	13.7	13.4	3	38.2	39	20.3	2.4	22	--	209.5
3	117.8	409.7	15.6	91.9	58.4	16.9	--	--	222.7	6	22.8	24.1	677	10.7	--	11	52.6	87.2
Avg	71.27	155.4	30.2	44.9	34.47	9.83	2.15	1.8	80.27	9.03	9.07	29.2	249.7	12.5	2.2	13.2	52.6	115.3
Min	23.7	15.9	15.6	16.4	12.3	6.1	2	0.8	4.4	6	1.4	24.1	33.2	6.6	2	6.7	52.6	49.2
Max	117.8	409.7	55.6	91.9	58.4	16.9	2.3	2.8	222.7	13.4	22.8	38.2	677	20.3	2.4	22	52.6	209.5
Damini VI seam 2nd site																		
1	51.2	77.2	25.1	24.8	17.7	3.9	1.3	--	21.2	10.1	1.4	26.3	48.4	8.2	2	6.6	--	77.3
2	62.3	34.4	53.7	21.8	40.3	5.3	1	1.5	26.8	11.5	2.3	31.6	29.4	16.1	2.3	14.5	0.2	142.6
3	60.7	18	50.6	13.7	34.1	6.4	1.1	2.1	7.8	11.9	2.4	35.3	53.6	19.5	1.9	20.3	--	200
Avg	58.07	43.2	43.13	20.1	30.7	5.2	1.13	1.8	18.6	11.1	2.03	31.0	43.8	14.6	2.0	13.8	0.2	139.9
Min	51.2	18	25.1	13.7	17.7	3.9	1	1.5	7.8	10.1	1.4	26.3	29.4	8.2	1.9	6.6	0.2	77.3
Max	62.3	77.2	53.7	24.8	40.3	6.4	1.3	2.1	26.8	11.9	2.4	35.3	53.6	19.5	2.3	20.3	0.2	200
Damini V																		
1	94.6	--	155.9	14.7	63.1	--	--	1.8	33.8	23.5	27.1	44.8	--	31.6	--	45.9	--	209.5
2	57.9	--	70.8	21.4	28	--	--	5.1	14.8	15.3	8.1	42	--	17	--	16.1	4	148.7
3	22.9	--	31	24.8	13.3	--	--	1.6	4.2	15.4	--	34.5	--	--	--	--	--	28.1
4	41.1	--	47	24.5	33.4	12.5	--	1.6	12.2	8.7	--	73.3	271.5	10.4	--	11.5	--	101.2

Mine/Seam with sample no.	Cr	Co	V	Ni	Cu	Zn	Cd	As	Pb	Ga	Rb	Sr	Ba	Nb	U	Th	Mo	Zr
Avg	54.13	--	76.18	21.35	34.45	12.5	--	2.53	16.25	15.7	17.6	48.6	271.5	19.6	--	24.5	4	121.8
Min	22.9	--	31	14.7	13.3	12.5	--	1.6	4.2	8.7	8.1	34.5	271.5	10.4	--	11.5	4	28.1
Max	94.6	--	155.9	24.8	63.1	12.5	--	5.1	33.8	23.5	27.1	73.3	271.5	31.6	--	45.9	4	209.5
Bangwar																		
1	84.8	--	90.9	26.7	42.7	22.9	--	--	22.7	22.7	66.2	31.9	163.5	24.6	--	22.4	--	240.6
2	67.5	--	82.4	29	33.8	9.4	--	--	17.6	19	35.4	23.9	17	16.5	--	13.4	--	159.1
3	44.7	--	35.3	27.9	21.6	15	--	--	12.6	62.3	12.5	12	--	7	--	4.5	--	61.9
4	108.6	--	183.6	51.7	54	116.3	--	--	31.1	15.2	36.1	26.4	--	15.7	--	22	--	85.1
Avg	76.4	--	98.05	33.83	38.03	40.9	--	--	21	29.8	37.55	23.5	90.25	15.9	--	15.5	--	136.6
Min	44.7	--	35.3	26.7	21.6	9.4	--	--	12.6	15.2	12.5	12	17	7	--	4.5	--	61.9
Max	108.6	--	183.6	51.7	54	116.3	--	--	31.1	62.3	66.2	31.9	163.5	24.6	--	22.4	--	240.6
Amalai																		
1	49.4	54.7	33.5	34.7	22.8	5.1	2	1.4	4.9	13.9	6.2	17.7	37.7	7.2	0.9	4.6	--	55.9
2	38.7	40.9	31.7	32.3	20.2	5.5	1.9	0.7	3.7	13.2	3.1	16.1	34.8	6.6	2.3	4.8	--	48.5
3	25.1	47.3	29.9	22.9	20.2	5.4	0.6	--	4.4	7.3	3.7	17	21.7	6.4	1.1	5.1	--	64.1
4	51.6	42.6	46	13.7	36.3	7	--	3.8	20.5	14.2	17.5	21.7	937	13.9	3	12.4	--	136.6
5	51.3	26.6	46.4	11.9	25.5	23.9	1	0.7	7.3	8.6	8.2	22.9	32.6	11.3	2.3	12	--	121.8
6	29.9	58.2	41.9	15.3	31.8	25.5	1.6	--	17.2	11.1	10.6	91.7	491.4	11.6	3.2	8.5	--	112.5
7	40.9	43	39.4	18.2	23.5	7.5	1.8	0.8	13.5	9.5	5	55.3	24.3	10.3	1.4	9.4	--	104.2
8	41.7	48	42.5	40.5	25.7	7.4	--	1.4	5.7	25.7	6.4	50.1	20.2	6.6	1.8	4.3	--	58.1
Avg	41.08	45.16	38.91	23.69	25.75	10.91	1.48	1.47	9.65	12.9	7.59	36.5	199.9	9.24	2	7.64	--	87.71
Min	25.1	26.6	29.9	11.9	20.2	5.1	0.6	0.7	3.7	7.3	3.1	16.1	20.2	6.4	0.9	4.3	--	48.5
Max	51.6	58.2	46.4	40.5	36.3	25.5	2	3.8	20.5	25.7	17.5	91.7	937	13.9	3.2	12.4	--	136.6

4.7.4 X-ray Diffraction (XRD) Study of Coals

Coal is a complex, heterogeneous material composed of organic macerals and inorganic mineral matter. Understanding its structural and mineralogical composition is crucial for evaluating its quality, potential for industrial use, and environmental impact. Among various analytical techniques, X-ray diffraction (XRD) has emerged as a powerful tool for characterizing the crystalline phases present in coal (Lu et al., 2001; Gupta, 2007; Saikia et al., 2007). XRD provides detailed insights into the crystallographic structure and phase identification. This analysis can provide non-destructive, accurate, and reproducible information about coal's mineralogical and structural composition. Knowledge of mineral content, such as quartz, kaolinite, pyrite, and calcite, is essential for predicting ash behaviour, slagging, fouling, and pollutant emissions during thermal conversion (Ward 2002; Saikia et al., 2007; Manoj 2016).

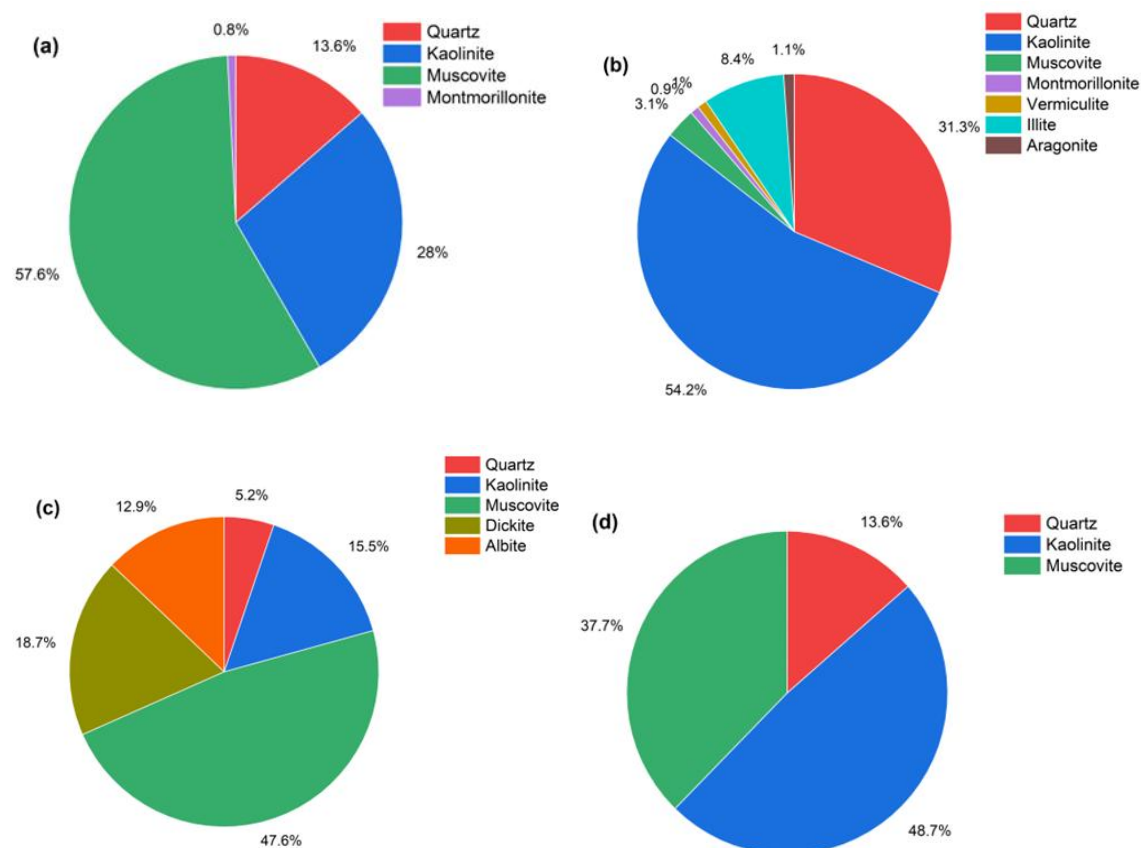
The objective of XRD analysis in coal is to identify and quantify the mineral constituents, assess the degree of crystallinity of carbonaceous matter, and examine the structural transformations that occur during coal formation, by elucidating the crystalline and amorphous phase, XRD facilitate the deeper understanding of coal's inorganic component, which helps in paleoclimate and paleodepositional reconstruction (Panda et al., 2025; Pillai et al., 2023).

XRD is a powerful tool for determining the crystalline phase present in the coal samples. The mineral phase identified by XRD analysis can be of two types of origin: syngenetic (formed during the coal formation) and epigenetic (formed after the coal formation). Based on the XRD analysis, all the coal seams show distinct mineral phases present in coals. Quantification of XRD analysis has been performed using Rietveld refinement (Rietveld, 1969; Ward et al., 2002).

4.7.4.1 Occurrence and distribution of mineral matter in Sohagpur coals

Quartz, a common silicate mineral, is present in all mines, with the highest concentration recorded in Damini V at 35.40%, indicating significant sand or detrital input in that seam. Kaolinite, a dominant clay mineral, appears prominently in all samples, especially in Khairaha VII (59.30%) and Damini V (56.10%), suggesting intense chemical weathering and leaching in the depositional environment. Muscovite, mica group mineral, is also widely distributed, with peak values in Sharda (57.50%), Amalai (50.40%), and Rajendra (47.60%), suggesting a significant contribution from metamorphic or igneous sources. Montmorillonite is sparsely present, recorded only in Dhanpuri (0.90%) and Sharda (0.80%), while vermiculite, often formed through mica weathering, recorded solely in Dhanpuri (1.00%). Illite, another clay mineral associated with low-grade metamorphism or diagenesis, occurs in several seams, indicating a widespread diagenetic alteration of clay minerals. Aragonite, a carbonate mineral often formed in chemical precipitate environments. Dickite, a high-temperature polymorph of kaolinite, is found exclusively in Rajendra (18.7%), suggesting localized hydrothermal activity or alteration. Albite, a feldspar mineral, appears only in Rajendra (12.9%), indicating unique sedimentary input or low-grade metamorphic influence in that seam. Antigorite, a member of the serpentine group usually found in ultramafic rock settings, is recorded solely in Khairaha VII (14.5%), implying a possible contribution from such rock types in that region. Anatase, a titanium oxide mineral, is notably absent from all samples except Damini V (1.4%), suggesting minimal heavy mineral enrichment or specific diagenetic conditions required for its formation. Mine-wise, Amalai is dominated by muscovite (50.40%) and kaolinite (29.70%) with significant quartz (19.80%), indicating a clay- and mica-rich composition. Bangwar features high kaolinite (43.90%), quartz (25.30%), and an exceptionally high illite content (30.70%), suggesting to moderate diagenetic transformation. Dhanpuri has

kaolinite (54.20%) and quartz (31.30%), reflecting a complex depositional and post-depositional environment. Damini V is rich in kaolinite (56.10%) and quartz (35.40%). Damini VI shows a more balanced mix of quartz (30.00%), kaolinite (27.60%), and muscovite (24.50%), with small amounts of illite and aragonite, reflecting a varied source material. Khairaha VI contains high kaolinite (48.50%) and muscovite (37.50%) but lower quartz (13.50%), indicating a less sandy, more clay-rich environment. Khairaha VII has the highest kaolinite content (59.30%). Rajendra is distinctive with very low quartz (5.20%) but high muscovite (47.60%), Dickite (18.70%), and a unique presence of Albite (12.90%), suggesting strong chemical alteration or diagenesis. Sharda is dominated by muscovite (57.50%), kaolinite (28.00%), and quartz (13.60%), with minor montmorillonite, reinforcing its clay-rich nature. Figure 4.14 shows the distribution of minerals in Sohagpur coals on a pie chart.



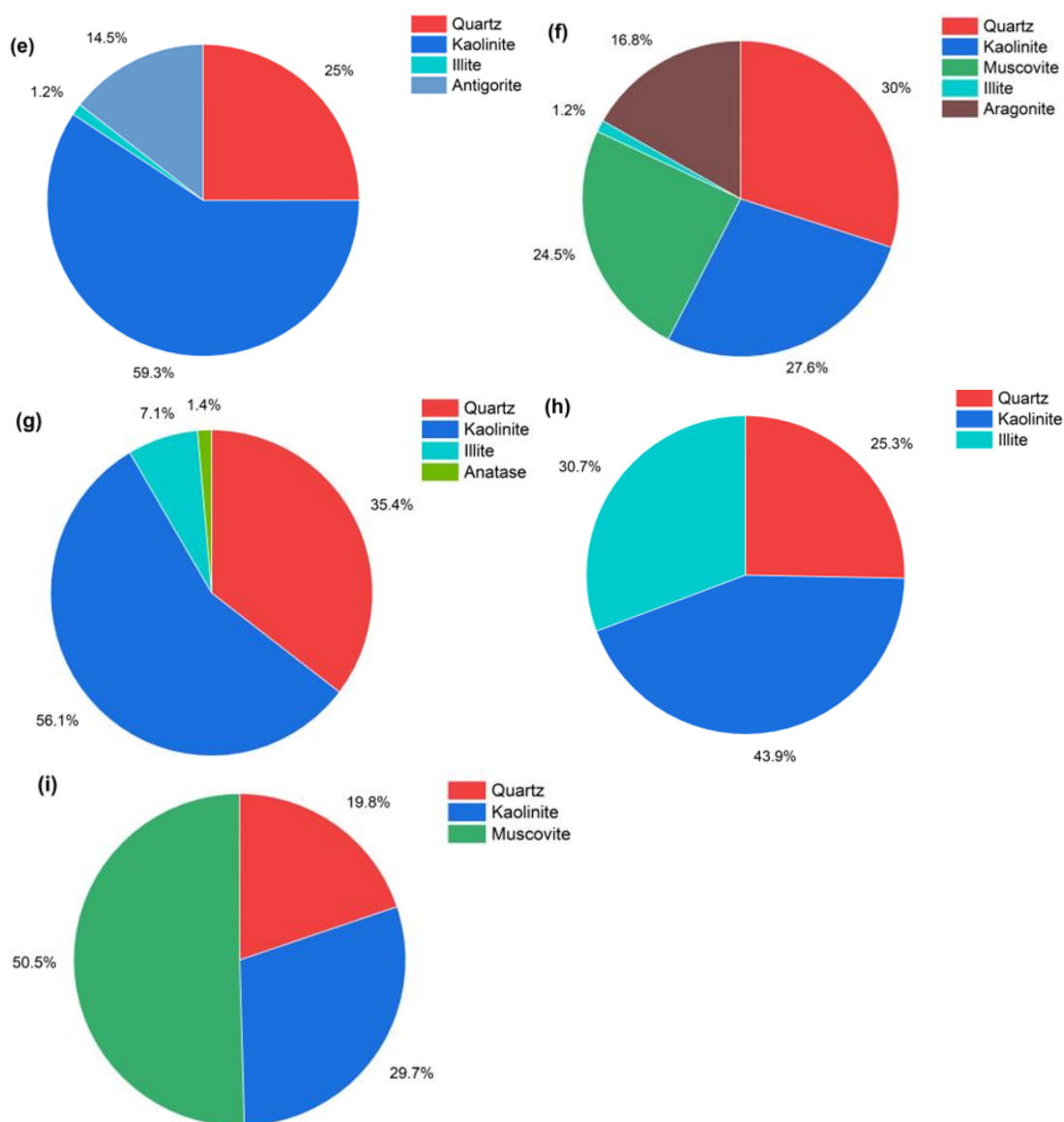


Figure 4.14 Pie chart representing the quantitative presence of mineral in each mine/seam (a) Sharda, (b) Dhanpuri, (c) Rajendra, (d) Khairaha VI, (e) Khairaha VII, (f) Damini VI, (g) Damini V, (h) Bangwar, and (i) Amalai.

4.7.5 Fourier Transform Infrared (FTIR) Spectroscopy of Sohagpur coals

FT-IR (Fourier Transform Infrared) analysis is a technique used to identify the functional groups and chemical bonds in coal by measuring its infrared absorption spectrum. FT-IR is one of the oldest and most efficient spectroscopic techniques for identifying the organic and inorganic functional groups present in coals. Scientists across the world use this technique to identify organic and inorganic functional groups (Painter et al. 1985;

Sobkowiak and Painter 1992; Walker and Mastalerz 2004; Mastalerz et al. 2010; Painter et al. 1982; Sharma and Wadhwa 1997; Singh 2004).

Fourier Transform Infrared (FT-IR) spectroscopy is an essential analytical technique for understanding the chemical composition of coal. It provides detailed information about the various functional groups present within the coal matrix (Painter et al., 1985; Chen et al., 2015). These functional groups, including hydroxyl, carboxyl, carbonyl, methylene, and aromatic structures, are critical because they influence the surface reactivity of coal and its ability to adsorb gases such as coalbed methane (CBM). The presence and abundance of these groups determine factors such as polarity, hydrogen bonding potential, and overall adsorption capacity, which are vital for gas storage and extraction studies (Panwar et al., 2017a,b; Kumar et al., 2022; Li et al., 2024; Wang et al., 2025a).

In addition to organic functional groups, FT-IR also detects inorganic components in coal. Minerals such as carbonates, silicates, and sulphates exhibit distinct infrared absorption bands, allowing their identification. Understanding these inorganic constituents is important because they reveal the paleodepositional environment of the coal seam and help explain coal's geological history. Moreover, inorganic components detected by FT-IR complement other analytical methods such as ultimate analysis and X-ray diffraction (XRD). Ultimate analysis provides elemental composition, while XRD identifies crystalline mineral phases. Integrating these techniques gives a comprehensive understanding of both the organic and inorganic functional groups of coal.

4.7.5.1 Occurrence and distribution of functional groups in Sohagpur coals

In the present day, this is one of the most important tools to use in coal characterization, especially in coal combustion, coke making process, and amphiphilicity character of coal (Guo and Bustin 1998; Dutcher and Crelling 2000; Yaman et al. 2001; Vandenbroucke

2003; Mastalerz et al. 2010; Yao et al. 2012; Zodrow et al. 2012; Balachandran 2014, Kishor et al 2025b, Srivastava et al. 2025).

The FT-IR peaks were identified based on the literature from previous studies, for which the wavenumber (cm^{-1}) assignment for each peak, as shown in Figure 4.15, and details are given in Table 4.20.

Table 4.20 Wavenumber and their associated functional groups present in Sohagpur coals (Painter et al., 1985; Mastalerz et al., 2010; Chen et al., 2015).

Peak No.	Wavenumber (cm^{-1})	Assignment
1	~3692	Kaolinite
2	~3620	Kaolinite
3	~3400	OH Stretching
4	~3010	Aromatic C-H
5	~2950	Aliphatic CH ₃
6	~2920	Aliphatic CH, CH ₂ and CH ₃
7	~2850	Aliphatic CH, CH ₂ and CH ₃
8	~1690-1720	C=O, ketone, aldehyde, and -COOH
9	~1600	Aromatic ring stretch
10	~1450	CH ₂ and CH ₃ bend, possibility of some aromatic ring modes
11	~1375	CH ₃ groups
12	~1100-1300	C-O stretch and O-H bend in phenoxy structures, ethers
13	~1100	Aliphatic ethers, alcohols
14	~1035	Kaolinite
15	~1000	Muscovite
16	~908	Kaolinite
17	~790	Quartz
18	~750	1,2-substituted, <i>i.e.</i> , 4 neighbouring H
19	~689	Kaolinite
20	~528	Kaolinite
21	~452	Quartz

The presented table summarizes FTIR (Fourier Transform Infrared) spectra, identifying characteristic transmittance peaks, their corresponding wavenumbers in cm^{-1} , and their spectral assignments to functional groups and mineral phases. This data is essential for the qualitative analysis of the sample's chemical and mineralogical composition. A total of 21 peaks were identified, spanning a wide spectral range from ~3692 cm^{-1} to ~452 cm^{-1} .

¹, providing comprehensive insights into organic and inorganic constituents of the material. The high-wavenumber region, particularly between $\sim 3692\text{ cm}^{-1}$ and $\sim 3620\text{ cm}^{-1}$ (peaks 1 and 2), exhibits sharp absorption bands characteristic of inner-surface hydroxyl (--OH) stretching vibrations specific to kaolinite. The presence of multiple --OH bands in this region is a strong indicator of kaolinite's well-ordered crystalline structure and its unique hydroxyl environments. Kaolinite is further confirmed by additional peaks at $\sim 1035\text{ cm}^{-1}$ (peak 14), $\sim 908\text{ cm}^{-1}$ (peak 16), $\sim 689\text{ cm}^{-1}$ (peak 19), and $\sim 528\text{ cm}^{-1}$ (peak 20). At $\sim 3400\text{ cm}^{-1}$ (peak 3), a broader absorption is observed, typically associated with O--H stretching vibrations from adsorbed or bound water molecules and possibly from hydroxyl groups present in various hydrous phases. This region may overlap with kaolinite hydroxyls but often reflects a more general water-related absorption. Peak 4 at $\sim 3010\text{ cm}^{-1}$ corresponds to aromatic C--H stretching vibrations, implying the presence of aromatic hydrocarbons or organic matter within the sample. Peaks 5 to 7 ($\sim 2950\text{ cm}^{-1}$, $\sim 2920\text{ cm}^{-1}$, and $\sim 2850\text{ cm}^{-1}$, respectively) represent symmetric and asymmetric stretching vibrations of aliphatic CH , CH_2 , and CH_3 groups. These features are indicative of saturated hydrocarbon chains, which could be part of organic matter, contamination, or possibly synthetic compounds. The region between ~ 1690 and 1720 cm^{-1} (peak 8) is significant, because it corresponds to C=O stretching vibrations in ketones, aldehydes, and carboxylic acid groups. This suggests the presence of oxidized organic matter or functional groups resulting from organic degradation or reaction with the environment. The adjacent peak at $\sim 1600\text{ cm}^{-1}$ (peak 9) is typically attributed to aromatic ring stretching or possibly C=C bonds, indicating further evidence of aromatic structures or unsaturated organic species. Peak 10, observed at $\sim 1450\text{ cm}^{-1}$, is associated with bending vibrations of --CH_2 and --CH_3 groups and may also include contributions from aromatic skeletal modes, particularly in substituted benzene rings. This may reinforce the presence of

complex organic matter. Peak 11, located at $\sim 1375\text{ cm}^{-1}$, is linked specifically to CH_3 bending modes and is common in both aliphatic and some aromatic compounds. The region from $\sim 1100\text{--}1300\text{ cm}^{-1}$ (peak 12) is complex and often exhibits overlapping bands from C–O stretching and O–H bending vibrations, especially in phenolic, ether, or alcohol-containing structures. This band is crucial in identifying oxygen-containing organic compounds and phenoxy structures. Similarly, peak 13 at $\sim 1100\text{ cm}^{-1}$ may indicate the presence of aliphatic ethers or alcohols, further complicating the organic phase. In terms of mineral identification beyond kaolinite, peak 15 at $\sim 1000\text{ cm}^{-1}$ is assigned to muscovite, a mica group phyllosilicate, whose Si–O stretching vibrations are typically centred around this region. The appearance of this peak suggests that the sample contains muscovite, either as a natural impurity or as a co-occurring phase with kaolinite. Quartz, a crystalline form of silica, is identified by two characteristic peaks: $\sim 790\text{ cm}^{-1}$ (peak 17) and $\sim 452\text{ cm}^{-1}$ (peak 21), corresponding to Si–O bending vibrations. These peaks are diagnostic of quartz and are commonly observed in soil, sedimentary, and clay samples. Additionally, peak 18 at $\sim 750\text{ cm}^{-1}$ is indicative of 1,2-disubstituted aromatic rings (i.e., benzene rings with two adjacent hydrogen atoms), providing further evidence of aromatic compounds within the organic matrix. The FTIR spectrum represented in Figure 4.15 confirms the coexistence of multiple mineral phases- primarily kaolinite, muscovite, and quartz, alongside a range of organic functional groups, including aliphatic chains, aromatic rings, hydroxyl, carbonyl, ether, and possibly carboxylic acid groups. The dominance of kaolinite-related peaks suggests it is the major mineral component, while the presence of muscovite and quartz indicates natural mineralogical complexity.

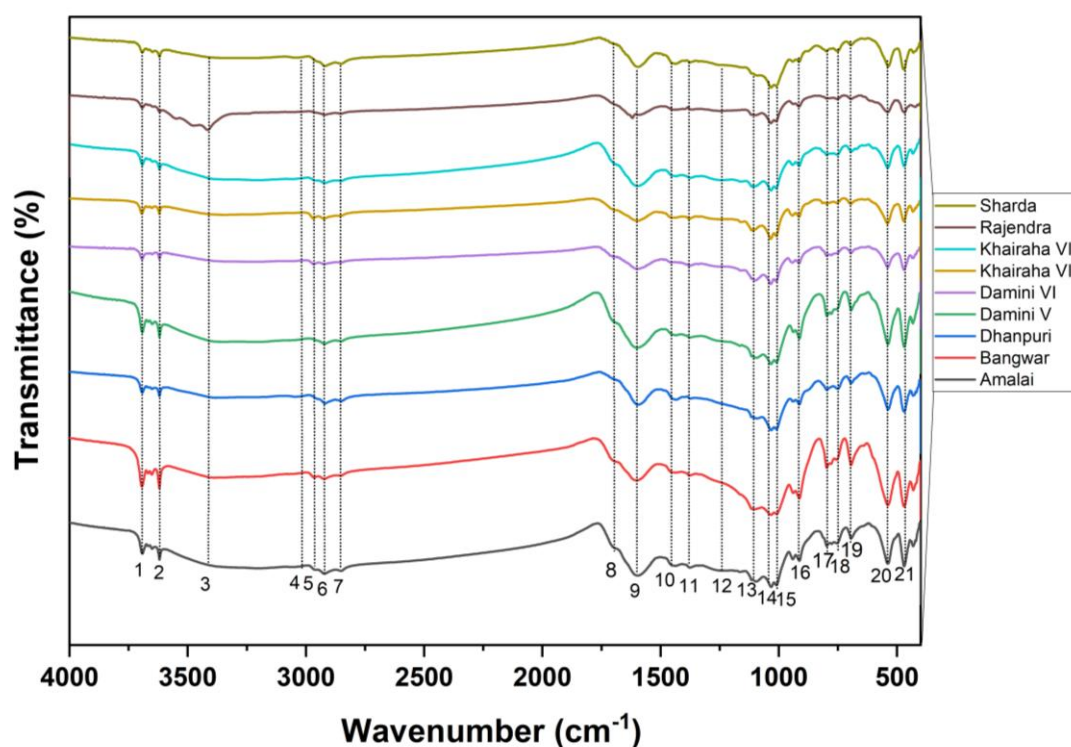


Figure 4.15 FT-IR spectra of Sohagpur coals.

4.8 Gas adsorption, pore and surface characterization

4.8.1 Low-Pressure Gas Adsorption (LPGA)

Gas adsorption is a fundamental phenomenon, that play a pivotal role in characterizing porous materials, such as coal (Sing 1985; Thommes et al., 2015). At its core, gas adsorption refers to the accumulation of gas molecules on the surface of a solid due to physical or chemical interactions. This process is particularly significant at low pressures, where the interaction between gas molecules and the surface is dominated by weak van der Waals forces, allowing detailed study of surface properties and porosity (Sing 1985; Thommes et al., 2015; Mastalerz et al., 2017; Hou et al., 2017). Low-pressure gas adsorption is widely employed to probe microporous and mesoporous structures, providing insights into surface area, pore volume, and pore size distribution, which are critical parameters for evaluating the storage and transport properties of coal (Sing 1985; Kumar et al., 2025b).

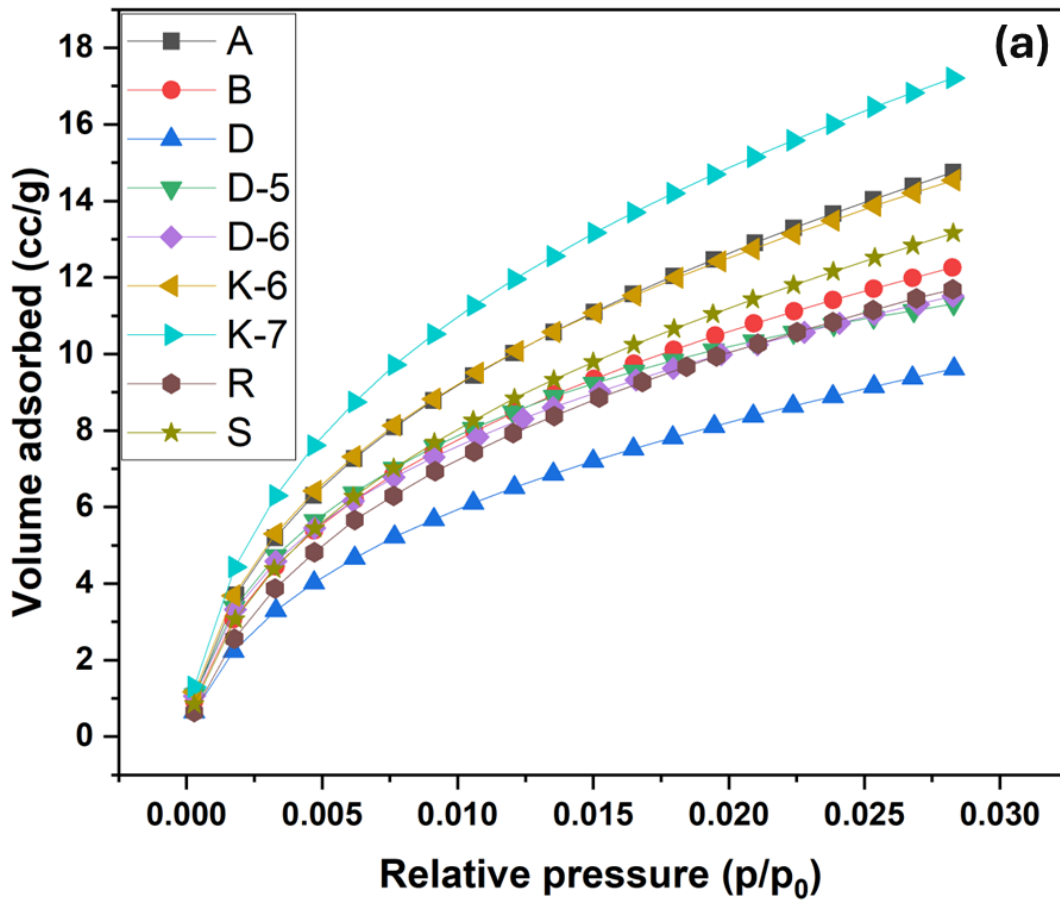
Gas adsorption can be broadly classified into two types: physical adsorption (physisorption) and chemical adsorption (chemisorption). Physisorption occurs through weak, reversible van der Waals forces without altering the chemical structure of the adsorbent, while chemisorption involves stronger, often irreversible chemical bonds between the adsorbate and the surface. Understanding the type of adsorption is essential, as it influences experimental conditions, adsorption isotherms, and interpretation of surface properties (Parera et al., 2012; Roquerol et al., 2014; Hazra et al., 2018; Kishor et al., 2025a).

Several factors affect gas adsorption, including temperature, pressure, surface area, pore structure, and the nature of both the gas and the solid (Mastalerz et al., 2007). Temperature and pressure govern the kinetic energy of gas molecules and their tendency to adhere to surfaces. Surface area and pore structure determine the extent of adsorption, with micropores exhibiting a highly adsorption potential due to confinement effects. Additionally, the chemical composition and surface functionality of the coal influence the adsorption capacity and selectivity for specific gases (Mastalerz et al., 2012; Li et al., 2016; Yan et al., 2020).

The study of gas adsorption is particularly important in coal science; it serves as a reliable method for pore characterization. Low-pressure gas adsorption techniques, such as nitrogen adsorption at 77 K and carbon dioxide at 273 K, allow precise determination of specific surface area, pore volume, and pore size distribution, which are crucial for understanding gas storage, permeability, and transport in coal seams (Sing 1985; Thommes et al., 2015). These parameters have direct implications for coalbed methane adsorption and enhanced coalbed methane recovery.

LPGA analysis was performed to measure the pore attributes in the coal samples. Two different adsorbates were used in this analysis. Nitrogen (N_2) was used for the mesopore and to some extent up to the macropore, while carbon dioxide (CO_2) was used for the micropores.

The N_2 isotherm was plotted over a range of relative pressure range of up to 1.00, while the CO_2 isotherm ranges from 0.0003 to 0.03. Non-Local Density Functional Theory (NLDFT) has been used to calculate the pore parameters of micropores, and the Brunauer–Emmett–Teller (BET) and Barrett-Joyner-Halenda (BJH) methods have been used to determine the specific surface area (SSA), pore size distribution (PSD), average pore diameter (APD), and total pore volume (TPV) of mesopores and macropores of coal.



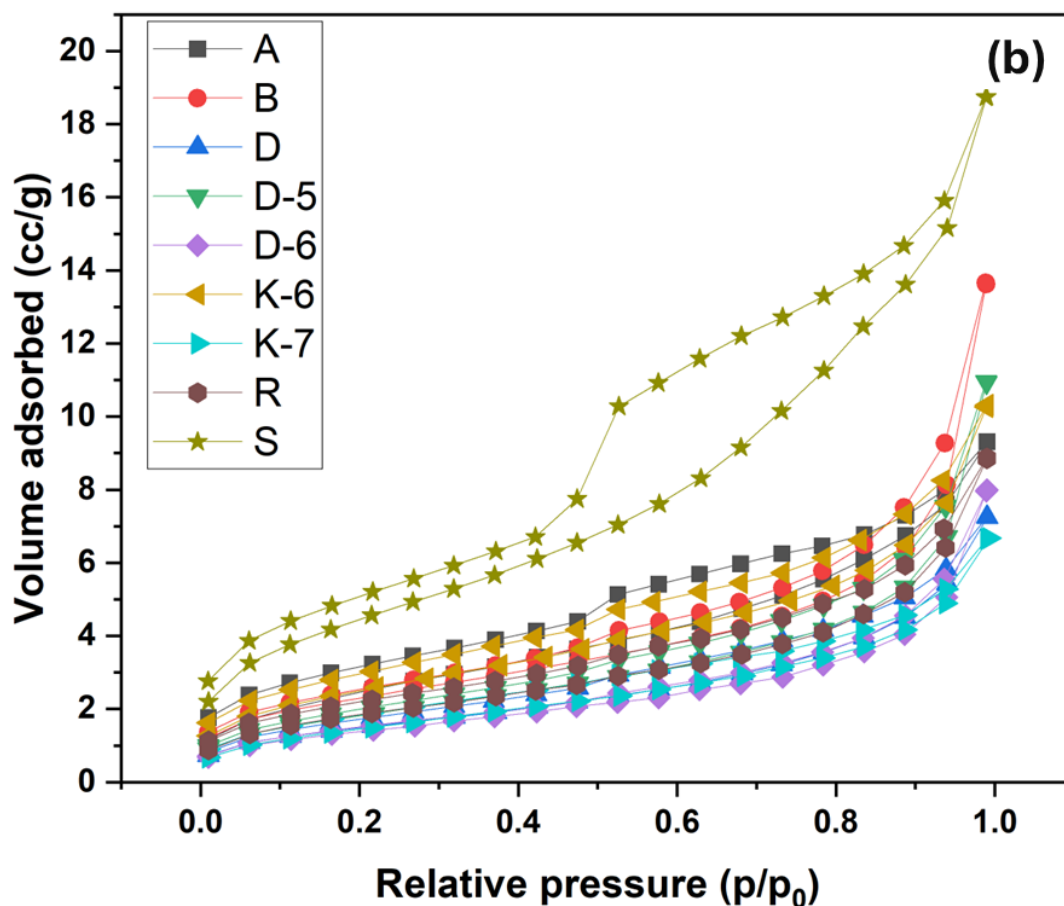


Figure 4.16 CO₂ adsorption isotherm (a), N₂ sorption isotherm (b), on the X-axis is the range of relative pressure, and the Y- axis represents the amount of volume adsorbed in these coals.

where A- Amalai, B- Bangwar, D- Dhanpuri, D-5 – Damini V, D-6 – Damini VI, K-6 – Khairaha VI, K-7 – Khairaha VII, R- Rajendra and S- Sharda.

Figure 4.16 describes that the N₂ sorption isotherm belongs to the Type IIB category, which encompasses both mesopores and macropores, while the CO₂ adsorption isotherm falls into the IUPAC Type I category, which characterizes the material as microporous (Rouquerol et al., 2014). According to Rouquerol et al. (2014), during N₂ sorption, powdered geological material (such as cements, clay, etc.) falls in the Type IIB isotherm, which combines the IUPAC type II and H3 hysteresis loop. When the pore width is more than 4 nm, a hysteresis loop is observed in the material with mesopores, whereas Type II is indicative of macropores (Thommes et al., 2015). The tensile strength effect, which also accounts for a large portion of the presence of smaller mesopores in these coals, is

responsible for the abrupt drop in the N₂ isotherm after desorption in the range of 0.4 to 0.5 (Groen et al., 2003).

The Dubinin-Radushkevich (DR) model, Dubinin-Astakhov (DA), and Density Functional Theory (DFT) were used to process the CO₂ adsorption data. As previously mentioned by Kumar et al. (2025b), the DR model was used to determine the micropore surface area, which varies from 99.429 to 174.38 m²/g, the DA model was used to determine the micropore volume, which ranges from 0.042 to 0.077 cc/g, and the DFT and DA models were used to characterize the pore size. The Brunauer–Emmett–Teller (BET) equation was utilized to process the N₂ adsorption data. The BET surface area ranged from 5.128 to 16.252 m²/g.

The BET method is used to obtain information on multilayer adsorption, which is the and extension of Langmuir adsorption. The BET model is used to calculate the surface area, and the following equation is used in this model-

$$\frac{1}{V \left(\frac{p_o}{p} - 1 \right)} = \frac{1}{V_m C} + \frac{C - 1}{V_m C} \left(\frac{p}{p_o} \right)$$

Where p is the pressure, V is the adsorbed volume, p/p_o is the relative pressure, V_m is the volume adsorbed as a monolayer, and C is the net heat adsorption constant.

The Dubinin method assumes that adsorbate molecules fill the micropore space. For this technique, the D-R and D-A models were used for the surface area and volume of the micropore, respectively. The equations of the D-R and D-A methods are as follows-

D-R method

$$W = W_o \exp \left[- \left\{ \left(\frac{RT}{\beta E} \right) \ln \left(\frac{p_o}{p} \right) \right\}^2 \right]$$

D-A method

$$W = W_o \exp\left[-\left\{\left(\frac{RT}{\beta E}\right) \ln \left(\frac{p_o}{p}\right)\right\}^n\right]$$

Where W is the pore volume filled at relative pressure, W_o is the total volume of the micropores, β is the sorbate affinity coefficient, E is the characteristic energy, R is the ideal gas constant, T is the temperature, and p_o/p is the inverse of the relative pressure.

The DFT model can be used to characterize the pores of micro and mesopores. The model involves two steps process. Initially, the kernel is generated from the test data to determine the pore size distribution, which is used as a reference for subsequent calculations. After which pore size distribution is obtained and an integral adsorption equation corresponds to the kernel. Below is the equation used in the DFT model-

$$N\left(\frac{p}{p_o}\right) = \int_{D_{min}}^{D_{max}} N\left(\frac{p}{p_o}, D\right) f(D) dD$$

Where $N(p/p_o)$ is the number of moles adsorbed at pressure P , D is the pore size in nanometres, $N(p/p_o, D)$ is the kernel obtained from the theoretical isotherms with different pore widths, and $f(D)$ is the pore size distribution of the heterogeneous solid adsorbent.

The Barrett–Joyner–Halenda (BJH) model uses the Kelvin equation to calculate the pore volume, which ranges from 0.009 to 0.026 cc/g. The DFT model, which is better suited to mesopores, yields pore volume values ranging from 0.009 to 0.025 cc/g. Both the DFT and BJH models are used to characterize the pore size. DFT is used to characterize pores up to 36 nm in mesopore ranges, while BJH is used for the entire mesopore range and smaller macropores found in coal samples. Table 4.21 lists the different pore characteristics derived from the N_2 and CO_2 isotherms.

Table 4.21 Pore attributes obtained from CO₂ and N₂ isotherms for Sohagpur coals.

Sample name	CO ₂ Isotherm		N ₂ Isotherm		
	DR Micropore Surface Area (m ² /g)	DA Micropore Volume (cc/g)	BET Surface Area (m ² /g)	BJH Pore Volume (cc/g)	DFT Pore volume (cc/g)
Amalai	150.075	0.073	9.207	0.012	0.013
Bangwar	123.857	0.054	8.325	0.019	0.017
Dhanpuri	99.429	0.048	5.474	0.01	0.01
Damini V	112.715	0.042	6.755	0.015	0.014
Damini VI	111.298	0.048	5.128	0.011	0.01
Khairaha VI	145.308	0.07	9.15	0.013	0.012
Khairaha VII	174.38	0.077	5.575	0.009	0.009
Rajendra	129.069	0.053	6.751	0.012	0.012
Sharda	137.338	0.067	16.252	0.026	0.025

4.8.2 Small Angle X-Ray Scattering

Small-Angle X-Ray Scattering (SAXS) has emerged as a powerful technique for analyzing nanoscale pores in coal. SAXS operates by measuring the scattering of X-rays from electron density variations within the material, allowing determination of pore size distributions, shapes, and specific surface areas (Radlinski et al., 2004; Zhao et al., 2014). Unlike gas adsorption methods, which rely on model assumptions to infer pore volumes from adsorption isotherms, SAXS directly measures structural features non-destructively and provides statistically averaged data over the bulk sample (Radlinski et al., 2004; Zhao et al., 2014). Compared to MIP, which is primarily sensitive to meso- and macropores and may alter fragile coal structures under high pressure, SAXS preserves the native pore network and is particularly suited for investigating micropores that govern adsorption-driven processes (Jiang et al., 2019; Kumar et al., 2025b). SAXS can provide the pore size distribution of open and closed pores present in coal samples from the x-ray scattering profile, whereas other gas adsorption only relies on open pores, where gas can easily insert (Chandra et al., 2020; Bal et al., 2024).

The presence of mineral matter also affects the pore size distribution, depending on the type of mineral present in the coal, and it contributes to scattering signals. If rigid

minerals like Quartz are abundant, then pores can be reduced, whereas clay minerals, such as Kaolinite, which provide sheet-like pores, tend to detect more pores present in the coal samples.

From the CBM extraction perspective, nanoscale pores characterized by SAXS are crucial for coalbed methane extraction. These pores dominate methane adsorption capacity and strongly influence desorption kinetics, while their connectivity governs gas diffusion through the coal matrix. Detailed knowledge of pore size distribution, morphology, and connectivity supports improved modelling of gas transport, prediction of reservoir performance, and design of extraction strategies (Chandra et al., 2020; Kumar et al., 2025b). SAXS-based pore characterization, integrated with other methods, therefore provides a robust framework for linking coal microstructure to macroscopic gas transport and storage behaviour, bridging fundamental understanding and practical applications (Li et al., 2020; Bhapker et al., 2023).

Small-Angle X-ray Scattering (SAXS) measurements for the coal samples were analysed using the MATLAB-based MATSAS script. This computational tool facilitated the extraction of the scattering intensity (I) as a function of the scattering vector (Q), producing $I(Q)$ profiles that are fundamental to understanding the samples internal nanostructure. The scattering profiles in the script are calculated by using Scattering Length Density (SLD) and mean density for each coal sample, which are critical parameters for accurate interpretation of the SAXS data.

For the analysis, void spaces-representing pores within the coal matrix-were assigned an SLD value of zero, following the assumptions described by Kumar et al. (2025b). This convention allows for a clearer distinction between the solid matrix and pore spaces, as SAXS is inherently sensitive to variations in electron density. The resulting I vs. Q

profiles are shown in Figure 4.17 and serve as the basis for further characterization of pore structure.

The MATSAS script processes the SAXS data to identify and quantify various pore attributes, specifically in the mesoporous (2–50 nm) and macropores (>50 nm) regimes. Since SAXS does not rely on gas adsorption or liquid intrusion, it is particularly effective at probing both accessible (open) and inaccessible (closed) pores- features that are often overlooked or underestimated by other porosimetry methods (Bal et al., 2024; Chandra et al., 2020). This capability makes SAXS a powerful tool for comprehensive pore structure analysis, particularly in complex materials such as coal.

Based on the SAXS results, several pore characteristics have been quantified, and the data are summarized in Table 4.22. The mesopore surface area among the analyzed samples ranges from 7.574 to 52.189 m²/g, indicating considerable variability in the mesoporous content across different coal types. Similarly, the macropore surface area ranges from 1.033 to 2.858 m²/g. In terms of pore volume, the mesopores contribute between 0.014 and 0.059 cm³/g, while the macropore volume spans from 0.015 to 0.050 cm³/g. These variations suggest differences in pore development, connectivity, and heterogeneity among the coal samples, likely influenced by their geological origin, rank, and thermal maturity.

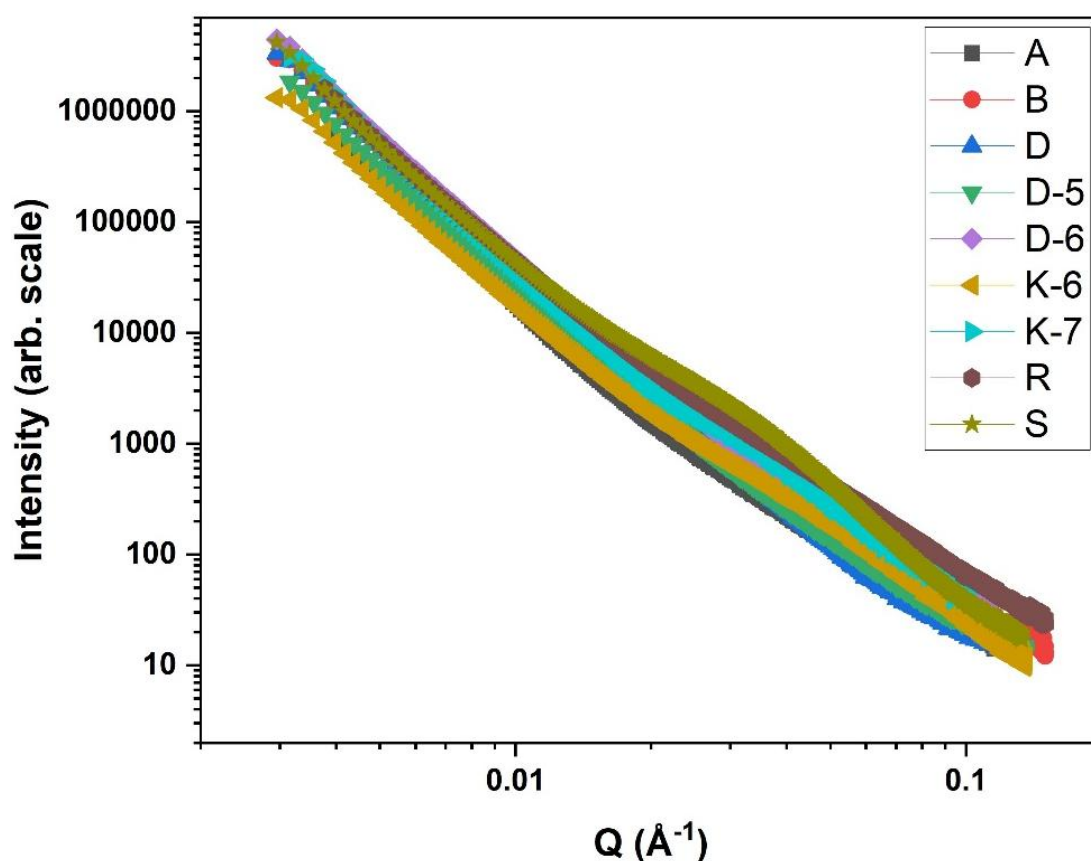


Figure 4.17 Intensity scattering profile of coal samples by SAXS analysis.

where A- Amalai, B- Bangwar, D- Dhanpuri, D-5 – Damini V, D-6 – Damini VI, K-6 – Khairaha VI, K-7 – Khairaha VII, R- Rajendra and S- Sharda.

Table 0.22 Pore attributes obtained from SAXS analysis of Sohagpur coals.

Code of Samples	Total Pore Area, m ² /g	Macropore Area, m ² /g	Mesopore Area, m ² /g	Total Pore Volume, cc/g	Macropore Volume, cc/g	Mesopore Volume, cc/g
Amalai	10.803	1.072	9.731	0.030	0.015	0.014
Bangwar	30.593	2.858	27.736	0.088	0.048	0.040
Dhanpuri	9.850	2.275	7.574	0.058	0.041	0.017
Damini V	14.142	1.572	12.570	0.046	0.027	0.019
Damini VI	16.067	2.785	13.283	0.076	0.050	0.026
Khairaha VI	17.304	1.033	16.271	0.039	0.018	0.022
Khairaha VII	19.465	2.728	16.736	0.077	0.047	0.031
Rajendra	54.454	2.265	52.189	0.094	0.035	0.059
Sharda	31.591	2.485	29.106	0.093	0.046	0.047

4.8.3 Mercury intrusion porosimetry

Mercury intrusion porosimetry (MIP) is a widely used technique for characterizing the pore structure of coal. The method relies on the principle that mercury is a non-wetting liquid, meaning it does not spontaneously enter pores due to surface tension. To penetrate

the pores, external pressure must be applied. The pressure required is inversely proportional to the pore diameter, a relationship described by Washburn's equation. In this way, smaller pores require higher intrusion pressures, allowing researchers to estimate pore sizes from the measured pressures (Li et al., 2018; Jiang et al., 2019; Wang et al., 2025b; Kumar et al., 2025b).

Coal contains a complex network of pores, typically classified as macropores (>50 nm), mesopores ($2\text{--}50$ nm), and micropores (<2 nm). MIP is particularly effective for detecting meso- and macropores, such as fractures, cleats, and matrix voids, which are important for gas storage and fluid transport (Zhang et al., 2023). However, it is less effective for micropores because extremely high pressures would be required, which could damage the sample.

Mercury intrusion porosimetry (MIP) is highly significant for coalbed methane (CBM) reservoirs because it provides critical information on pore structure and porosity which directly control gas storage and flow (Ma et al., 2018; Xu et al., 2024). In CBM reservoirs, methane is stored primarily in micropores of the coal matrix and flows through cleats and fractures (macropores and mesopores) to reach production wells (Laxminarayana and Crosdale 1999). MIP allows us to quantify the volume, size distribution, and connectivity of meso- and macropores, which are essential for understanding how easily methane can migrate through the coal seam. Knowing the pore size distribution enables estimation of gas storage capacity and effective drainage pathways, both of which are key for reservoir evaluation and production forecasting (Li et al., 2018, 2020; Ma et al., 2018; Xu et al., 2024).

As the LPGA provides the pore size characterization up to 110nm and SAXS also provides an almost similar range of pores, the main difference is that LPGA is only

capable of detecting the open pores present in coal samples, while SAXS detects accessible as well as non-accessible pores (Chandra et al., 2020; Bal et al., 2024). Since these two methods only range up to hundreds of nm, MIP provides pore size distribution up to thousands of nm, which also covers the fractures and cleats present in coal samples. Smaller pores are responsible for gas adsorption, while larger pores, such as macropores, fracture and cleats, are responsible for gas flow within the CBM reservoir, as shown in Figure 4.18.

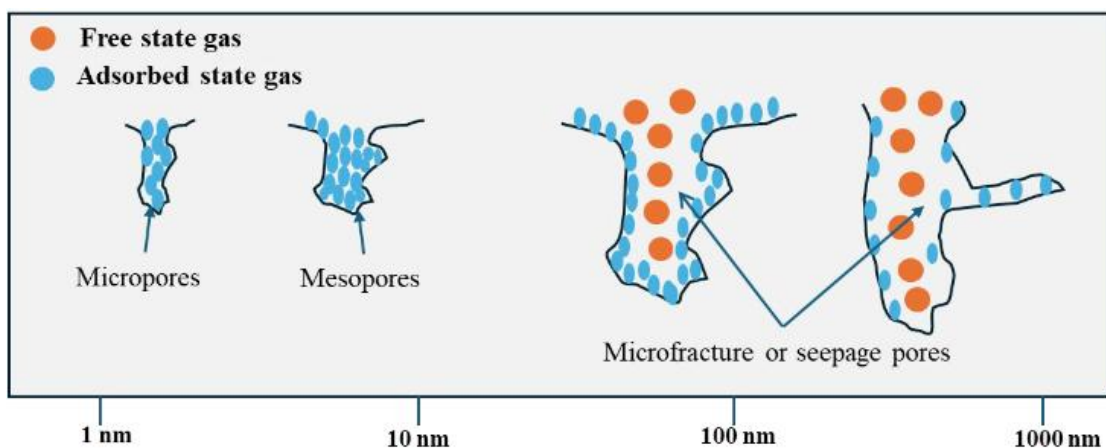


Figure 4.18 Pore size and respective adsorbed/free state for coal bed methane.

Mercury Intrusion Porosimetry (MIP) curves are also affected by the mineral matter on pore-throat systems. Clay mineral infilling reduces effective pore-throat diameters, which can be reflected in MIP data as a shift toward smaller throat sizes and a decrease in mercury-accessible porosity. Carbonate and pyrite concentrations can occlude or cement pore spaces, leading to higher entry pressures for mercury and reduced cumulative intrusion volumes. Additionally, pore blockage by mineral matter produces hysteresis between the intrusion and extrusion curves and an irregular pore-size distributions, indicating restricted connectivity and ink-bottle-type pores.

The mercury intrusion porosimetry (MIP) curve, in Figure 4.19, shows the relationship between applied pressure and the cumulative volume of mercury intruded into the coal samples. Each sample exhibits a distinct intrusion profile, reflecting differences in pore

structure. These variations highlight the heterogeneity in pore characteristics across the analyzed coal types. Mercury intrusion into the pore structure is controlled by capillary forces, with the applied pressure determining the size of pores that can be accessed (Bal et al., 2024). Smaller pores require higher pressures for mercury to overcome the surface tension barrier and enter, while larger pores are filled at lower pressures. The intrusion of mercury into pores of varying sizes is governed by capillary forces and the curvature of the liquid–gas interface, which dictates the pressure required for penetration. Each applied pressure corresponds to a specific pore diameter, making this approach fundamentally reliant on the Kelvin equation, which relates intrusion pressure to pore size. The instrument measures the volume of mercury entering the sample as pressure increases. The total volume of mercury intruded provides an estimate of the overall pore volume of the sample, while the pore throat radius is calculated using the Washburn equation, which incorporates both the applied pressure and the contact angle of mercury (Jiang et al., 2019; Kumar et al., 2025b). The pore characteristics were derived from the intrusion data using the Washburn equation. This equation relates the applied pressure to the pore radius, assuming cylindrical pore geometry, and considers the surface tension and contact angle of mercury. The Washburn equation is expressed as:

$$r = -2Y \cos \theta / P_{\text{Hg}}$$

In the above equation, where r is the pore radius, Y is the surface tension, which is 480.00 mN/m, θ is the contact angle of mercury on the porous material, which is 140° , and P is the pressure.

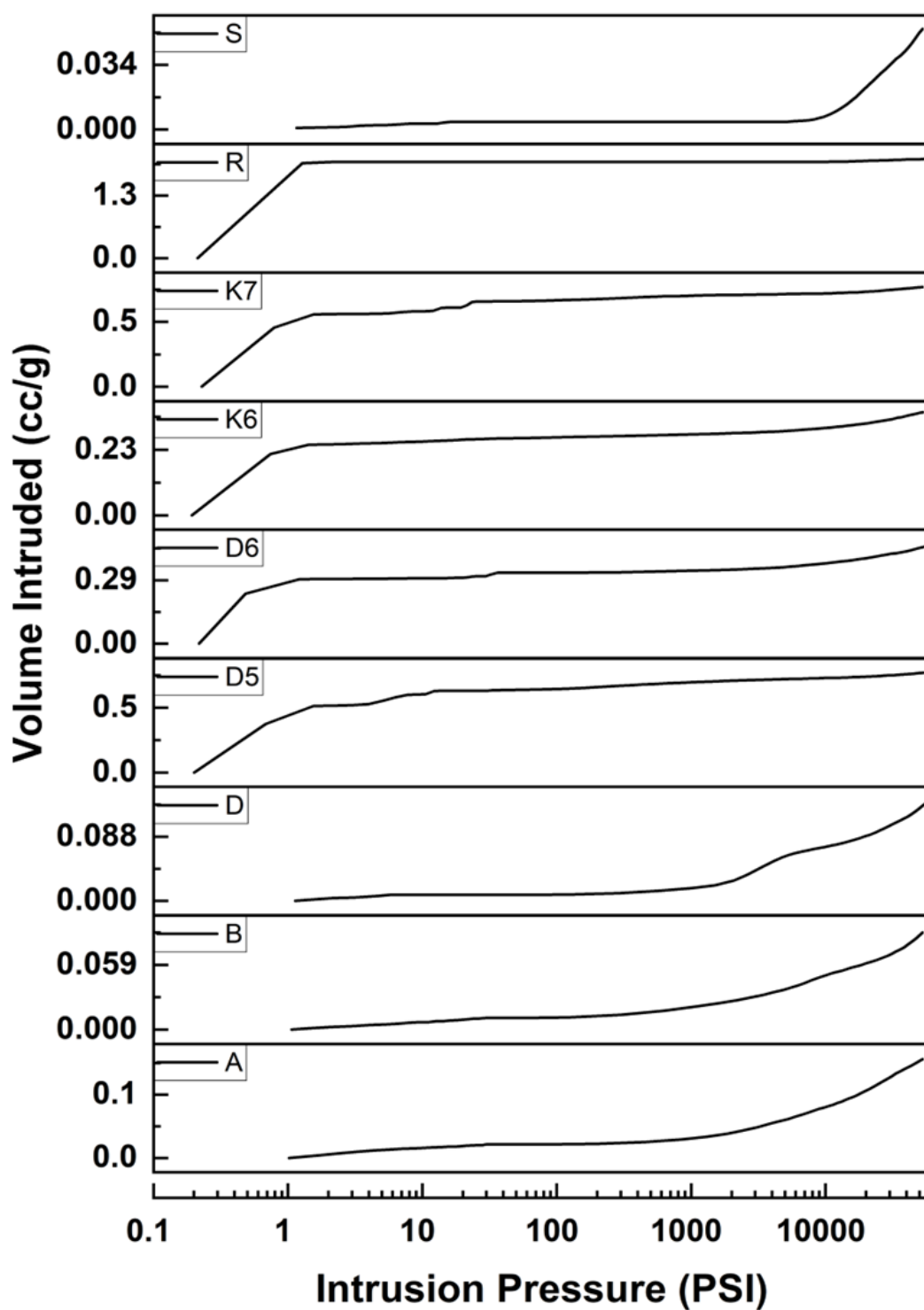


Figure 4.19 Mercury intrusion pressure vs mercury volume intruded graph for coal samples.

where A- Amalai, B- Bangwar, D- Dhanpuri, D-5 – Damini V, D-6 – Damini VI, K-6 – Khairaha VI, K-7 – Khairaha VII, R- Rajendra and S- Sharda.

4.8.4 High pressure CO₂ adsorption

Gas adsorption in coal is a critical process for understanding coalbed methane (CBM) recovery, CO₂ sequestration, and enhanced methane production (Bae and Bhatia 2006; Li et al., 2010; Wang et al., 2015). Coal is a naturally porous material with a complex network of micropores, mesopores, and macropores, which allows it to store gases such as methane, carbon dioxide, and hydrogen (Bakshi et al., 2020; Shukla et al., 2025). Gas adsorption occurs primarily through physical interactions between the gas molecules and the internal surfaces of coal, and the extent of adsorption is influenced by factors such as pressure, temperature, and pore structure (Sing 1985; Thommes et al., 2015).

High-pressure gas adsorption (HPGA) occurs at pressures typically above 1 MPa and is especially relevant to CO₂ storage or enhanced coal bed methane recovery. Under these pressures, the adsorption behaviour becomes highly non-linear, and standard adsorption models, such as the Langmuir isotherm, often require modification (Bae and Bhatia 2006; Tang and Ripepi 2017; Ma et al., 2018). High pressures allow coal to adsorb significantly more gas as molecules are forced deeper into micropores and mesopores; coal compressibility and pore deformation can further influence storage capacity. HPGA is of practical importance for predicting in situ gas storage, planning CBM extraction, and designing CO₂ sequestration strategies, as it reflects the actual gas adsorption potential under reservoir conditions (Li et al., 2010; Wang et al., 2015).

In contrast, low-pressure gas adsorption (LPGA) occurs at pressures below 1 MPa, typically in the kilopascal range, and is commonly used in laboratory settings to characterize pore size distributions and surface areas. At low pressures, adsorption is primarily confined to the pores, and pore deformation is negligible, and the measured adsorption reflects the intrinsic properties of the coal matrix. LPGA is therefore used for

BET surface area analysis, pore size distribution, of gas-coal interactions, rather than practical gas recovery predictions (Thommes et al., 2015; Hazra et al., 2018).

At high pressures, coal can adsorb significantly more gas, allowing accurate prediction of coalbed methane (CBM) production potential and CO₂ sequestration capacity. HPGA also accounts for interactions in larger pores and the effects of supercritical gases, giving insight into practical reservoir performance rather than just laboratory-scale surface characteristics. This makes HPGA essential for designing enhanced coalbed methane recovery (ECBM) strategies (Bae and Bhatia 2006; Tang and Ripepi 2017)

One major drawback of HPGA is that the coal structure may change under high pressures, leading to pore swelling, shrinkage, or deformation. These structural changes can affect adsorption behaviour, sometimes increasing gas uptake (pore expansion) and in other cases if pores collapse (Shukla et al., 2025). Such physical changes complicate the interpretation of adsorption data more complexly and can introduce uncertainties in predicting long-term gas storage and recovery (Wang et al., 2015).

Despite its advantages, HPGA has several limitations. Experimentally, it requires specialized high-pressure equipment, making it more costly and time-consuming than low-pressure experiments. HPGA data can be affected by coal heterogeneity and experimental conditions, leading to variability in adsorption measurements. Additionally, modelling adsorption at high pressures is more complicated, often requiring modified isotherms or supercritical adsorption models, which can introduce uncertainty if the coal's behaviour deviates from ideal assumptions.

The high-pressure CO₂ adsorption isotherms presented in Fig. 4.20 provide insight into CO₂ adsorption behaviour as a function of pressure, up to 50 bar (5000 kPa). Across the investigated pressure range, all samples exhibit a typical adsorption behaviour,

characterized by an increase in CO₂ uptake with increasing pressure, consistent with physisorption-dominated mechanisms on microporous or mesoporous materials. However, Sample S displays a notable deviation from this general trend. While it initially follows the same adsorption trajectory as the other samples, showing a progressive increase in CO₂ adsorption volume with pressure up to approximately 45 bar, a distinct decline in adsorption capacity is observed beyond this point. This anomalous behaviour may indicate the onset of pore saturation, structural rearrangement, partial pore collapse under high pressure, or changes in the dynamics of adsorbate-adsorbent interaction at elevated pressure.

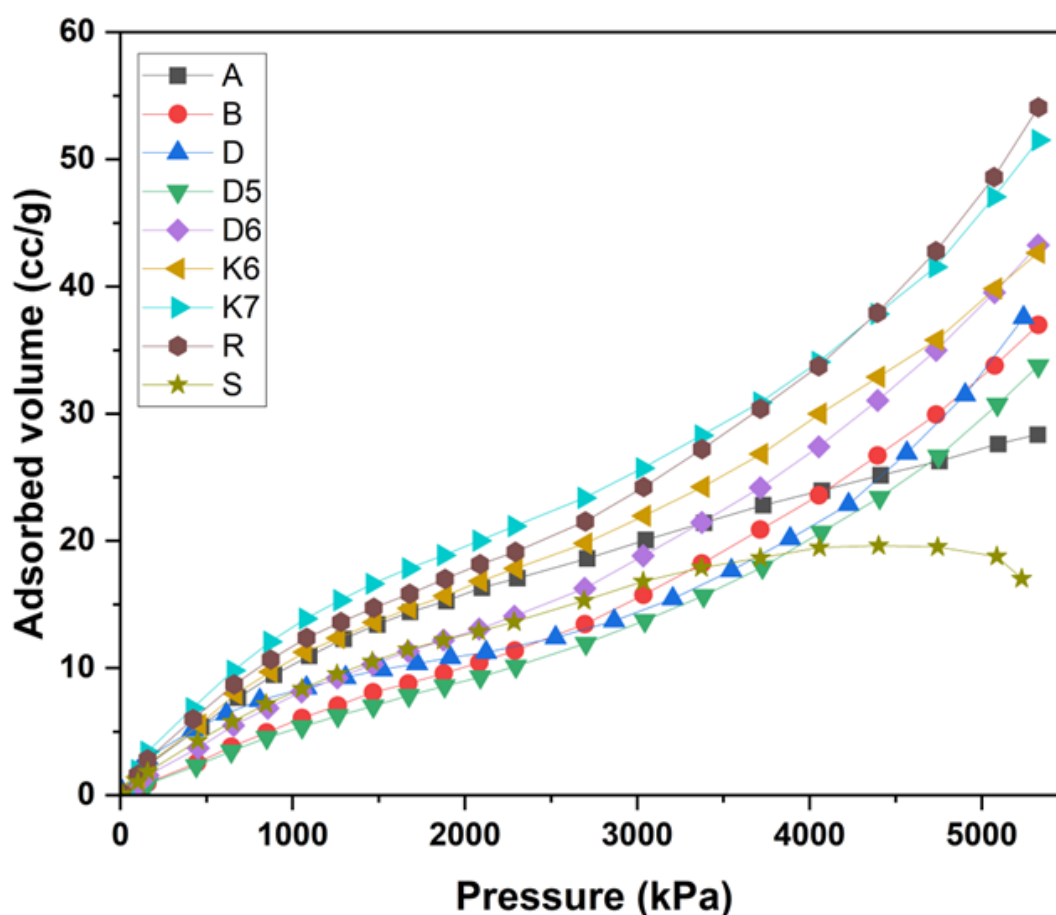


Figure 4.20 High-pressure CO₂ adsorption isotherm of coal samples.

4.8.5 Scanning electron microscopy

Scanning Electron Microscopy (SEM) is a powerful tool for visualizing the surface morphology and microstructure of coal at high magnifications, often ranging from

hundreds to hundreds of thousands of times (Creelman and Ward 1996). SEM allows direct observation of pores, microfractures, and cleat systems, providing information on pore shape, size, and connectivity (Gupta 2007; Zou et al., 2020). This makes SEM particularly valuable for understanding the microstructural controls on gas storage and transport in coal. Unlike indirect methods, SEM images reveal the actual spatial distribution of pores and microfractures, which are critical for gas adsorption and permeability (Nie et al., 2015; Zou et al., 2020).

As discussed earlier, Mercury Intrusion Porosimetry (MIP) data indicate the presence of numerous pores in coal, ranging in size from hundreds to thousands of nanometers. These meso- and macropores play a critical role in gas storage and transport, particularly as pathways for free gas (Laxminarayana and Crosdale 1999; Nie et al., 2015). Scanning Electron Microscopy (SEM) provides a complementary perspective by directly imaging these pores and microfractures at high magnification. The SEM images not only visually confirm the pore sizes suggested by MIP but also reveal their shapes, orientations, and interconnections, which MIP cannot capture. Moreover, SEM is extremely useful in identifying the cleat system and the natural fracture network in coal because it allows detailed observation of cleat patterns, spacing, and connectivity (Nie et al., 2015; Song et al., 2019; Xin et al., 2019; Zou et al., 2020).

Scanning Electron Microscopy is highly effective for examining the distribution of mineral matter and mineral–organic associations at the micro to nanoscale (Singh et al., 2015). SEM imaging reveals the spatial distribution, morphology, and textural relationships of minerals such as clays, carbonates, and pyrite within the organic matrix. When coupled with EDS (Energy-Dispersive Spectroscopy), SEM enables mineral identification and elemental mapping, allowing distinction between detrital, authigenic, and diagenetic minerals. SEM also helps identify mineral infilling, pore-lining, and pore-

bridging minerals, and their direct associations with organic matter, such as mineral encapsulation of organic particles or organic matter coating mineral surfaces (Singh and Singh 1995; Singh et al., 2015). This information can provide insights into pore development, mineral-controlled pore blockage, and the influence of mineral–organic interactions on reservoir quality and gas storage behaviour.

SEM provides direct visual and compositional evidence of mineral distribution, pore morphology, and mineral–organic associations, which can corroborate results from other analytical techniques. It visually confirms the presence of micropores and mesopores inferred from gas adsorption and reveals pore-throat geometry, mineral infilling, and blockage that explain MIP measurements of restricted connectivity and ink-bottle pores. SEM also supports SAXS by showing nanoscale pores and heterogeneities in pore shape, providing morphological context to the scattering data. Furthermore, SEM-EDS can validate mineral phases identified by XRD and their spatial relationships with the organic matrix, as well as confirm elemental concentrations observed by XRF, thereby highlighting how specific minerals influence pore development and connectivity. Together, SEM integrates micro to nanoscale observations with bulk and indirect measurements, enabling a comprehensive understanding of pore structure, mineral matter distribution, and mineral–organic interactions.

Despite its advantages, SEM has some limitations. It provides only surface images, which may not fully represent the 3D internal pore structure. Additionally, SEM cannot quantify a sample's pore volume or surface area.

Scanning Electron Microscopy (SEM) imaging of the sample provided detailed insights into the microstructural features, particularly highlighting the presence of microfractures and pores. The SEM images showed a complex network of microfractures characterized

by narrow, irregular cracks that traversed the material matrix, ranging in length from a few micrometres to several tens of micrometres (Song et al., 2019; Xin et al., 2019). These microfractures exhibited distinct edges and often showed branching or intersection points, indicative of stress concentration zones and the material's inherent brittleness or prior mechanical deformation. The fracture surfaces exhibited a rough texture in many areas, suggesting brittle fracture mechanisms, while some zones showed smoother, more polished surfaces, possibly related to shear or sliding actions along the cracks (Liu et al., 2017; Xin et al., 2019). Alongside the microfractures, numerous pores of diverse sizes and morphologies were clearly visible in the SEM images (Figure 4.21).

The pore system observed in the Sohagpur coal samples comprises pores ranging from a few to hundreds of micrometres, as revealed by SEM analysis. These pores predominantly occur as void spaces within the coal matrix, as shown in Figure 4.21c and 4.21d, commonly referred to as intraparticle pores (Figure 4.21a and 4.21b). Morphologically, the intraparticle pores display considerable variability, ranging from nearly spherical and sub-rounded forms to irregular, elongated, and interconnected geometries (Mou et al., 2021). The spatial distribution of pores within the coal matrix is markedly heterogeneous. Certain regions exhibit high pore density with enhanced interconnectivity, forming effective pathways for gas storage and migration, whereas other regions appear comparatively compact, characterized by isolated or poorly connected pores. This heterogeneity in pore structure is a critical factor controlling gas adsorption capacity, diffusion behaviour, and overall permeability of the coal seam.

These intraparticle pores play a fundamental role in coalbed methane (CBM) systems, as providing abundant surface area for methane adsorption. Additionally, their presence and connectivity are highly favourable for CO₂ sequestration in coal seams, particularly under

enhanced coalbed methane (ECBM) recovery scenarios (Roslin et al., 2020; Kishor et al., 2023b).

SEM observations further reveal the presence of well-developed microfracture networks within the coal samples. These microfractures exhibit an irregular reticular sub-pattern (I₂ type), consistent with the classification proposed by Su et al. (2001), and strongly support the tectonic origin of cleat and microfracture development as shown in Figure 4.21 d, e. The orientation and interlinking nature of these microfractures indicate that they were likely generated or enhanced by tectonic stresses acting on the coal seams after deposition.

The microfracture system is highly important for CBM production, as it serves as the primary conduit for gas flow from the microporous matrix to the wellbore. Moreover, these fracture networks significantly enhance permeability, thereby facilitating CO₂ injection and migration during ECBM operations (Gathitu et al., 2009; Liu and Nie, 2016; Zhang et al., 2017). Consequently, the combined presence of a well-developed intraparticle pore system and tectonically induced microfractures provides ample surface area for gas adsorption and thereby enhances the suitability of the Sohagpur coal seams for both methane extraction and long-term CO₂ sequestration.

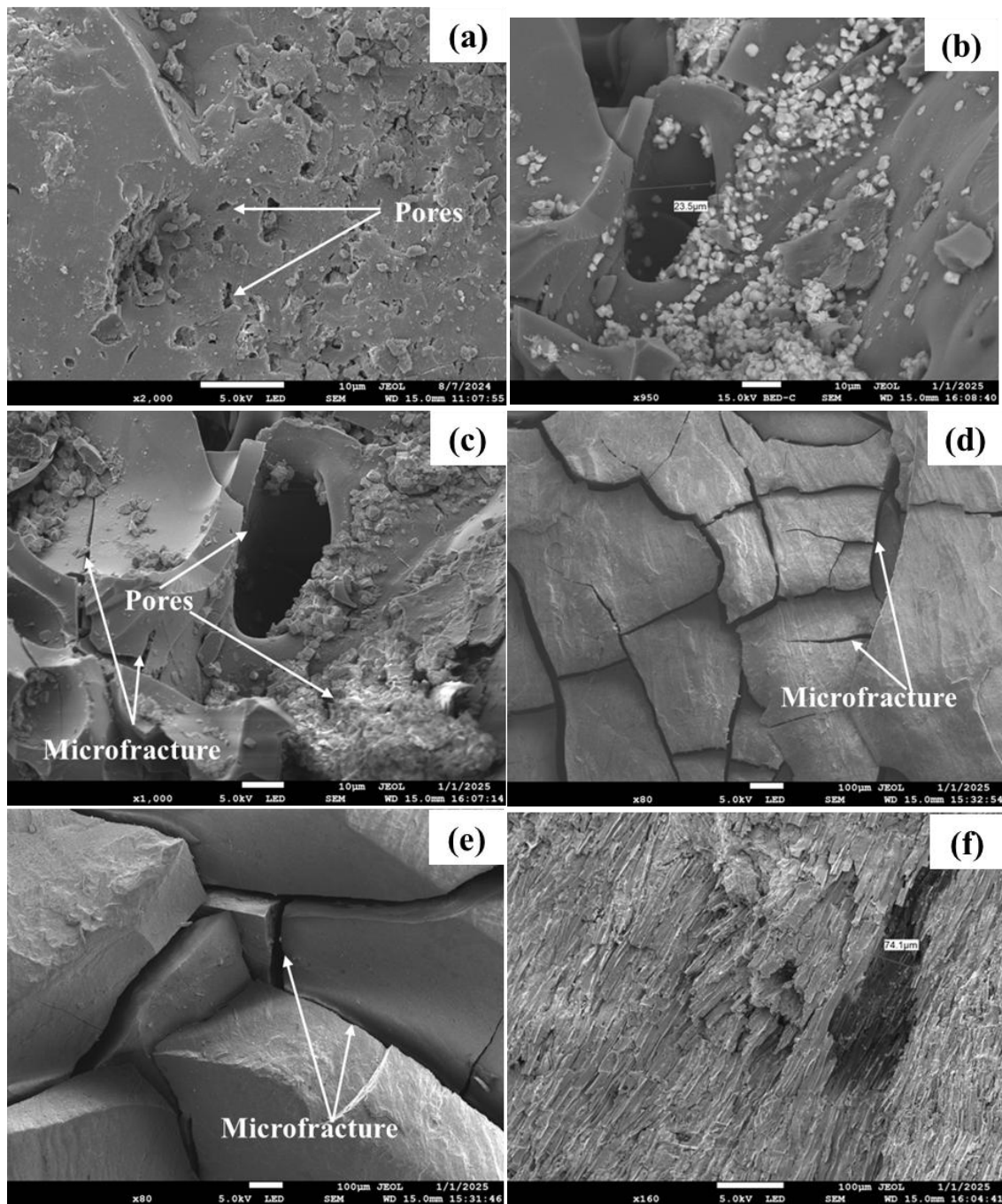


Figure 4.21 SEM images of coal samples showing numerous microfractures and pores present in the coal samples with varying length and size.

Chapter: 5

Maturation & Source Rock Potential with special reference to Coal Bed Methane

5.1 Introduction

Post-depositional subsidence affects physicochemical stage of coalification, which is known as the “maturation” or “rank” of organic matter. Temperature and pressure rise in response to the geothermal gradient and to the thickening of the overburden during subsidence and sedimentation. The lignite undergoes physicochemical alteration to become subbituminous coal, bituminous coal, semi-anthracite coal, anthracite coal, and finally meta-anthracite coal. The organic matter undergoes several changes during the diagenesis, catagenesis, and metagenesis processes, including changing micro constituents (Smith and Cook 1980; Chandra and Chakrabarti 1989), losing CO and CO₂ (Kopp and Bennett 2001), losing volatiles (Hayatsu et al. 1988; Kopp et al. 2000; Murchison 2004), and more. These changes also affects the organic matter’s petrographic and physicochemical characteristics (Gorbanenko and Ligouis 2014; Varma et al. 2018; Acharyya 2019). Fluorescence intensity measurement (for low-rank coal), carbon content, volatile matter, moisture content, calorific value, spore colour (Thermal Alteration Index/TAI), vitrinite/huminite reflectance, production index (PI), and T_{max} (°C) obtained by Rock-Eval Pyrolysis are some of the proxies that may serve as maturity indicators of the organic matter (Wilkins et al. 1992). Among all these parameters, vitrinite reflectance is the most widely used for the maturation.

The organic substances that make up coal may be able to produce liquid or gaseous hydrocarbons. A source rock is one that has produced or has the potential to produce significant amounts of hydrocarbons. Organic matter can be categorized as immature, mature, or over-mature in relation to its capacity for producing petroleum and

hydrocarbons. Any rock's stage as a source rock is determined by evaluating its bitumen, maturity level, kerogen (insoluble organic matter) type, and organic content both quantitatively and qualitatively. Another reliable technique for determining the level of organic matter maturation and measuring the amount of distillable compounds produced from the source rock is rock-eval pyrolysis.

The present study is undertaken to evaluate the thermal maturation and source rock potential of coal seams from the Sohagpur Coalfield, with special reference to their capability for Coal Bed Methane (CBM) generation. Coal Bed Methane is an important unconventional hydrocarbon resource, and its generation is closely related to the degree of coalification, organic matter type, and thermal evolution of coal seams (Rice, 1993). An assessment of these parameters is therefore essential for understanding the CBM potential of coal-bearing basins.

The Sohagpur Coalfield is part of the Gondwana basins of central India and contains thick, laterally persistent coal seams considered prospective for CBM generation (Mondal et al., 2021; Kishor et al., 2023b). However, the effectiveness of coal seams as methane source rocks depends on their rank and maturity, as methane generation in coals predominantly occurs during the medium- to high-rank stages of coalification (Tissot and Welte, 1984; Levine, 1993). Petrographic parameters such as vitrinite reflectance and maceral composition, along with geochemical characteristics, provide reliable indicators of thermal maturity and hydrocarbon generation potential.

Understanding the relationship between organic matter composition and coal rank is crucial for evaluating methane generation and retention within coal seams. Gondwana coals exhibit significant variability in maceral composition and maturity driven by differences in peat-forming environments and tectono-thermal history, which directly

influence their CBM prospectivity. A systematic evaluation of these aspects in the Sohagpur Coalfield is therefore necessary to identify coal seams with favourable conditions for methane generation and storage.

The maturity assessment of Sohagpur coals has been done with the help of chemical and petrological parameters. During the maturity assessment of Sohagpur coals, chemical parameters such as volatile matter (daf basis), rock eval data, and petrographic parameters, mean vitrinite reflectance, have been used.

5.2 Rank based on the chemical and petrological parameters

Vitrinite reflectance (R_o) is a crucial parameter for assessing coal maturation. In peat-forming environments, this gives information about the extent of coalification following the deposition of plant material (Taylor et al., 1998). In addition to vitrinite reflectance (R_o), another measure of coal rank is the volatile matter percentage (VM%) on a daf basis. As the rank rises, the VM content on a daf basis falls, and the sample with the highest volatile matter is classified as low-rank coal sample. In the coals of the Sohagpur coalfield, VM content on a daf basis ranges from 30.41 to 36.43%, R_o values range from 0.59 to 0.88, as shown in Table 5.1. These values indicate that coals from the Sohagpur coalfield are bituminous in nature, as shown in Figure 5.1, based on the ASTM classification scheme.

Table 5.1 Mean vitrinite reflectance % and VM % (daf) values of Sohagpur coals.

Sample Name	Mean R_o %	VM % (daf)
Sharda	0.71	32.74
Dhanpuri	0.78	30.41
Rajendra	0.62	34.99
Khairaha VI	0.59	36.83
Khairaha VII	0.64	33.19
Damini VI (1st Site)	0.87	32.80
Damini VI (2nd Site)	0.88	33.13
Damini V	0.68	36.29
Bangwar	0.64	35.30
Amalai	0.71	32.59

Rank	Refl Rm Oil	V.M. (daf) %	C. (daf)	Bed Moisture	Cal. value Btu/lb (kcal/kg)	Rank of Coals		Applicability of different rank parameters			
USA						V.M. (daf)	Refl Rm Oil				
Peat	0.2	68									
		64	Ca. 60	Ca. 75							
Lignite	0.3	60									
		56		Ca. 75	7200 (4000)						
Sub Bitu.	C 0.4	52									
	B 0.4	48	Ca. 71	Ca. 75	9900 (5500)						
C	A 0.5	44									
B	0.6	40	Ca. 77	Ca. 8-1.0	12600 (7000)						
A	0.7	36									
	0.8	32									
High Volatile Bituminous	1.0	28									
	1.2	24	Ca. 87		15500 (8650)						
Medium Volatile Bituminous	1.4	20									
	1.6	16									
Low Volatile Bituminous	1.8	12									
	2.0	8									
Semi Anthracite		4									
			Ca. 91		15500 (8650)						
Anthracite	3.0										
	4.0										
Meta- A.											

Figure 5.1 Rank of the Sohagpur coals based on the vitrinite reflectance (R_o) and volatile matter (daf basis) in the schemes representing the different stages of coalification according to ASTM classification (modified after Stach et al., 1982).

The scheme proposed by Kotter (1960) for rank determination using the maximum values of vitrinite reflectance (R_o %max) and volatile matter (daf%) as parameters, showed that coal from the Sohagpur coalfield ranges from the Gas Flammkohle to Gaskohle as shown in Figure 5.2.

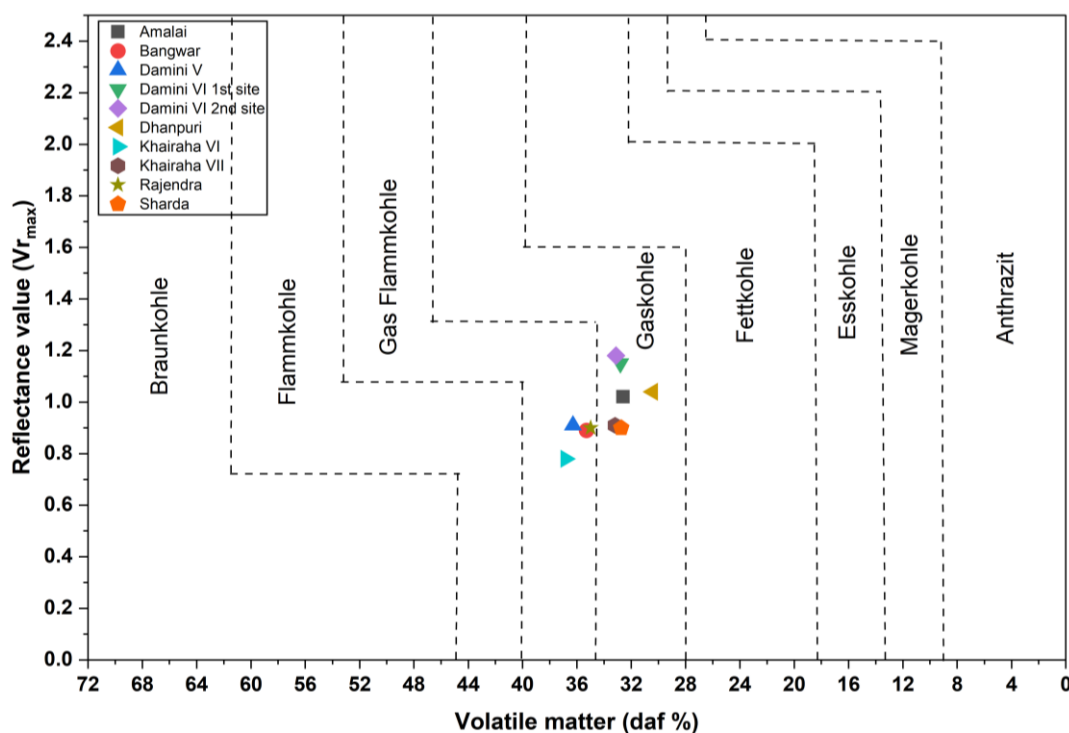


Figure 5.2 Rank of Sohagpur coals in the diagram proposed by Kotter (1960) using vitrinite reflectance and volatile matter (daf) as parameters.

5.3 Maturity assessment by the Rock Eval Pyrolysis method

Rock-Eval pyrolysis is a widely used geochemical technique for characterizing the quantity, type, and thermal maturity of organic matter present either as concentrated organic material (e.g., coal) or as dispersed organic matter (DOM) within sedimentary rocks. A key advantage of this method is that it enables direct analysis of organic matter within the rock matrix, eliminating the need for prior separation. Additionally, Rock-Eval enables the rapid, sequential analysis of a large number of samples under standardized thermal conditions.

The organic compounds released during thermal decomposition are quantitatively measured. Importantly, oxygenated compounds derived from mineral matter are excluded from analysis. The technique provides quantitative data on the distribution of volatile and non-volatile organic fractions, source rock hydrocarbon potential, and organic matter maturity.

The pyrolysis process begins with an isothermal phase at 300°C for 3 minutes, during which free hydrocarbons volatilize and are detected as the S1 peak using a flame ionization detector (FID). Subsequently, the temperature is increased from 300°C to 550°C at a ramp rate of 25°C/min to thermally crack kerogen, releasing additional hydrocarbons as indicated the S2 peak (also detected by FID). The temperature at which the S2 peak reaches its maximum is referred to as $T_{\max}$, an important maturity parameter that reflects the type and degree of transformation level of kerogen.

Simultaneously, CO₂ released from the breakdown of oxygen-containing functional groups in kerogen is trapped in the 300–390°C range. This CO₂ is then released during the cooling phase and measured as the S3 peak using a thermal conductivity detector (TCD). The instrument also calculates Total Organic Carbon (TOC), a fundamental measure of organic richness.

The parameter definitions and interpretive guidelines were initially proposed by Larter (1984) and later refined by Murchison (1987) for application in Rock-Eval pyrolysis. Several key geochemical indices are derived from these measurements:

- S1 Peak: Represents the quantity of free hydrocarbons (e.g., oil and gas) thermally liberated from the organic matter under a helium atmosphere. This value is approximately equivalent to the amount of hydrocarbons extractable through solvent extraction methods.
- S2 Peak: Indicates the amount of hydrocarbons generated through the thermal cracking of kerogen during pyrolysis in a helium atmosphere. This peak reflects the kerogens generative potential in the sample.
- S3 Peak: Represents the quantity of carbon dioxide (CO₂) evolved from the thermal degradation of oxygen-containing functional groups within the kerogen.

- $T_{\max}$: The temperature at which the maximum rate of hydrocarbon generation (S2 peak) occurs during pyrolysis. It serves as an indicator of the thermal maturity of the sample's organic matter.
- TOC (Total Organic Carbon): Refers to the total amount of organic carbon present in the sediment or rock sample. It reflects the quantity of organic matter available for hydrocarbon generation.
- Genetic Potential (GP): Calculated as the sum of S1 and S2, representing the total hydrocarbon-generating potential of the sample.
- Production Index (PI): Defined as the ratio of S1 / (S1 + S2), this parameter is used to assess the extent of organic matter transformation.
- Hydrogen Index (HI): Calculated as $HI = (100 \times S2) / TOC$, it indicates the proportion of hydrogen-rich, pyrolyzable material relative to the TOC. HI is often used to infer the biological origin of the organic matter, with marine-derived lipids and proteins generally having higher HI values than land-plant-derived carbohydrates.
- Oxygen Index (OI): Calculated as $OI = (100 \times S3) / TOC$, this index represents the relative oxygen content in the organic matter and is used for kerogen type classification.

Rock Eval pyrolysis was performed to assess the type, quantity and maturity of the organic matter present in these coal samples. The Total organic carbon (TOC) values of these coals range from 46.68 to 61.3 wt.%, The thermal maturity ($T_{\max}$) ranges from 423.5 to 445 °C, Hydrogen Index (HI) ranges from 92 to 280, Oxygen Index (OI) ranges from 3.8 to 10.33, while Generation Potential (S1+S2) ranges from 36.77 to 129.34. Table 5.2 shows the various parameters obtained from the Rock Eval and TOC analyses of these coal samples.

Table 5.2 Rock eval parameters and TOC (wt.%) values of Sohagpur coals.

Sample name	TOC (wt. %)	S1 (mg HC/g rock)	S2 (mg HC/g rock)	S3 (mg HC/g rock)	T _{max} (°C)	HI	OI	CaCO ₃ (wt. %)	PI
Amalai	55.6	0.94	60.11	3.1	425	104	5.125	5.44	0.03
Bangwar	50.82	0.74	36.31	3.74	425	92	9.4	5.47	0.07
Dhanpuri	58.18	1.44	79.7	2.26	445	131	3.8	4.97	0.04
Damini V	55.75	0.48	83.07	4.26	424	147	7	5.99	0.01
Damini VI	46.68	0.52	36.25	3.38	423.5	163.67	10.33	17.85	0.04
Khairaha VI	59.99	0.75	82.57	4.74	425	136	7.2	7.05	0.02
Khairaha VII	61.3	0.69	65.69	4.94	425	106	7.4	6.44	0.02
Rajendra	55.09	0.67	80.84	4.31	425	147	7.4	5.45	0.02
Sharda	56.75	1.97	127.37	2.05	429	280	5.88	13.07	0.03

Thermal maturity of organic matter was evaluated using Rock-Eval pyrolysis, a widely applied geochemical technique that quantifies hydrocarbon generation potential and the extent of organic matter transformation. The method provides key parameters such as S1 (free hydrocarbons), S2 (hydrocarbons generated during pyrolysis), S3 (CO₂ released from oxygen-bearing functional groups), T_{max} (temperature at maximum S2 yield), and derived indices including Hydrogen Index ($HI = 100 \times S2/TOC$), Oxygen Index ($OI = 100 \times S3/TOC$), and Production Index ($PI = S1/[S1+S2]$). Among these, T_{max} serves as the most direct indicator of maturity, with values <435 °C denoting immature kerogen, 435–455 °C corresponding to the oil window, and >470 °C reflecting overmature, gas-prone conditions. The PI increases progressively with maturation, while HI decreases due to the breakdown of hydrogen-rich moieties. Cross-plots of HI versus OI (pseudo–van Krevelen diagrams) and T_{max} versus PI provide further validate of maturity trends and kerogen type evolution. However, interpretation must consider kerogen type, mineral matrix effects, and low S2 yields, which may bias T_{max} and index values.

5.3.1 Reliability of $T_{\max}$ in Coals

Rock–Eval $T_{\max}$, the temperature at which the maximum rate of hydrocarbon generation occurs during pyrolysis, is widely used to assess thermal maturity. However, in coal samples, its reliability is influenced by maceral composition, hydrogen content, mineral matter, and rank. $T_{\max}$ is highly reliable in low- to medium-rank, vitrinite-rich coals with moderate hydrogen content and sufficient reactive organic matter, where the S_2 peak is well defined and correlates with vitrinite reflectance and elemental ratios, reflecting progressive coalification and the onset of thermogenic methane generation (Espitalié et al., 1985; Peters, 1986). $T_{\max}$ becomes unreliable in high-rank coals with extremely low S_2 , in oxidized or weathered samples, or when bitumen or residual moisture complicates the pyrolysis signal. Therefore, $T_{\max}$ should not be used in isolation; it should be interpreted alongside vitrinite reflectance, maceral composition, and elemental ratios to assess maturity and methane generating potential (Tissot and Welte, 1984).

The thermal maturity ($T_{\max}$) ranges from 423.5 to 445 °C, the Hydrogen Index (HI) ranges from 92 to 280, Oxygen Index (OI) ranges from 3.8 to 10.33, and the Generation Potential (S_1+S_2) ranges from 36.77 to 129.34. Production index (PI) ranges from 0.01 to 0.07.

Based on the above $T_{\max}$ and PI values the coal samples from Sohagpur fall within the Immature to mature window as shown in Table 5.3, and a cross plot plotted between $T_{\max}$ and HI values as (Figure 5.3) also supports this immature to mature window for these coals.

Table 5.3 Rock eval parameters with maturity index.

Window	$T_{\max}$	PI
Immature	< 435°C	0.00-0.10
Mature	435-455	0.10-0.30
Post-mature (wet gas)	455–470°C	0.30–0.50
Post-mature (dry gas)	> 470°C	> 0.40–0.50

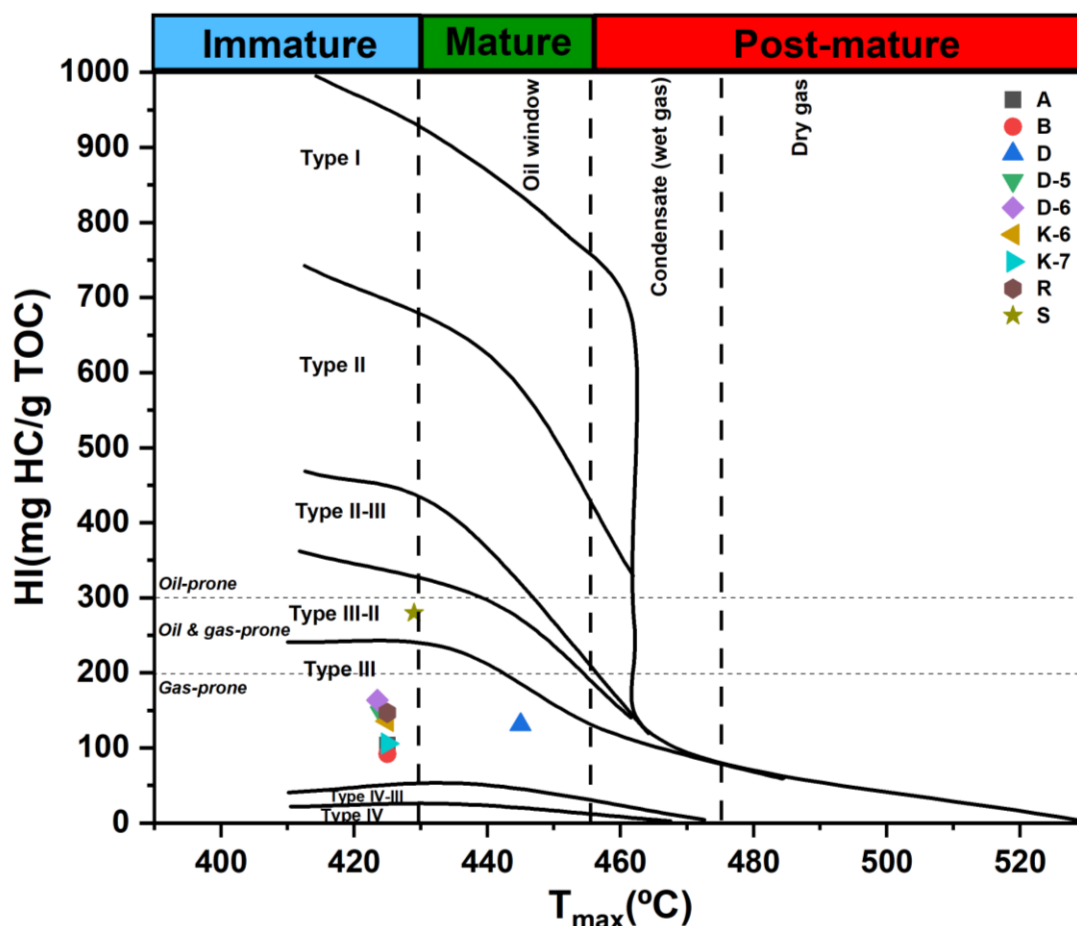


Figure 5.3 $T_{\max}$ and HI plot shows that coals from Sohagpur fall in the Immature to Mature zone.

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra, and S: Sharda.

Pyrolysis data indicate a very low production index ($PI < 0.1$) for the analyzed coals, reflecting minimal hydrocarbon generation and suggesting thermal immaturity as shown in Figure 5.4 (Peters, 1986). However, the applicability of PI and $T_{\max}$ as sole maturity indicators is limited, particularly for Type III kerogen, where $T_{\max}$ values may be affected by several controlling factors, including total organic carbon (TOC) content, organic matter composition, sulphur content, and the influence of the mineral matrix in organic-lean sediments (Peters, 1986). These factors can lead to suppressed or anomalous $T_{\max}$ values, potentially resulting in misleading maturity interpretations.

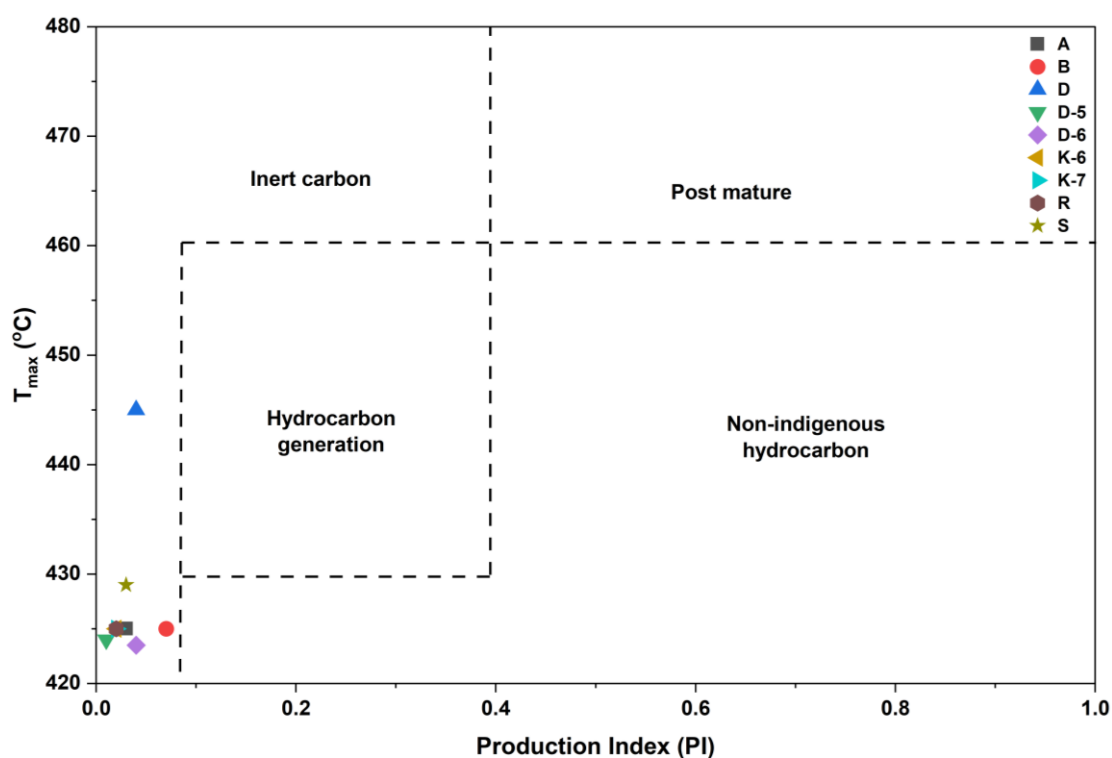


Figure 5.4 Plot of Production Index vs T_{max} showing the hydrocarbon generation zone (after Peters 1986).

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra, and S: Sharda.

To overcome these limitations, an integrated thermal maturity assessment was conducted using both T_{max} and vitrinite reflectance. The consistently low T_{max} values (<435 °C), coupled with low vitrinite reflectance value provide strong evidence that the coals have not experienced sufficient thermal stress to enter the main hydrocarbon generation window, as shown in Figure 5.5. Based on these parameters, the studied coals are classified as immature to early mature source rocks of medium rank. Consequently, their hydrocarbon generation potential is limited, with a tendency toward the generation of biogenic gas and only minor amounts of immature oil, consistent with established source rock maturity models (Peters & Cassa, 1994).

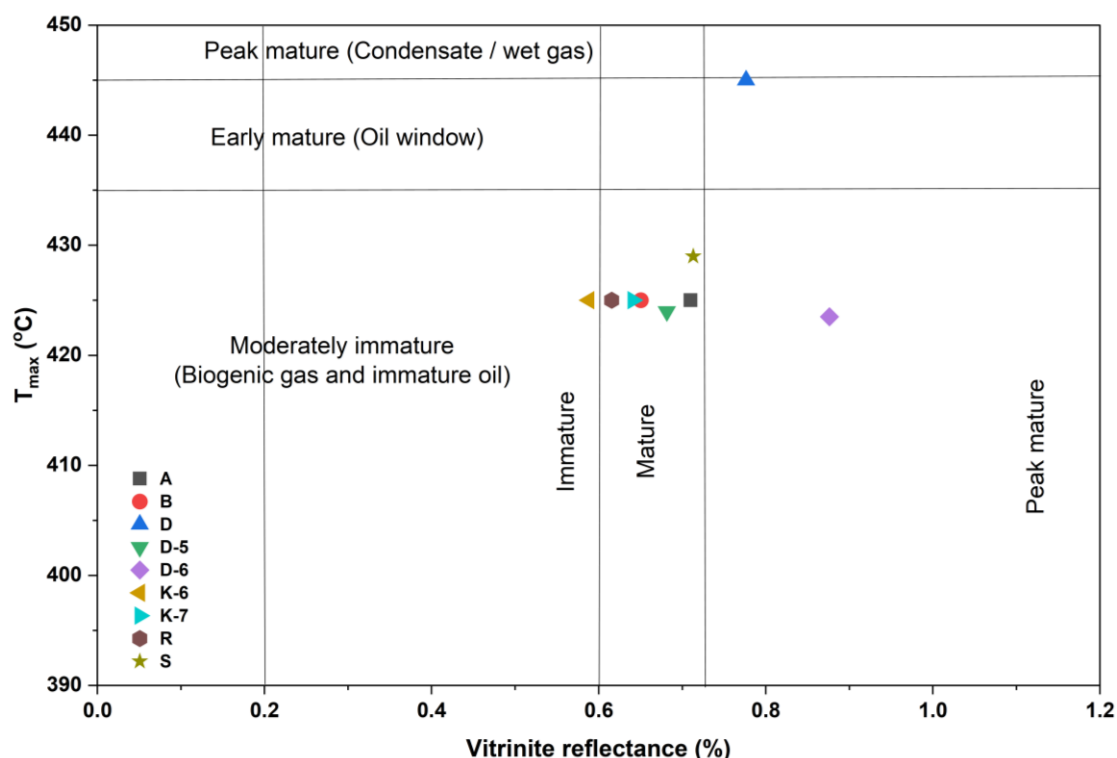


Figure 5.5 Plot of vitrinite reflectance and T_{max} showing the maturity levels (after Peters and Cassa 1994).

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra and S: Sharda.

5.4 Thermal maturity assessment using integrated petrographic and geochemical proxies

The thermal maturity of the coal samples has been assessed using T_{max} , vitrinite reflectance (R_o %), and elemental atomic ratios (H/C and O/C). While these parameters collectively indicate that the coals have attained maturity levels suitable for thermogenic methane generation, certain discrepancies among individual indicators are common in coal-bearing sequences and require careful interpretation.

The T_{max} values range from 423.5 to 445°C, indicating a broad maturity range within the early to peak gas generation window. However, the Dhanpuri sample exhibits a relatively high T_{max} of 445°C, indicating a more advanced maturity stage than other samples. This elevated T_{max} is not fully matched by an exceptionally high vitrinite reflectance value (0.78% R_o), suggesting a slight mismatch between pyrolysis-derived and optical maturity

parameters. Such discrepancies may arise due to the influence of mineral matter and bitumen content, or from the suppression of $T_{\max}$ in hydrogen-rich coals, as well as from the known limitation of Rock–Eval $T_{\max}$ in coals, where the kerogen structure and residual moisture can affect pyrolysis behaviour.

Vitrinite reflectance values vary from 0.59 to 0.88% R_o , indicating high-volatile to medium-volatile bituminous rank. In some samples, such as Khairaha VI (0.59% R_o), the R_o % suggests relatively low maturity, whereas $T_{\max}$ values ($\sim 425^\circ\text{C}$) indicate attainment of early gas generation conditions. This inconsistency can be attributed to vitrinite reflectance suppression, commonly observed in Gondwana coals, where higher hydrogen content, maceral composition dominated by vitrinite, or the presence of liptinite may lead to lower measured reflectance values than to true thermal maturity.

The atomic H/C and O/C ratios further reflect progressive coalification but also display variability that does not always correlate directly with $T_{\max}$ or R_o %. For example, Bangwar, despite having a moderate R_o % (0.65%) and $T_{\max}$ (425°C), shows relatively high H/C (0.75) and O/C (0.23), suggesting less advanced chemical evolution. This may reflect variations in original peat composition, depositional environment, or differential oxidation, rather than differences in burial temperature alone. Conversely, Sharda, with a moderate R_o % (0.71%), exhibits a very low O/C ratio (0.07), indicating advanced devolatilization and loss of oxygen-rich functional groups, possibly influenced by localized thermal effects or prolonged residence times at elevated temperatures.

Such discrepancies highlight that no single parameter can independently define coal maturity with complete reliability. $T_{\max}$ primarily reflects the thermal response of organic matter during programmed pyrolysis, vitrinite reflectance records cumulative thermal exposure, and elemental ratios are influenced by both thermal evolution and the original

organic matter composition. Therefore, variations among these indicators are expected, especially in structurally complex Gondwana basins where heterogeneous burial histories, facies changes, and post-depositional tectonic events have affected coal seams differently.

5.5 Coals of the Sohagpur coalfield as a Hydrocarbon Source Rock

The petrological and geochemical characteristics of coal samples from the Sohagpur coalfield have been used to evaluate these coals for their as a Hydrocarbon source rock potential. The type of organic content, its amount, and the maturity of the source rock all affect a source rock's capacity to produce hydrocarbons.

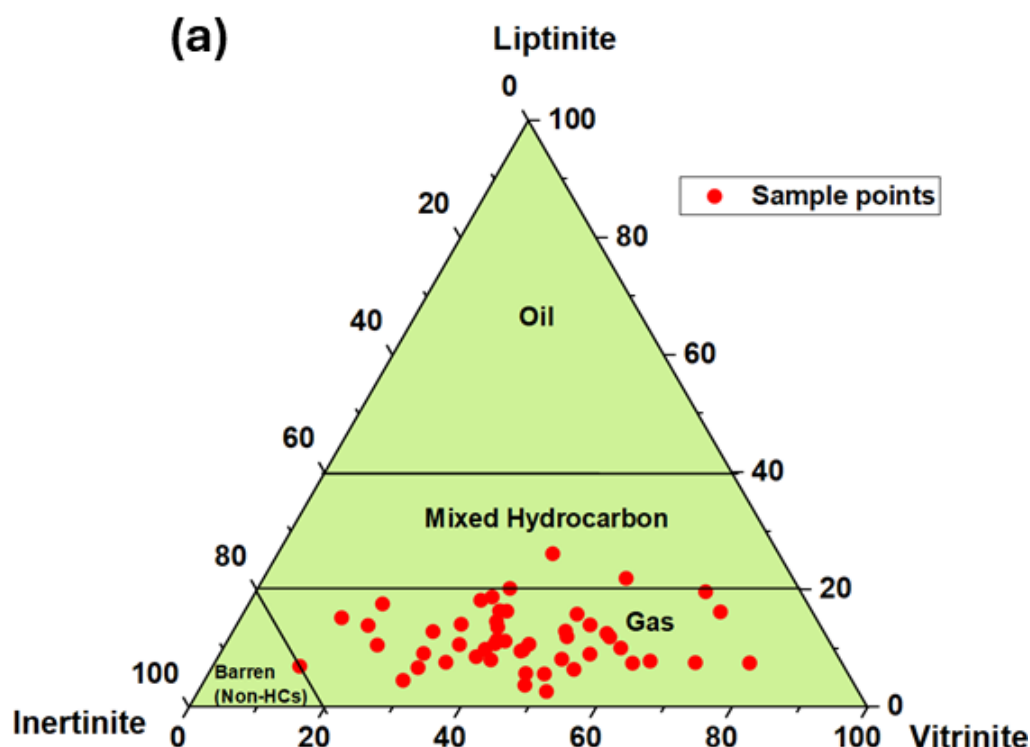
5.5.1 Based on organic matter

Kerogen is an organic substance that functions as a precursor of hydrocarbons. Bitumen is the remaining part of organic matter, while the Kerogen constitutes up to 80-99% of the total organic matter (Tissot and Welte, 1984). Kerogen, which is related to the organic matter and products of its alteration, can be characterized using maceral identification terminology. In type I, alginite can be the signature maceral, while for kerogen type II, the macerals belong to the liptinite group, such as sporinite, cutinite, resinite, bituminite, exsudatinitite, and Suberinitite can be signature macerals. The vitrinite groups of macerals belong to the kerogen type III, while all macerals from inertinite groups fall in kerogen type IV (Pashin 2008).

The behaviour of coal macerals also justifies the liquefaction process. Due to their thermoplastic in nature, the vitrinite macerals actively participate and help in liquefaction, while due to the presence of more aliphatic groups, the liptinites have higher yield, and the inertinite macerals remain inert or less reactive during the whole process (Suárez-Ruiz and Crelling 2008).

According to the micropetrographic results, all three macerals type are present in Sohagpur coals. The hydrocarbon source rock properties of coal samples from the Sohagpur coalfield are determined from maceral concentrations (Taylor et al., 1998). The abundance of vitrinite, inertinite, and liptinite maceral groups indicates that the material is gas-prone, inert, and oil/gas-prone, respectively, according to Tissot and Welte (1984) and Taylor et al. (1998).

A low quantity of liptinite macerals suggests that the Sohagpur coals are gas-prone and belong to Kerogen type III, whereas vitrinite and inertinite macerals are abundant. According to Tissot and Welte's (1984) ternary plot based on micropetrography data, these materials may be capable of producing gas. Likewise, the samples belong to Kerogen Type III, according to a different ternary plot proposed by Cornford (1979) as shown in Figure 5.6.



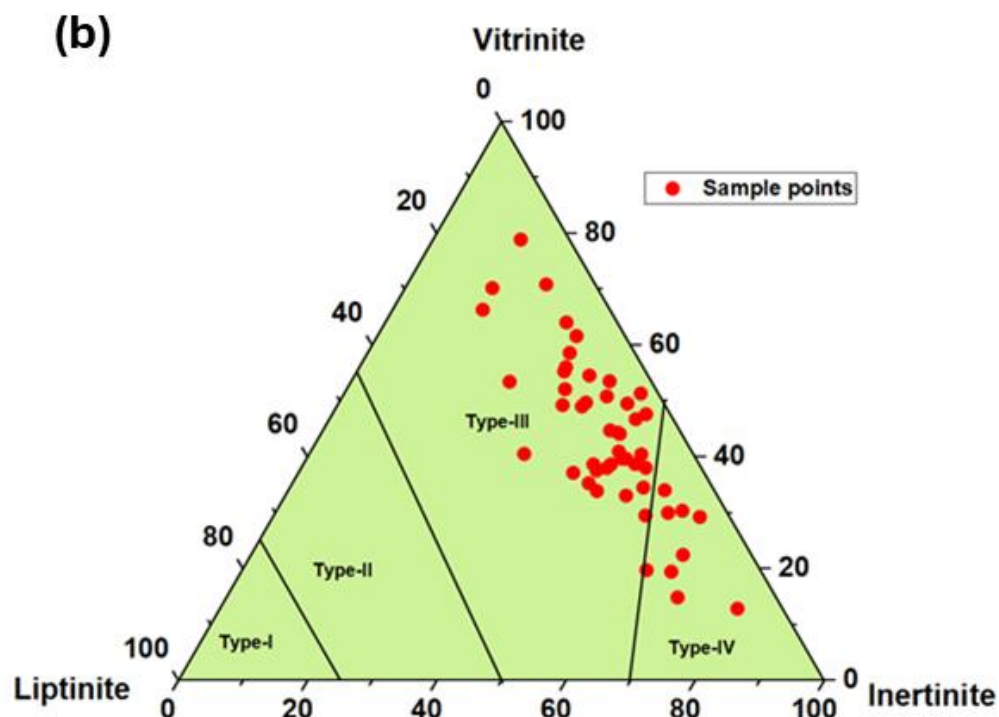


Figure 5.6 Based on micropetrography data, the hydrocarbon source rock potential of Sohagpur coals falls in the gas-prone zone (a) and majorly in Kerogen type III (b).

5.5.1.1 Maceral control on hydrocarbon generation behaviour of Sohagpur coals

The maceral composition of coal plays a critical role in controlling the type and yield of hydrocarbons generated during coalification. The maceral-based ternary plots presented in Figure 5.6a and Figure 5.6b illustrate the relationship between vitrinite, liptinite, and inertinite contents and their influence on hydrocarbon generation behaviour of the Sohagpur coals. The distribution of sample points on these diagrams reflects the dominance of vitrinite and inertinite macerals with subordinate liptinite, a characteristic feature of Sohagpur coals deposited under relatively oxidizing conditions (Jasper et al., 2017).

5.5.1.1.1 Role of vitrinite vs inertinite rich coals

As shown in Figure 5.6b, most of the samples plot within the Type-III kerogen field, with several points extending toward the Type-IV domain, indicating an increase in inertinite content. Vitrinite-rich coals are primarily derived from woody terrestrial plant material

and are known to be effective precursors for thermogenic gas generation, particularly methane, at appropriate maturity levels (Tissot and Welte, 1984; Levine, 1993). The clustering of Sohagpur coal samples in the Type-III field suggests that vitrinite is the principal contributor to hydrocarbon generation, favouring gaseous hydrocarbons over liquid products. Samples that fall closer to the Type-IV field reflect higher inertinite proportions. Inertinite, being oxidized or charred organic matter, is generally considered to have poor hydrocarbon-generating capacity, resulting in dilution of reactive organic matter and reduced generation potential. However, inertinite-rich coals may still contribute positively to CBM systems by providing enhanced microporosity and adsorption sites for methane storage, even though their role in hydrocarbon generation is limited.

5.5.1.1.2 Hydrocarbon enrichment in liptinite poor coals

The liptinite–vitrinite–inertinite ternary plot in Figure 5.6a shows that the majority of the samples fall within the gas and mixed hydrocarbon fields, with no samples plotting in the oil-prone liptinite-rich domain. Liptinite macerals are hydrogen-rich and are typically responsible for liquid hydrocarbon generation; however, their low abundance in Gondwana coals restricts oil generation potential (Taylor et al., 1998). Despite being liptinite-poor, the Sohagpur coals display hydrocarbon enrichment in the gas-prone fields, indicating that methane generation is primarily controlled by the thermal evolution of vitrinite rather than liptinite contribution. This observation is consistent with the depositional environment of Gondwana coals, where oxidizing fluvial and deltaic settings limited the preservation of hydrogen-rich organic matter (Panwar et al., 2017b; Gopinathan et al., 2024).

5.5.1.1.3 Hydrocarbon yield

The maceral distribution depicted in Figure 5.6a and 5.6b suggests a moderate to low overall hydrocarbon yield, primarily governed by the balance between vitrinite richness and inertinite dilution. Samples positioned well within the Type-III field are expected to yield relatively higher volumes of thermogenic gas than those approaching the Type-IV domain, where inertinite reduces the effective hydrocarbon generation potential (Levine, 1993). Although, the limited liptinite content restricts total hydrocarbon yield, the maturity levels attained by these coals enhance methane generation efficiency, making them suitable candidates for CBM exploration rather than conventional petroleum systems.

5.5.1.1.4 Gas vs liquid prone source characteristics

The combined interpretation of Figure 5.6a and Figure 5.6b clearly indicates that the Sohagpur coals are predominantly gas-prone source rocks. The concentration of samples within the gaseous hydrocarbons, coupled with their dominance in the Type-III kerogen domain, confirms that liquid hydrocarbon generation is negligible. The absence of samples in the oil-prone liptinite-rich region in the figures further supports this interpretation.

5.5.1.2 Mineral matter influence on thermal maturity and hydrocarbon generation

Mineral matter constitutes an integral component of coal and plays a significant role in influencing thermal maturity, hydrocarbon generation, and methane accumulation in coal-bearing basins (Taylor et al., 1998; Levine, 1993).

The presence of mineral matter can modify the apparent thermal maturity of coals by influencing pyrolysis parameters such as $T_{\max}$. High mineral matter content, particularly clay minerals and carbonates, may suppress or shift $T_{\max}$ values due to catalytic effects

or dilution of organic matter during Rock–Eval analysis (Peters 1986; Espitalié et al., 1985). As a result, $T_{\max}$ derived maturity estimates may locally underestimate or overestimate true thermal maturity, especially in Gondwana coals where mineral matter content is often high and heterogeneously distributed (Gopinathan et al., 2024).

Mineral matter also influences the thermal evolution of organic matter by controlling heat conductivity and retention within coal seams. Quartz- and carbonate-rich minerals enhance thermal conductivity, promoting more efficient heat transfer and potentially accelerating organic matter maturation. In contrast, clay-rich assemblages may act as thermal insulators, leading to localized maturity variations within the basin (Hunt, 1996). Such mineralogical heterogeneity can result in uneven coalification patterns, which partly explain the maturity discrepancies observed between adjacent coal seams in Gondwana basins.

Mineral matter also affects the methane generation pathways. Certain minerals, particularly clays and transition-metal-bearing phases, can act as catalysts that enhance the cracking of organic matter and promote thermogenic methane generation at comparatively lower temperatures (Tissot and Welte, 1984). In coalbed methane reservoirs, mineral matter also affects methane retention and producibility. Clay minerals influence the development of microporosity and adsorption capacity, while carbonate cementation may reduce cleat permeability, limiting gas migration and desorption efficiency (Clarkson and Bustin, 1999). The presence of clay minerals in these coals may catalyze the cracking of organic matter during thermal decomposition. This catalytic effect enhances the cracking of organic matter, thereby promoting the generation of gas and improving the overall decomposition of organic matter for thermogenic methane generation.

5.5.2 Based on the Geochemical values

Jones and Edison (1978) proposed a cross-plot to identify kerogen type based on the atomic ratios of hydrogen, carbon, and oxygen. The geochemical parameters obtained from the Ultimate analysis have been used to classify the kerogen type present in the Sohagpur coals. Based on the H/C and O/C atomic ratios, a cross-plot was created, which suggests that these samples fall within the kerogen type III, as shown in Figure 5.7, and supports the kerogen type identified from micropetrography and rock eval parameters.

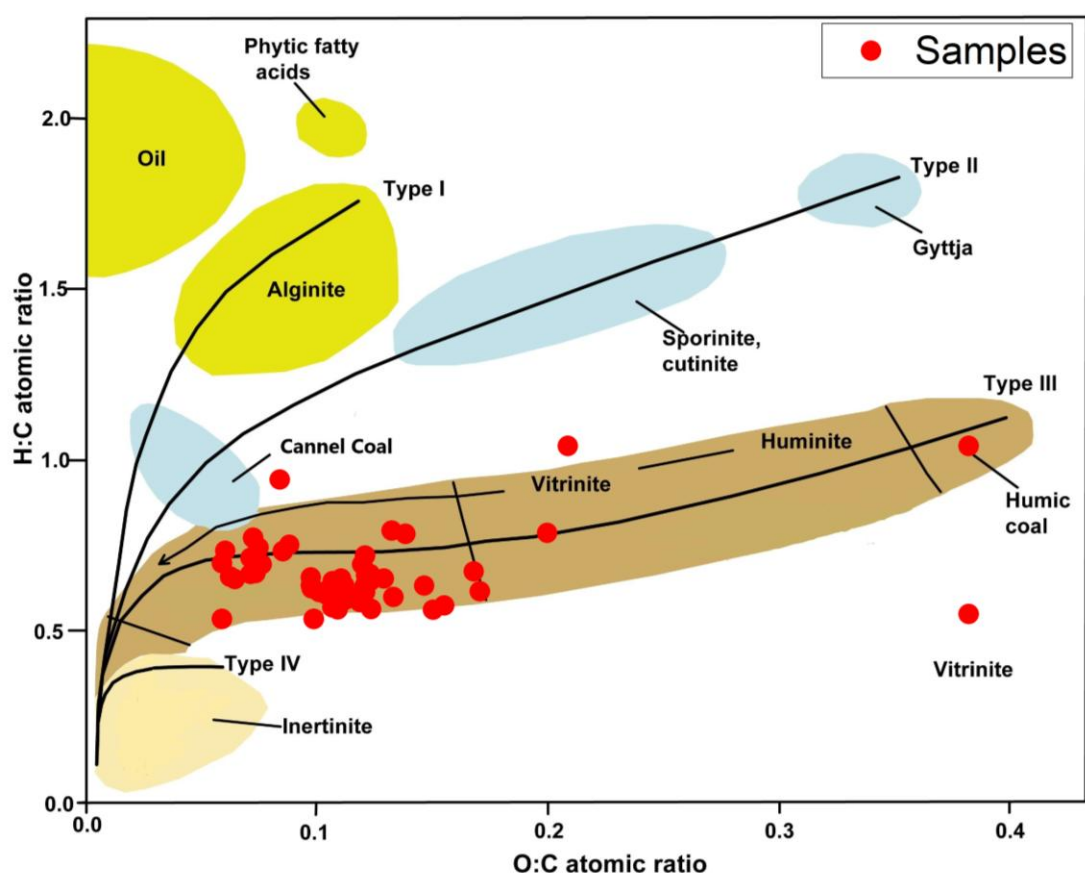


Figure 5.7 Kerogen type of the coals from Sohagpur coalfield based on the O:C versus H:C atomic ratios (after Jones and Edison, 1978).

5.5.3 Based on Rock Eval Parameters

Hydrogen index (HI) and oxygen index (OI) also help determine the type of organic matter present in samples; these parameters are calculated from pyrolysis analysis. Peters (1986) proposed a model based on the HI and OI, which distinguished the kerogen types.

When Sohagpur coals are plotted on this graph, the samples fall in the kerogen type III, as shown in Figure 5.8.

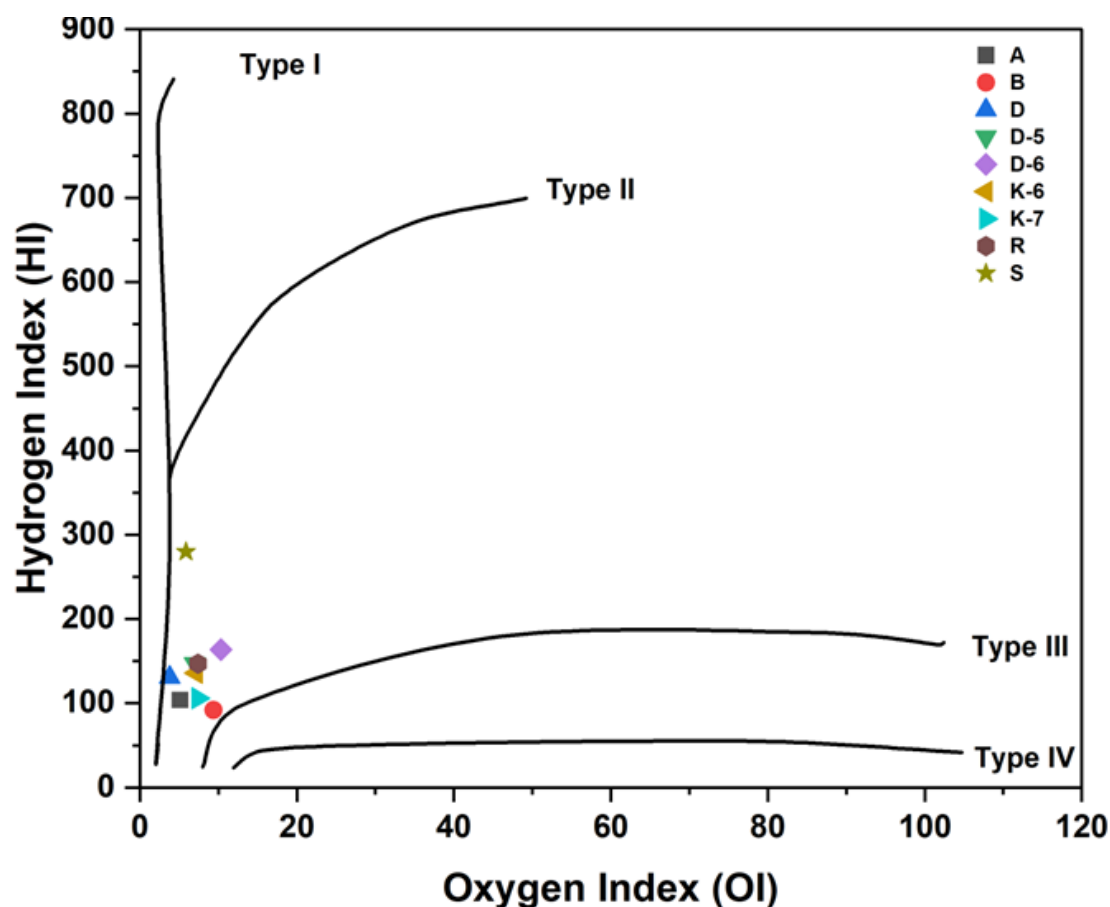


Figure 5.8 Kerogen type based on the hydrogen index (HI) versus oxygen index (OI) values showing Sohagpur coals fall in the kerogen type III (after Peters 1986).

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra, and S: Sharda.

Another cross plot proposed by Peterson (2005) using data of vitrinite reflectance and hydrogen index of coals from Sohagpur coalfield also supports the previous outcome of type III kerogen being gas prone.

It suggests that most of these coals contain Type III kerogen, which can generate only gas, and that some of them also contain mixed Type II and III kerogen, which is oil as well as gas-prone, as shown in Figure 5.9.

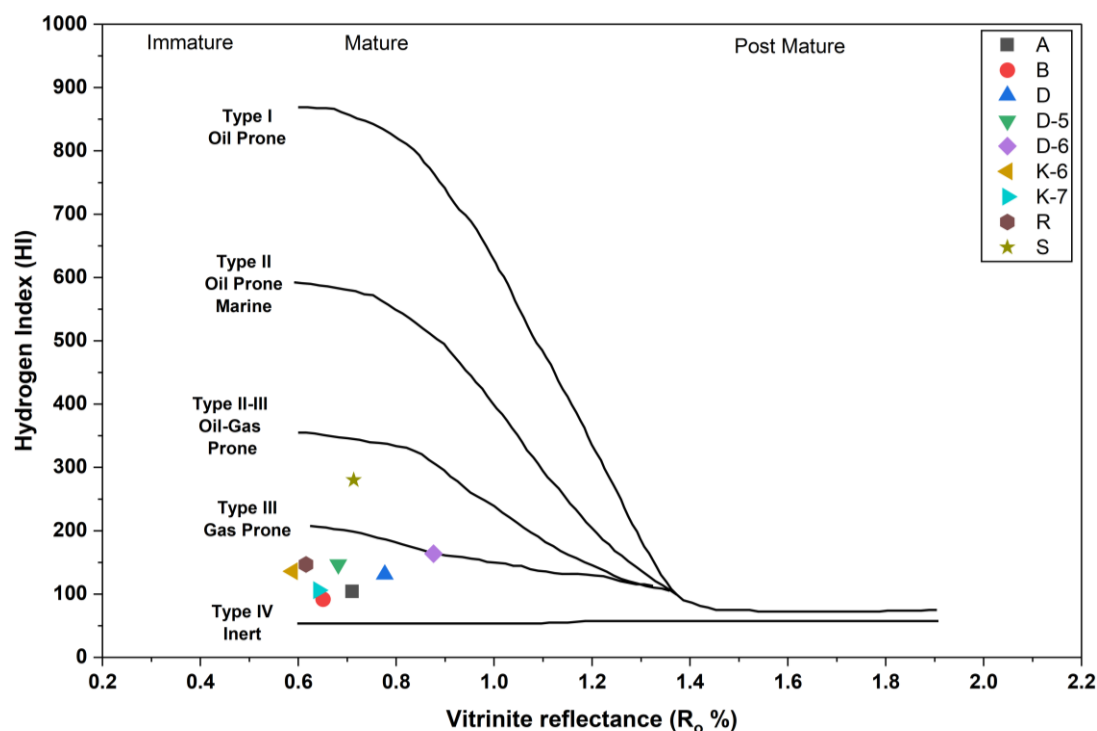


Figure 5.9 Cross plot between vitrinite reflectance (R_o %) and Hydrogen Index (HI) of coals of Sohagpur coalfield (adopted after Petersen 2005).

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra, and S: Sharda.

Langford and Blanc-Valleron (1990) also discussed and established relationship among the kerogen type present, their origins, the nature of expelled hydrocarbons as reflected in the S2 peak of Rock eval analysis, and TOC (wt.%). Based on these data, a cross plot is shown in Figure 5.10, which again supports the previous conclusion that these coals have gas-prone type III kerogen, with some having a mixture of type II-III, capable of generating both liquid and gaseous hydrocarbons.

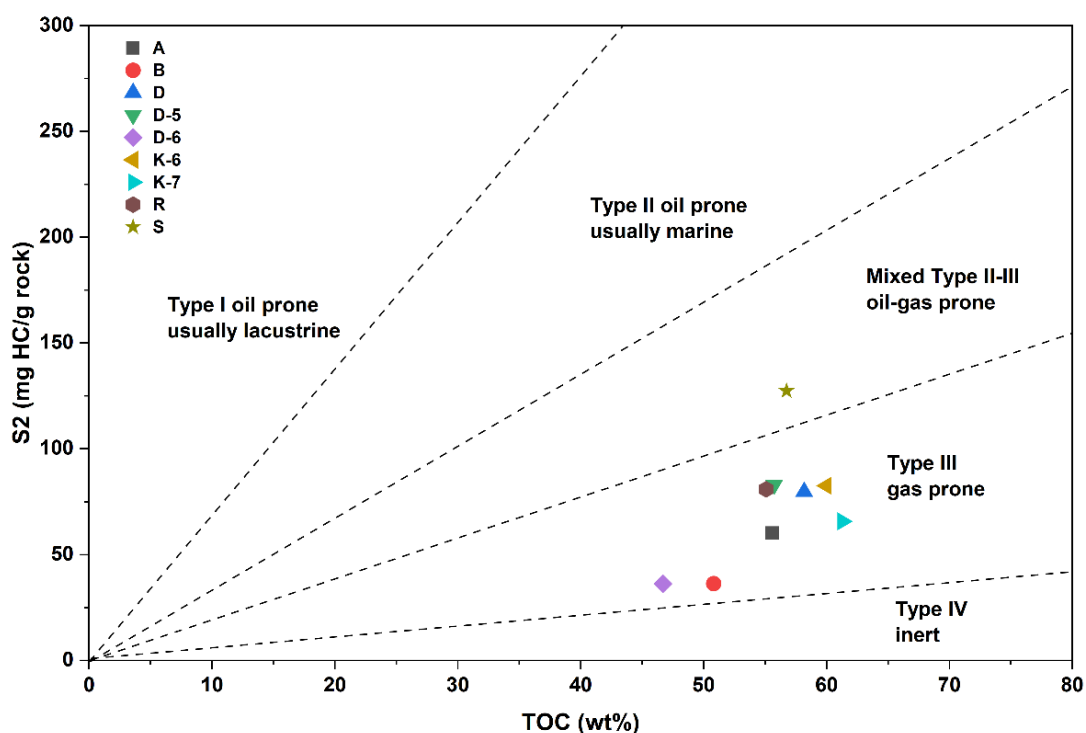


Figure 5.10 Plot of remaining hydrocarbon potential (S2) versus TOC for coals of Sohagpur coalfield (after Langford and Blanc-Valleron, 1990).

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra, and S: Sharda.

5.5.4 Quantity of organic matter

Total organic carbon (TOC) is a parameter used to describe the amount of organic matter in samples. According to Petersen and Nytoft (2006), who examined the hydrocarbon generative potential of coals of various ages, Permian coals have high potential because their S2 values are several times higher than their S1 values. This suggests that a significant amount of hydrocarbons is expelled during maturation than are present in free form. In source rock, the retained hydrocarbon that can be released during maturation is indicated by the S2. The TOC values vs S2 chart, as shown in Figure 5.11, shows that Sohagpur coals show excellent generation potential upon maturation (Peters and Cassa 1994; Dembicki 2009).

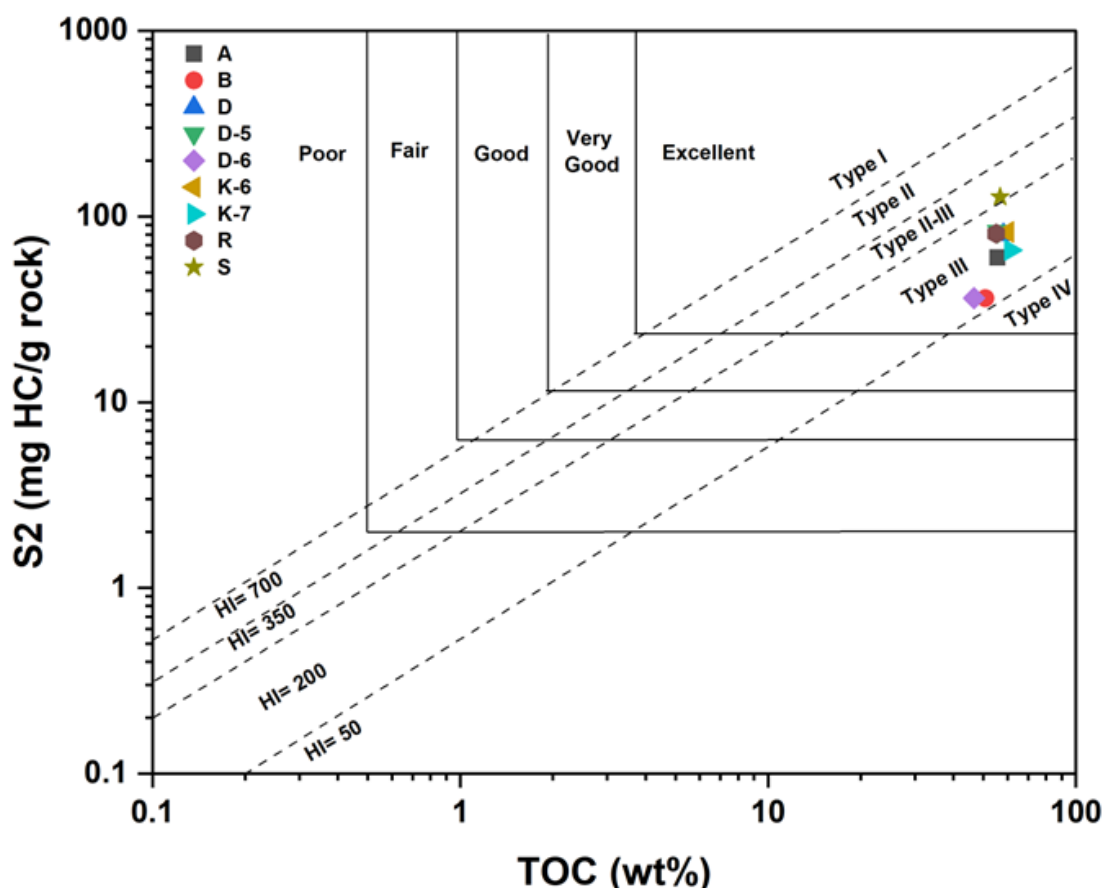


Figure 5.11 Cross plot between total organic carbon (TOC) and S2 showing coals from Sohagpur coalfield have excellent generation potential (Peters and Cassa 1994; Dembicki 2009).

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra. and S: Sharda.

Various rock eval parameters and their corresponding hydrocarbon source rock generation potential are shown in Tables 5.4, 5.5 and 5.6 according to Peters (1986). This suggests that Sohagpur coals have very good to excellent generation potential as a mixed to gaseous hydrocarbon source.

Table 5.4 Rock eval parameters describing source rock generative potential (Peters 1986).

Quantity	TOC (wt. %)	S1 (mg HC/g rock)	S2 (mg HC/g rock)
Poor	0-0.5	0-0.5	0-2.5
Fair	0.5-1.0	0.5-1.0	2.5-5.0
Good	1.0-2.0	1.0-2.0	5.0-10.0
Very Good	>2.0	>2.0	>10.0

Table 5.5 Total Organic Carbon and its Source Rock Implications (after Peters 1986).

TOC (wt. %)	Source Rock Implications
0-0.5	Negligible Source Capacity
0.5-1.0	Slight Source Capacity
1.0-2.0	Moderate Source Capacity
>2.0	Good to Excellent Source Capacity

Table 5.6 Hydrogen index and its principal products (after Peters 1986).

HI (mg HC/g C _{org})	Principal Product	Relative Quantity
<150	Gas	Small
150-300	Oil and Gas	Small
300-450	Oil	Moderate
450-600	Oil	Large
>600	Oil	Very Large

The above outcome is further supported by another cross plot, which is plotted between the genetic potential (S₁+S₂) versus TOC and shows that coals from Sohagpur coalfield fall in the very good to excellent generation potential due to high concentration of TOC, expelled hydrocarbon (S₂), and free hydrocarbon (S₁) as shown in Figure 5.12.

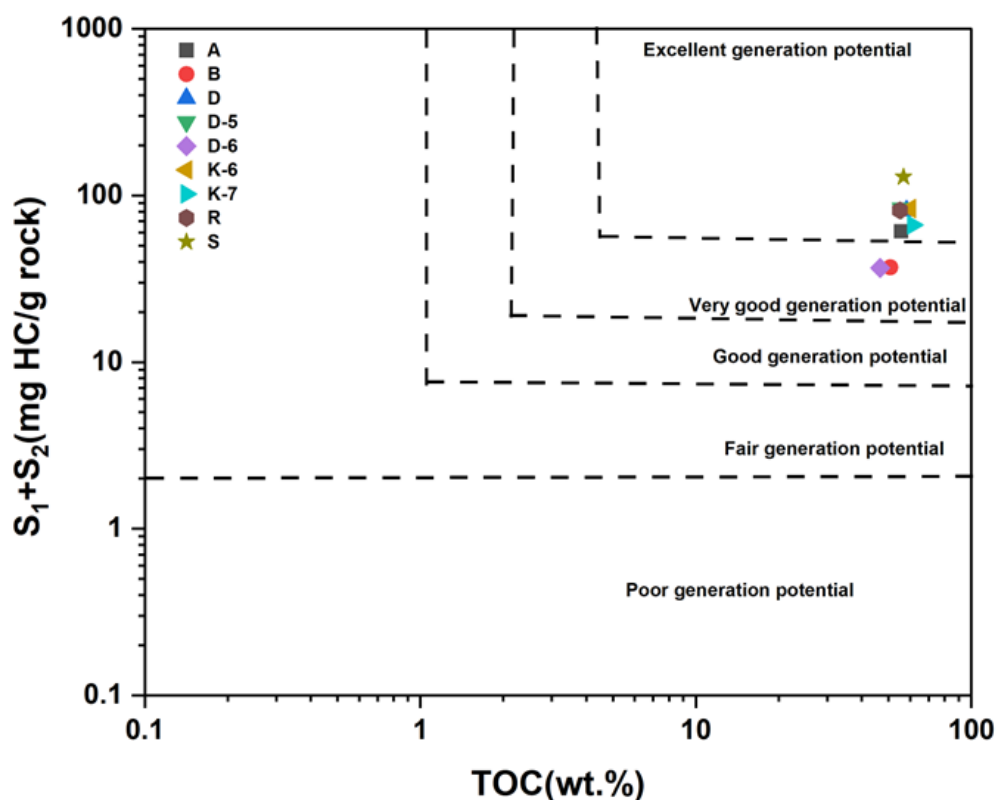


Figure 5.12 Plot of TOC vs S₁+S₂ showing the genetic potential of coal samples from Sohagpur coalfield.

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra, and S: Sharda.

5.6 Key findings of the maturation study

The integrated thermal maturity assessment of Sohagpur coal samples, using both $T_{\max}$ and vitrinite reflectance (R_o), indicates that these coals are immature to early mature hydrocarbon generation window ($T_{\max} < 435\text{ }^{\circ}\text{C}$; $R_o = 0.59\text{--}0.88$) (Peters & Cassa, 1994; Taylor et al., 1998). The volatile matter content (30.41–36.43% daf) and ASTM rank classification further confirm that the coals are medium-rank bituminous. Kerogen type shows that most samples plot in the Type-III domain, highlighting vitrinite as the principal hydrocarbon-generating maceral, favouring gaseous hydrocarbons, particularly methane, over liquids (Tissot & Welte, 1984; Levine, 1993). Some samples extend toward the Type-IV field, indicating higher inertinite content, which reduces reactive organic matter and limits hydrocarbon generation, though it may enhance microporosity and methane adsorption. Total organic carbon (TOC) and pyrolysis S2 values suggest that, despite their current immaturity, the coals possess excellent hydrocarbon generation potential upon further maturation, consistent with Permian coal source rock models (Peters and Cassa 1994; Peters 1986). Overall, the study demonstrates that Sohagpur coals are currently early-stage gas-prone source rocks, with vitrinite controlling hydrocarbon generation and inertinite influencing storage potential, indicating favourable conditions for coal bed methane (CBM) generation potential.

5.7 Comparative evaluation of hydrocarbon source rock potential of Sohagpur coalfield with other coalfields of Gondwana basins

A comparative assessment of hydrocarbon source rock characteristics of the Sohagpur coalfield with other Gondwana coalfields reveals broadly similar geochemical attributes, particularly in terms of organic richness, maturity, and kerogen type (Table 5.7). Previous

studies from the Ib River Basin (Varma et al., 2015) and various blocks of the Raniganj coalfield (Panwar et al., 2017a, 2017b, 2020; Misra et al., 2018) report high TOC values (25–82 wt.%), indicating excellent organic matter preservation and strong source rock potential. Comparable TOC ranges are observed in the Sohagpur coalfield (46.68–61.3 wt.%), placing it well within the category of organically rich Gondwana coals.

Table 5.7 Comparative evaluation of hydrocarbon source rock potential of the Sohagpur coalfield with other Gondwana coalfields, showing variations in coal rank, TOC, T_{max}, HI, and inferred kerogen type.

Author	Coalfield	Rank	TOC	T _{max}	HI	Key Outcome
Varma et al. (2015)	Ib River Basin	sub bituminous to bituminous	25.35-57.17	428-438	202-294	Excellent hydrocarbon generation
Panwar et al. (2017a)	Kutli block, Raniganj	not described	58.83-78.93	393.44-418.03	186.79-405.50	Mixed type II-III to type III kerogen
Panwar et al. (2017b)	Sitarampur Block, Raniganj Coalfield	not described	69.82–82.05	421-427	187.17-322.04	Mixed type II-III to type III kerogen
Misra et al. (2018)	Jambad area, Raniganj Coalfield	sub bituminous to bituminous	44.01-70.85	422-456	47-318	Dominance of mixed kerogen Type II-III
Singh and Jha (2018)	South Karanpura Coalfield	sub-bituminous ‘A’ to high volatile bituminous ‘C’	17.33-81.93	422-435	65-234	Kerogen Type III gas-prone
Panwar et al. (2020)	Kalidaspur block, Raniganj	Bituminous	53.31-59.74	431-446	299-345	Mixed Type II and III kerogen
Pandey et al. (2024)	Mandakini–B block, Talcher-Mahanadi Basin	Bituminous	34.02-61.84	420-426	131-174	Mixed Type II and III kerogen
Gopinathan et al. (2024)	Singrauli coalfield	sub-bituminous to high volatile bituminous	38.36-56.05	420-425	163-279	Dominance of kerogen Type III
This study	Sohagpur coalfield	Bituminous	46.68-61.3	423.5-445	92-280	Kerogen Type III gas-prone

Varma et al. (2015) evaluated coals from the Ib River Basin and reported very high TOC values (25.35–57.17 wt.%) with T_{max} values ranging from 428 to 438 °C and HI values between 202 and 294 mg HC/g TOC. These parameters indicate organically rich coals

with excellent hydrocarbon generation potential, suggesting favourable conditions for both gas and minor liquid hydrocarbon generation at appropriate maturity levels.

Panwar et al. (2017a) studied the Kutli block of the Raniganj coalfield and documented exceptionally high TOC values (58.83–78.93 wt.%) and comparatively lower $T_{\max}$ values (393–418 °C), indicating immature to early mature conditions. The wide HI range (186.79–405.50 mg HC/g TOC) reflects a mixed Type II–III to Type III kerogen assemblage, suggesting variable hydrocarbon generation behaviour controlled by maceral composition. In a related study, Panwar et al. (2017b) examined the Sitarampur block of the Raniganj coalfield and reported even higher TOC contents (69.82–82.05 wt.%), $T_{\max}$ values of 421–427 °C, and HI values of 187.17–322.04 mg HC/g TOC, reaffirming the dominance of mixed Type II–III to Type III kerogen with gas-prone characteristics.

Misra et al. (2018) investigated coals from the Jambad area of the Raniganj coalfield and classified them as sub-bituminous to bituminous in rank. Their results show TOC values lies between 44.01 and 70.85 wt.% and $T_{\max}$ values of 422–456 °C, with highly variable HI values (47–318 mg HC/g TOC), indicating dominance of mixed Type II–III kerogen and heterogeneous hydrocarbon potential.

Singh and Jha (2018) assessed coals from the South Karanpura coalfield and reported a wide rank range from sub-bituminous ‘A’ to high-volatile bituminous ‘C’. TOC values ranged from 17.33 to 81.93 wt.%, $T_{\max}$ values from 422 to 435 °C, and HI values from 65 to 234 mg HC/g TOC, leading to the interpretation of predominantly Type III, gas-prone kerogen.

Panwar et al. (2020) focused on the Kalidaspur block of the Raniganj coalfield and identified bituminous coals with TOC values of 53.31–59.74 wt.%, $T_{\max}$ values of 431–

446 °C, and relatively high HI values (299–345 mg HC/g TOC), indicating mixed Type II and Type III kerogen with comparatively better liquid hydrocarbon potential.

Pandey et al. (2024) studied coals from the Mandakini–B block in the Kasola area of the Talcher–Mahanadi Basin and reported bituminous rank coals with TOC values of 34.02–61.84 wt.%, $T_{\max}$ of 420–426 °C, and HI values of 131–174 mg HC/g TOC, suggesting mixed Type II and III kerogen with moderate hydrocarbon generation potential.

Gopinathan et al. (2024) evaluated coals from the Singrauli coalfield and documented sub-bituminous to high-volatile bituminous ranks, TOC values of 38.36–56.05 wt.%, $T_{\max}$ values of 420–425 °C, and HI values of 163–279 mg HC/g TOC, indicating a dominance of Type III kerogen and gas-prone source characteristics.

Thermal maturity indicators across Gondwana coalfields show $T_{\max}$ values predominantly between ~420 and 446 °C, reflecting immature to early mature conditions. The Sohagpur coals ($T_{\max}$ 423.5–445 °C) closely match this maturity range, similar to coalfields such as Singrauli, Talcher–Mahanadi Basin, and Raniganj, suggesting a consistent burial and thermal history across these basins. Hydrogen Index (HI) values display considerable variability, ranging from low to moderate (47–405 mg HC/g TOC), reflecting differences in maceral composition and kerogen type. Sohagpur HI values (92–280 mg HC/g TOC) are comparable to those reported from Singrauli and South Karanpura coalfields, reinforcing the dominance of gas-prone organic matter. In comparison, the present study on the Sohagpur coalfield identifies bituminous-rank coals with high TOC (46.68–61.3 wt.%), $T_{\max}$ values of 423.5–445 °C, and HI values ranging from 92 to 280 mg HC/g TOC. These parameters closely resemble those reported from other Gondwana coalfields and confirm that the Sohagpur coals are dominated by Type

III, gas-prone kerogen, placing them among the most favourable CBM source rocks within the Indian Gondwana basins.

5.8 Liquefaction behaviour and oil yield

Macerals of coal behave differently during liquefaction procedures. According to Cudmore (1977), liquefaction is best achieved with more than 60% reactive macerals; similarly, liquefaction or hydrogenation is best achieved with a R_o % of less than 0.8 (Singh and Kumar 2017). As the vitrinite reflectance of Sohagpur coals ranges from 0.59 to 0.88 and the reactive macerals value ranges from 46.55 to 63.78, the coal samples are fairly suitable for liquefaction, as shown in Table 5.8. Liptinite produces larger outputs because of its increased aliphatic content, whilst vitrinite macerals dissolve easily and aid in liquefaction because of their thermoplastic qualities. Meanwhile, inertinite is less reactive and remains inert throughout (Suárez-Ruiz and Crelling 2008).

Table 5.8 Coal characteristics required for liquefaction or hydrogenation with values of Sohagpur coals.

Sl. No.	Properties of coal required for hydrogenation (after Cudmore, 1977)		Average range values of Sohagpur coals
1	Vitrinite reflectance (R_o %)	<0.8	0.59-0.88
2	H/C values	>0.75	0.54-1.06
3	Reactive macerals	>60%	46.55-63.78
4	Volatile matter (daf)	>35%	30.41-36.83

For the liquefaction behaviour of coal samples, conversion percentages and oil yield percentages are also computed. Guyot (1978) and Jin and Shi (1997) offered two formulas for calculating the conversion percentage. Jin and Shi's formula is dependent on the values of reactive metals, whereas Guyot's formula is dependent on the values of petrofactor. The combination of the Liptinite and Vitrinite maceral groups is known as the reactive macerals. The formulas for calculating the conversion factor, petrofactor, and oil yield (%) are shown below-

$$\text{Oil yield (\%)} = 0.22 (\text{RM}) + 44.8$$

$$\text{Petrofactor (PF)} = 1000 (\text{R}_{\text{max}}/\text{RM})$$

$$\text{Conversion \% (Guyot, 1978)} = 99 - 0.84 \text{ PF}$$

$$\text{Conversion (Jin and Shi, 1997)} = 0.2 (\text{RM}) + 76.6$$

Based on the above formulas, the values of Oil yield, Petrofactor, and conversion % have been calculated and presented in Table 5.9.

Table 5.9 Petrofactor, Oil Yield, and Conversion % of Sohagpur coal samples.

Sample Name	PF (Petro factor)	Oil Yield	Conversion (Jin & Shi, 1997)	Conversion (Guyot, 1978)
Sharda	17.08	58.04	88.64	84.65
Dhanpuri	19.96	56.22	86.99	82.23
Rajendra	14.12	58.80	89.33	87.14
Khairaha VI	12.21	58.83	89.36	88.74
Khairaha VII	18.09	55.85	86.65	83.80
Damini VI (1st Site)	18.18	58.72	89.25	83.73
Damini VI (2nd Site)	21.77	56.76	87.47	80.71
Damini V	19.48	55.04	85.91	82.63
Bangwar	16.77	56.43	87.17	84.91
Amalai	21.84	55.12	85.98	80.65

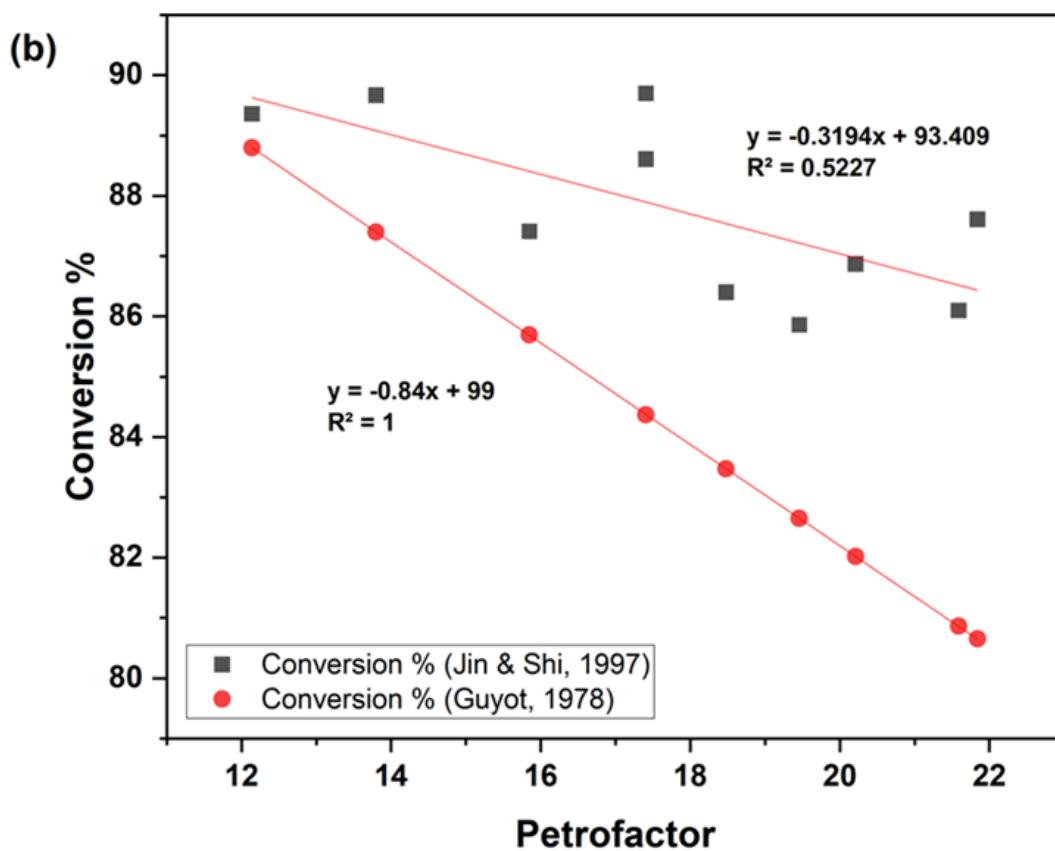
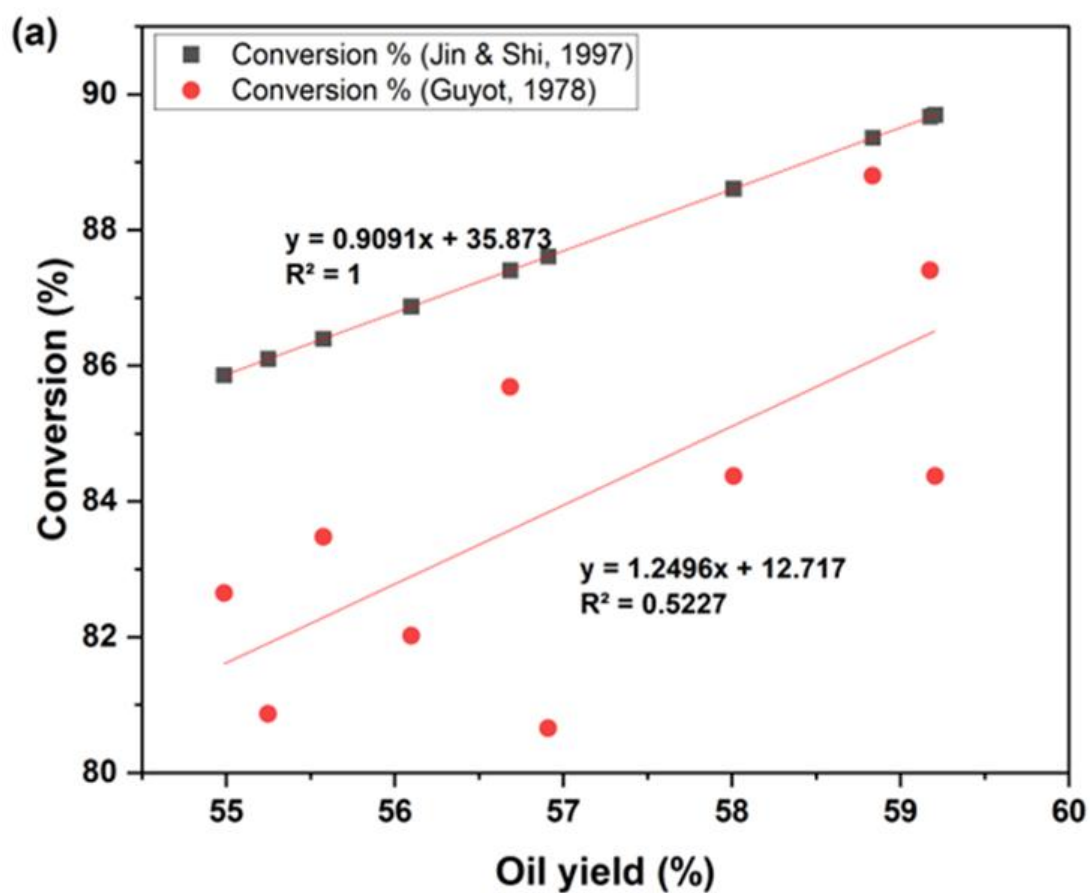


Figure 5.13 Conversion (%) with oil yield % (a) and with Petrofactor (b) for samples of Sohagpur coals.

The conversion percentage of these coals exhibits a negative association with Petrofactor and a positive correlation with oil yield (Figures 5.13a and b). The conversion percentage derived from Jin and Shi (1997) indicates that as the oil yield is converted into oil and made suitable for liquefaction, the oil yield increases. On the other hand, the negative correlation between conversion percentage and petrofactor indicates that a decrease in petrofactor is associated with a high conversion percentage in coal samples, while a higher petrofactor is associated with a lower conversion percentage.

Saxby (1982) noticed a relationship between the chemical composition of the coal and oil yield obtained by the open system pyrolysis by testing many coal and oil shale samples and proposed the formula:

$$\text{Oil wt. \%} = 66.7 \text{ H/C} - 57.0 \text{ O/C} - 33.3$$

Where oil wt. % will be on a dry, mineral-free basis.

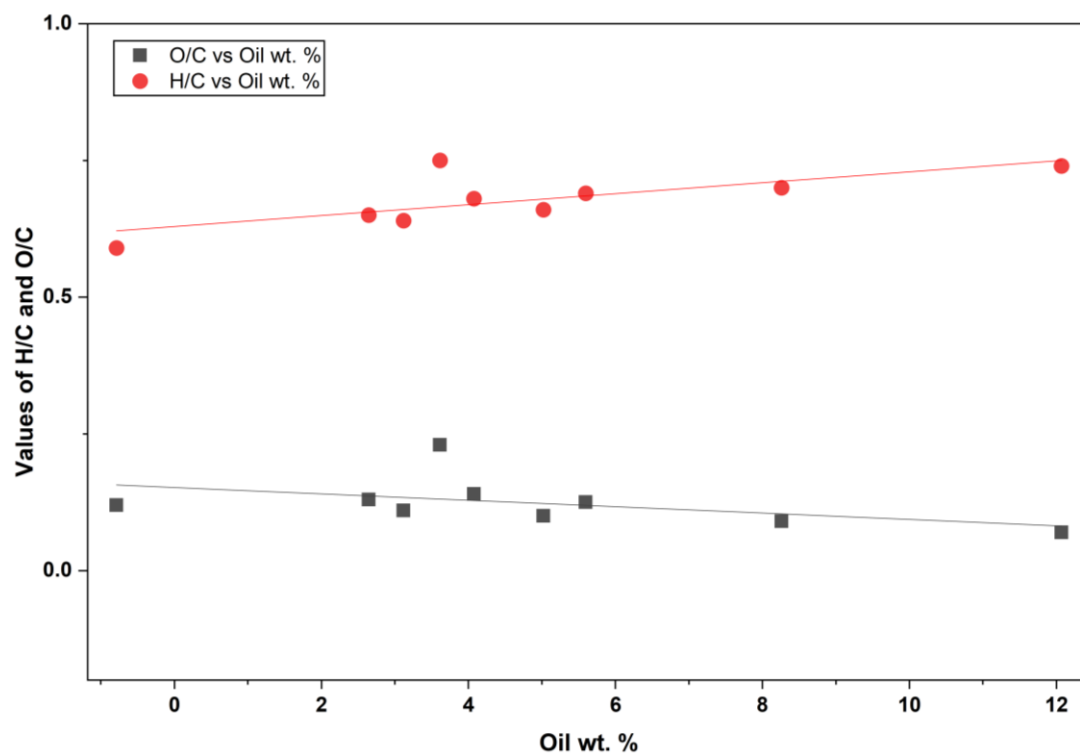


Figure 5.14 Cross plot of oil wt. % and the values of H/C and O/C for coals of the Sohagpur coalfield.

Based on the atomic H/C and atomic O/C ratios, the oil wt. % of Sohagpur coals have been calculated, and when the calculated values are plotted in a scatter plot, they shows a positive correlation with the H/C values, and a negative correlation with the O/C values, as shown in Figure 5.14.

The coals of the Sohagpur coalfield have been observed to be rich in hydrocarbon having excellent source of generation potential. To examine the relationship between reactive macerals and oil yield, TOC, S2, and HI in coals from Sohagpur coalfield, a multi-scatter plot with regression lines is shown in Figure 5.15, which indicates that all these variables are positively correlated with reactive macerals.

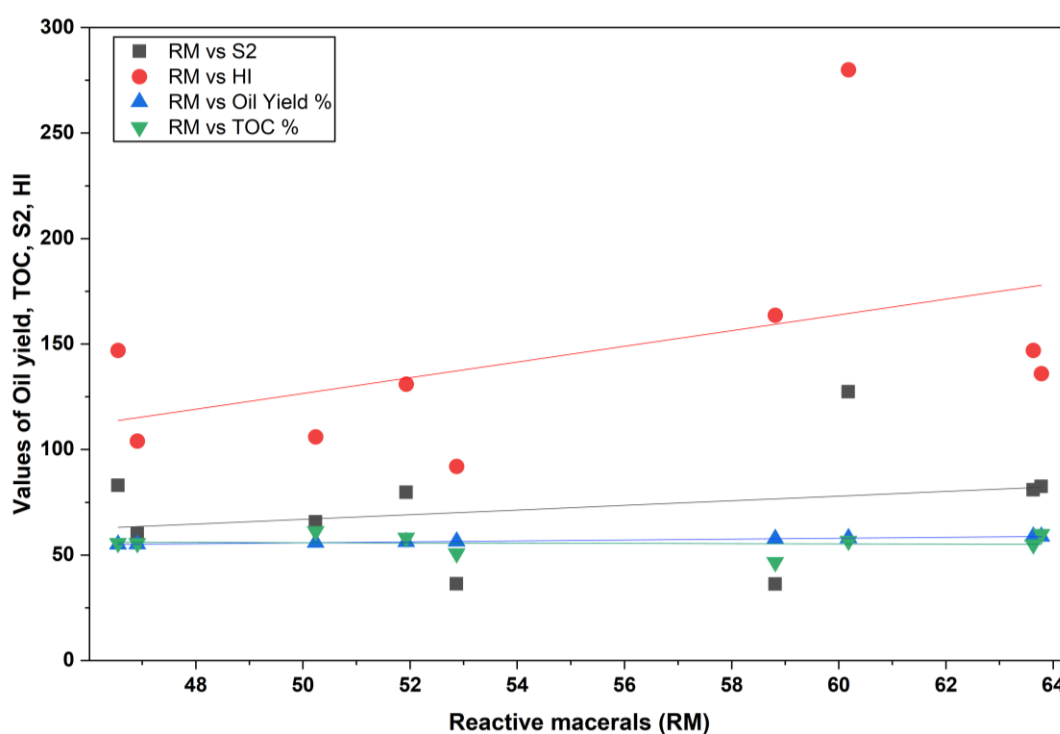


Figure 5.15 Correlation plot of total reactive macerals (RM) with Oil yield %, TOC, S2, and HI for coals of Sohagpur coalfield.

It suggests that as reactive maceral content increases, the hydrocarbon potential of coal increases. Among the correlated parameters, HI shows a strong positive correlation with reactive macerals, indicating that reactive macerals in coal contribute to the hydrocarbon

generation. A positive correlation of S₂ with reactive macerals suggests that the hydrocarbon released due to thermal cracking comes from the reactive macerals, which is also confirmed by the positive correlation of TOC with the reactive macerals

5.9 Coal bed methane potential

As per the previous section, these coals are of kerogen type III and have the potential to generate gaseous hydrocarbons. Coal bed methane (CBM) is also known as coal seam gas (CSG), coal seam natural gas, or coal seam methane (Moore, 2012). Coal may serve as both a source and a reservoir of methane. CBM is mostly composed of methane (CH₄), a colourless and odourless gas that is a major component of natural gas. CBM is considered a very clean-burning fossil fuel, but it also poses environmental risks from its extraction operations. Since 2007, coalbed methane has been commercially produced in India; however, CBM production remains low due to weak infrastructure and limited permeability (Kamble et al., 2022).

CBM is regarded as one of the most feasible solutions for closing the gap between energy supply and demand in India, the country with the second-fastest rate of economic growth (Ojha et al., 2013). In the current situation in India and around the world, it is a very demanding fuel (Ojha et al., 2011).

The interplay between hydrocarbon generation, storage and the adsorption properties of coal controls coal bed methane occurrences. Gas generation is the process by which methane is formed within coal seams, primarily through the thermal maturation of vitrinite-rich organic matter. Thermogenic methane is generated as coal undergoes coalification, with higher maturity coals producing greater amounts of methane from the decomposition of kerogen. Hydrogen-rich coals may also generate minor amounts of liquid hydrocarbons (Tissot and Welte, 1984).

Gas content represents the quantity of methane physically present in the coal at a given time, including both adsorbed gas on internal surfaces and free gas in fractures and cleats. It is influenced by coal rank, maceral composition, moisture content, and pressure-temperature conditions. Gas content is often measured in the field and provides an instantaneous snapshot of methane stored within the coal, reflecting both historical generation and dynamic equilibrium with surrounding formation pressures.

Gas in place, often quantified from adsorption isotherms, indicates the total methane a coal seam can store, including both adsorbed and free gas. The adsorption capacity of coal is controlled by surface area, microporosity, and maceral composition, with vitrinite-rich coals exhibiting higher adsorption potential compared to inertinite-dominated seams. Gas in place is therefore a theoretical measure of methane storage, whereas gas content reflects the actual amount present under in situ reservoir conditions (Clarkson and Bustin, 1999).

CBM formation can occur in two ways: biogenic and thermogenic. Both thermogenic and biogenic types of CBM are produced during the coalification process (Singh, 2010; Singh, 2011; Tang et al., 1996). Biogenic methane is produced by microbes on plant matter, whereas thermogenic methane is produced by the thermal and chemical conversion of vegetable matter to methane. CBM mostly occurs in the adsorbed state, with a small amount also present in the free state (Laxminarayana and Crosdale, 1999). According to published research, methane storage is primarily influenced by temperature, depth, mineral matter, fracture, coal rank, moisture, volatile matter, and coal type (Kim, 1977; Laxminarayana and Crosdale, 1999). Like the United States of America, Australia, and Canada, India should step up its efforts to explore and exploit CBM to ensure the country's energy security and support the development of cleaner fuel (Shah & Totlani, 2014). Forecasting the gas concentration with little effort and expense can be achieved

by employing methods that use correlations derived from coal properties (Asif et al., 2020).

Based on geochemical parameters and depth, several mathematical equations have been proposed to assess the coal bed methane potential. In this study, we used the three formulas given by Kim (1977), Meissner (1984), Ryan (1991), and Mavor et al. (1994).

5.9.1 Based on the Kim formula

Kim (1977) proposed an empirical relationship which showing that adsorbed gas content is also affected by depth, temperature and pressure, along with proximate parameters.

Gas content (cc/g) in the adsorbed state can be calculated by-

$$G=0.75 * [\{100-A-M\}/100] * [K(P)^N-0.14*(1.8D/100)]$$

Where G= Gas content (In adsorbed state, cc/g), A= Ash Content %, M= Moisture %, D= Depth of sample (m)

$$N = 0.315 - 0.01 * [F.C._{(daf)}/V.M._{(daf)}]$$

Where F.C. and V.M. are fixed carbon and Volatile matter % on a dry ash-free basis.

$$K = 0.8 * [F.C._{(daf)}/V.M._{(daf)}] + 5.6$$

Where F.C. and V.M. are fixed carbon and Volatile matter % on a dry ash-free basis.

$$P = P_{hyd} = 0.096 * D$$

Where D is depth in meters.

Table 5.10 Calculated parameters and adsorbed gas content for Sohagpur coals based on the Kim formula.

Sample/seam name	Depth (meter)	N	K	P	Gas Adsorbed (cc/g)
Sharda	17.70	0.29	7.25	1.70	4.90
Damini V	24.30	0.30	7.01	2.33	4.42
Dhanpuri	40.56	0.29	7.50	3.89	6.06
Amalai	41.60	0.30	7.26	3.99	5.97
Rajendra	59.08	0.30	7.09	5.67	6.58
Khairaha VI	59.58	0.30	7.02	5.72	6.27
Damini VI 1st site	61.26	0.29	7.24	5.88	5.62
Damini VI 2nd site	61.43	0.29	7.22	5.90	6.12

Sample/seam name	Depth (meter)	N	K	P	Gas Adsorbed (cc/g)
Khairaha VII	80.20	0.29	7.21	7.70	7.26
Bangwar	80.84	0.30	7.08	7.73	5.74

Based on the above equation, the adsorbed gas content in Sohagpur coals has ranged from 4.42 to 7.26 cc/g as shown in Table 5.10. Another conclusion is that as depth increases, the positive correlation with the adsorbed gas content shown in Figure 5.16 also increases.

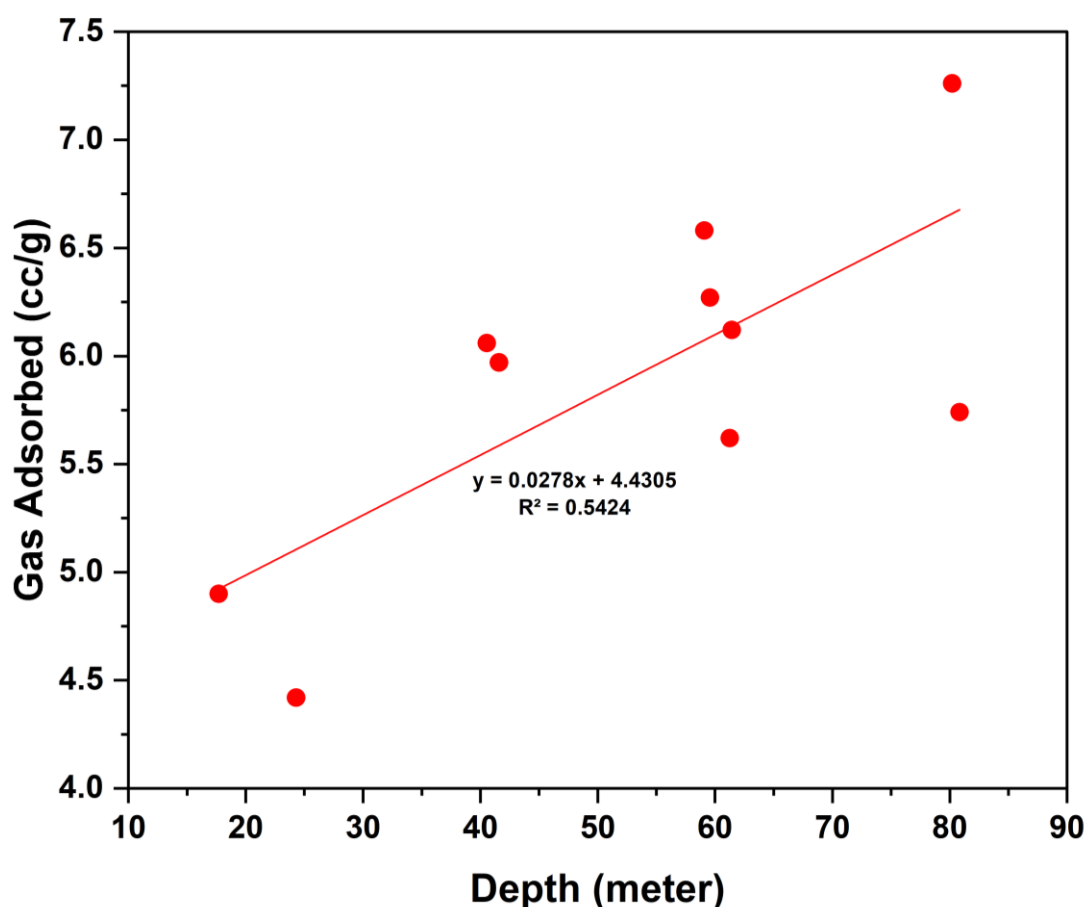


Figure 5.16 Adsorbed gas content from the Kim formula and its relationship with the depth.

The limitation of this formula is that Kim's (1977) formula estimates the adsorbed gas content from ash, moisture, fixed carbon, volatile matter, depth, and pressure, assuming homogeneous coal and linear depth–pressure relationships. It neglects variations in maceral composition, microporosity, and mineralogy.

5.9.2 Based on the Meissner formula

The nature of the source material, temperature, and pressure all a significant impact on the production of coal bed methane (Kishor et al., 2023b). Meissner (1984) developed a method for estimating methane gas based on using volatile matter on a dry ash-free basis.

The volume of methane generated increases exponentially as volatile material decreases. When the volatile percentage hits 37.80%, Meissner suggested that considerable thermal methane generation starts. To forecast the quantity of methane thermally produced from coal, Meissner originated a quantitative formula (Meissner, 1984).

$$\text{Volume of CH}_4 = -325.6 * \log(\text{V.M.}/37.8)$$

The above equation was used in the current study because the coal samples had characteristics comparable to those used by Meissner to forecast methane content in Cretaceous coals in the Rocky Mountains of the United States. In terms of rank, both coals are high volatile bituminous A. In the above equation, the VM has been taken on a dry ash-free basis.

Table 5.11 Samples and their corresponding methane content calculated from the Meissner formula.

Sample/seam name	Methane content based on the Meissner formula (cc/g)
Sharda	20.32
Damini V	5.80
Dhanpuri	30.81
Amalai	21.01
Rajendra	10.92
Khairaha VI	3.71
Damini VI 1st site	20.06
Damini VI 2nd site	18.65
Khairaha VII	18.39
Bangwar	9.88

Based on the above equation, methane values for the Sohagpur coals have been calculated, ranging from 3.71 to 30.81 cc/g as shown in Table 5.11. These values are calculated using

a mathematical equation, so they may differ from the actual methane present in the coal samples. The estimated methane content of 30.81 cc/g for the Dhanpuri coal sample is within the range reported for high-gas-content bituminous coal seams worldwide. Such values are typically associated with deeper, higher-rank coal seams possessing abundant microporosity and effective geological sealing, which enhance methane generation, adsorption, and preservation. Since the Meissner formula is an empirical estimation method, the calculated methane content reflects the expected gas-holding potential under representative in-situ reservoir conditions.

The key limitation of the Meissner (1984) formula is empirical and based on high-volatile bituminous A coals, so it may be inaccurate for coals of different rank, maceral composition, or depositional settings. It assumes volatile matter alone controls methane generation, ignoring mineral matter, porosity, pressure–temperature history, and in situ gas loss.

5.9.3 Based on the Ryan formula

Ryan (1991) proposed a mathematical equation to calculate the volume of gas with the help of depth, proximate constituents, and maximum values of vitrinite reflectance. The formula for gas content (cc/g) is given below-

$$V_{\text{gas}} = B \cdot (100 - M - A) / 100 / 32.037$$

Where V_{gas} shows the volume of gas (cc/g), and B is a parameter calculated with the below equation, while M and A are the moisture and ash %, respectively.

$$B = \ln(C) / 2.30259 - 1.095 / 0.003913$$

In the above equation, ln is the log on normal base, and C is the value calculated through the following formula with the help of depth and maximum vitrinite reflectance values-

$$C = D \cdot R^{2.5} - 0.2$$

Where D is the depth in meters and R is the value of maximum vitrinite reflectance.

Based on these equations, the gas volume for Sohagpur coals has been calculated, and is shown in Table 5.12, and the values range from 3.81 to 13.82 cc/g.

Table 5.12 Volume of gas and other parameters calculated from the Ryan formula.

Sample/seam name	Depth (m)	R _{max}	C	B	V _{gas} (cc/g)
Sharda	17.70	0.90	12.73	157.18	3.81
Damini V	24.30	0.91	18.05	246.39	5.07
Dhanpuri	40.56	1.04	42.34	464.24	10.59
Amalai	41.60	1.02	41.36	458.28	10.56
Rajendra	59.08	0.90	42.96	468.01	10.95
Khairaha VI	59.58	0.78	30.24	378.23	8.46
Damini VI 1st site	61.26	1.15	82.40	634.44	12.34
Damini VI 2nd site	61.43	1.18	88.14	651.64	13.82
Khairaha VII	80.20	0.91	60.03	553.51	12.92
Bangwar	80.84	0.89	57.23	541.30	10.10

As depth is one of the important parameters used to calculate the gas volume through this formula, the correlation between depth and gas volume is positive, as shown in Figure 5.17.

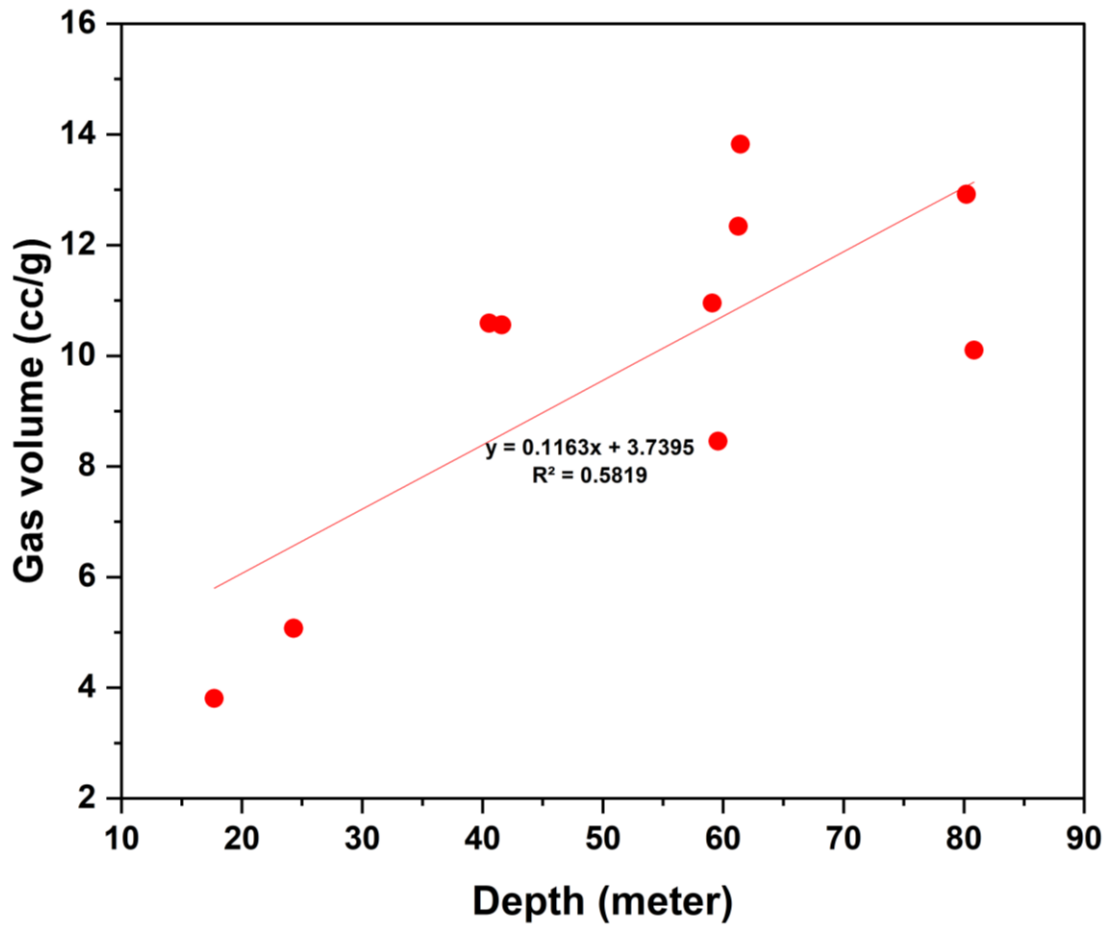


Figure 5.17 Gas volume (cc/g) from the Ryan formula and its relationship with the depth.

From a limitation perspective, Ryan's (1991) formula estimates coalbed gas volume using depth, proximate analysis, and maximum vitrinite reflectance. Gas content (V_{gas} , cc/g) is calculated from moisture, ash, depth, and vitrinite reflectance values through a logarithmic relationship. The approach integrates coal maturity and burial depth to predict in situ gas content, providing a practical tool for first-order CBM evaluation in coals with known rank and compositional characteristics.

5.9.4 Based on the Mavor formula

Mavor et al. (1994) proposed an equation to estimate the gas volume based on the inherent ash and moisture content of the coal samples. The empirical formula used to calculate the volume of gas is given below-

$$V_{\text{gas}} = 18.77 - 23.47 * A / (1 - M)$$

Where V_{gas} shows the volume of gas (cc/g), A shows the ash fraction, and M shows the moisture content.

Table 5.13 Samples and their corresponding gas volume from the Mavor formula.

Sample/seam name	Volume of gas based on Mavor formula (cc/g)
Sharda	14.53
Damini V	12.51
Dhanpuri	13.20
Amalai	14.27
Rajendra	15.23
Khairaha VI	14.44
Damini VI 1st site	11.48
Damini VI 2nd site	13.02
Khairaha VII	15.34
Bangwar	10.57

As shown in Table 5.13, the gas volume ranges from 10.57 to 15.34 cc/g according to the Mavor formula.

The limitation of the Mavor et al. (1994) formula is that it assumes coal gas content is controlled solely by ash and moisture, while ignoring coal rank, maceral composition, microporosity, depth, and thermal maturity. Being empirical, it is calibrated for specific coal types and may be inaccurate for coals with different ranks or depositional settings.

5.9.5 Mineral matter and ash influence on CBM generation potential

Mineral matter and ash content critically influence coal bed methane (CBM) generation, storage, and recoverability, both directly and through their effects on empirical methane prediction formulas. High ash yield affects vitrinite and other gas-generating macerals, reducing thermogenic methane yield, an effect explicitly incorporated in formulas such as Kim (1977) and Mavor et al. (1994), where gas content decreases proportionally with increasing ash and moisture (Kim, 1977; Mavor et al., 1994). Similarly, Meissner's (1984) volatile-matter-based formula indirectly reflects ash influence, as ash affects volatile content, delaying the onset of significant methane generation, while Ryan's (1991) depth-

and vitrinite reflectance dependent approach accounts for ash and moisture in combination with thermal maturity (Meissner, 1984; Ryan, 1991).

Beyond proximate constituents, minerals affect gas adsorption and storage. Carbonate and silicate minerals occupy micropores and cleats, reducing methane adsorption capacity (Clarkson and Bustin, 1999; Bustin et al., 2008). High ash content can also hinder cleat formation and permeability, limiting gas desorption even when methane has been generated. Thermal effects are also relevant: some minerals catalyze hydrocarbon cracking, while others barrier heat flow, influencing maturation and the applicability of depth- and maturity-based gas content formulas (Kim 1977; Clarkson and Bustin, 1999).

5.10 Comparative assessment of Coalbed Methane potential values of Sohagpur Coals with other Permian Coals

The potential of coalbed methane in Indian Gondwana coalfields has been evaluated using a variety of empirical approaches that integrate coal rank, burial depth, and proximate constituents, as shown in Table 5.14. The comparative evaluation of coalbed methane (CBM) potential values estimated using the empirical models of Kim (1977), Ryan (1991), and Mavor et al. (1994) highlights significant spatial variability in CBM prospectivity across Indian Permian coalfields.

Table 5.14 Comparative coalbed methane (CBM) potential of Sohagpur coals with other Permian coalfields in India using Kim (1977), Ryan (1991), and Mavor et al. (1994) models (Pophare et al., 2008; Kumar et al., 2015; Prabhu and Mallick, 2015).

Author	Coalfield	CBM Potential (cc/g)		
		Kim (1977)	Ryan (1991)	Mavor et al. (1994)
Pophare et al. (2008)	Sawang area, East Bokaro Coalfield	1.19-4.43	--	--
Kumar et al. (2015)	Moonidih Block, Jharia coalfield	17.91-18.71	--	--
Prabhu and Mallick (2015)	Bokaro	4.9–11.8	6.2– 13.5	12.7
	North Karanpura	6.1-8.8	8.8– 11.6	10.7
	Raniganj East	5.1–11.6	7.3– 13.4	9.91
	Sohagpur	4.9-7.1	8.8-12.1	14

	Barmer	0.8–0.9	7.4– 8.03	9.7
	Satpura	5.1–6.8	9.5– 11.9	11.4
	Sonhat	5.9–6.2	11.8– 12.3	14.2
	South Karanpura	5.3–6.4	10.3– 11.8	9.61
	Wardha	2.8–4.2	8.2– 11.3	10.7
	Birbhum	5.2–7.1	9.7– 11.9	9.3
	Godavari	4.1– 5.7	9.7–12.7	12.1
	Kothagudem	3.4– 5.2	9.5–13.1	13.6
	Mand Raigarh	3.1– 4.7	8.1–11.1	9.8
	Rajmahal	3.9– 5.2	7.6–9.4	9.5
	Singrauli	2.9– 3.8	7.5–9.4	10.5
	Tatapani Ramkola	5.2– 7.8	9.3–12.8	11.7
	IB Valley	3.1– 3.4	7.8–8.3	6.8
	Mannargudi	0.4– 0.6	4.9–7.1	14.2
	Rajmahal	5.3– 6.1	10.4–11.5	9.5
	Satpura	5.1– 7.6	9.5–12.9	11.4
	Talcher	2.9– 3.6	7.69–8.8	6.73
This Study	Sohagpur	4.42–7.26	3.81–13.82	10.57–15.34

Pophare et al. (2008) evaluated the CBM potential of coals from the Sawang area of the East Bokaro coalfield using the empirical relationship proposed by Kim (1977). Their estimated gas content values ranged from 1.19 to 4.43 cc/g, which are among the lowest reported for Indian Gondwana coalfields. These low values were attributed to comparatively shallow burial depths and limited thermal maturity, indicating marginal CBM prospectivity in the Sawang area of East Bokaro.

Kumar et al. (2015) investigated the Moonidih Block of the Jharia coalfield. Using the Kim (1977) model, they reported very high CBM potential values ranging from 17.91 to 18.71 cc/g. These exceptionally high values reflect favourable geological conditions, including greater burial depth, higher coal rank, enhanced cleat development, and optimal pressure–temperature regimes, making the Jharia coalfield one of the most prospective CBM basins in India.

A comprehensive regional comparison was provided by Prabhu and Mallick (2015), who applied the Kim (1977), Ryan (1991), and Mavor et al. (1994) models to multiple Permian

coalfields across India. Their study covered coalfields such as Bokaro, North and South Karanpura, Raniganj East, Sohagpur East, Barmer, Satpura, Sonhat, Wardha, Birbhum, Godavari, Kothagudem, Mand Raigarh, Rajmahal, Singrauli, Tatapani–Ramkola, IB Valley, Mannargudi, and Talcher. Kim model estimates in these coalfields generally ranged between 3 and 8 cc/g, with lower values observed in Mannargudi and Barmer and moderate values in Raniganj East, Satpura, Sonhat, and South Karanpura. Ryan model estimates were consistently higher (approximately 7–13 cc/g), emphasizing the role of depth and vitrinite reflectance in enhancing gas content predictions. The Mavor model yielded values (6.73–14.2 cc/g), reflecting the dominant control of ash and moisture content on gas storage capacity. Their results highlighted strong basin-to-basin variability in CBM potential.

The present study on the Sohagpur coalfield integrates these empirical approaches to provide updated estimates of CBM potential. The Kim model yields values between 4.42 and 7.26 cc/g, comparable to those reported for the Sohagpur, Raniganj East, and Satpura coalfields by Prabhu and Mallick (2015). Ryan model estimates range from 3.81 to 13.82 cc/g, indicating variability related to depth and maturity within the basin. The Mavor model produces relatively high values (10.57–15.34 cc/g), suggesting that it enhances methane adsorption capacity in Sohagpur coals.

The CBM potential estimated in this study is based on empirical equations and laboratory-based petrographical and geochemical data rather than direct in-situ gas content measurements. Consequently, the estimates represent the theoretical methane storage capacity of the coal samples under controlled experimental conditions and may not accurately reflect actual reservoir conditions. This approach does not account for factors such as reservoir heterogeneity, in-situ stress, pore pressure, groundwater conditions, cleat permeability, and gas saturation, all of which influence methane

occurrence and recoverability. Therefore, the estimated CBM potential should be considered a preliminary assessment and interpreted with caution when extrapolating to field-scale reservoir performance.

Chapter: 6

Discussions

6.1 Introduction

This chapter brings together the petrographic, geochemical, mineralogical and multiscale pore-fracture data from this study to give a complete process-based picture of the Permian coals from the Sohagpur coalfield in central India's Son Valley. The goal is to develop this understanding of the effects on paleoenvironments, the viability of coal bed methane (CBM), and the ability to store CO₂.

The previous result chapter displayed various datasets within their respective analytical domains. This includes coal petrography (maceral, microlithotype, and reflectance measurement), proximate and ultimate compositions, Rock-Eval pyrolysis, XRD-XRF mineral signatures, FT-IR structural chemistry, and pore architecture characterised by SEM, SAXS, LPGA, MIP, and high-pressure CO₂ adsorption. The goal of this discussion is to put all of these findings into one geological and reservoir stand: here, the conditions lead to peat formation, and processes that happened in the basin affected the organic and inorganic inputs, how coalification changes the coal's molecular structure, how the resulting coal fabric and mineral distribution affected pore hierarchy, adsorption behaviour, and flow-relevant connectivity.

In the present chapter, data generated during the present investigations of the coals of Sohagpur have been synthesised to present the regional scale variation and correlation of coals of different seams along with their petrochemical characteristics, kerogen type, the possibility of coal acting as source rock, thermal maturity and impact of major/minor elements present in these coals. The evolution of these coals has also been discussed with maceral, microlithotype and mineral matter analyses as well as geochemical analyses. Coal facies, along with the type of flora, depositional environment, and coalification trend,

have also been discussed in the present chapter. The discussion has been framed around the nature of flora, the development of coal facies, depositional similarity and geothermal history.

A combination of composition, maturity, and structural factors at various scales affects its capacity to generate the CBM and store CO₂. This integration is evident in the Sohagpur coals, which have three interconnected areas of control. Rock-eval indices and FTIR functional group patterns indicate increased aromaticity, loss of oxygen, and reorganization, thereby controlling the density of adsorption sites. The histories of these organic and inorganic factors interacted to alter the coal's pore and fracture structure at multiple levels. SAXS was examined at nanopores, and SEM examined at microfractures and mineral infill. These things work together to figure out how much storage and flow movement space is needed.

This chapter follows a chain of events that link processes to properties to uses: paleoenvironmental settings → maceral/microlithotype fabric → maturity and molecular structure → mineral matter origin and distribution → pore fracture hierarchy → adsorption and connectivity → implication for CBM and CO₂. In this framework, CBM potential is examined at the intersection of

- (i) Maturity suitability, and organic matter quality (for gas generation and retention)
- (ii) Micropore-centric adsorption capacity (gas in place)
- (iii) Fracture connectivity by mineral occlusion (deliverability)

The potential of CO₂ sequestration is evaluated using the same framework, acknowledging that CO₂ adsorption. However, the field's feasibility depends heavily on how easily pores can be reached, how easily they can be injected, and how likely it is that permeability will change due to sorption and mineralogical limits. This examines how

macerals, especially the difference between fabrics that are mostly vitrinite and those that are mostly inertinite, affect CO₂ uptake and help to identify the best place to store it.

This discussion aims to go beyond simple description by combining different independent places of evidence into a single interpretive model. This will make it easier to draw a strong, mechanism-based conclusion about the Sohagpur coal systems. The outcome encompasses a reconstruction of the Permian mire environments and the coalification history of the Son Valley basin, along with frameworks of screening criteria and conceptual controls to facilitate subsequent evaluation of CBM and CO₂ storage in the Sohagpur coalfield.

Coal-bearing basins represent complex geological systems whose petrographic and geochemical attributes govern not only their economic value but also their potential for emerging energy and environmental applications. In this context, the present chapter focuses on the Sohagpur coalfield, one of the significant Gondwana coalfields of India, and provides a comprehensive characterization of coals occurring in its various seams through an integrated petrographic and geochemical approach.

An extensive and systematically curated dataset has been generated to elucidate the intrinsic properties and regional variability of these coals. This dataset integrates a wide range of analytical techniques, including proximate and ultimate analyses, vitrinite reflectance measurements, maceral and microlithotype studies, and advanced geochemical and mineralogical investigations such as X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier-transform infrared spectroscopy (FTIR), and Rock-Eval pyrolysis. Together, these methodologies provide a robust framework for evaluating coal rank, composition, thermal maturity, and organic matter type, as well as the mineralogical and elemental associations present within the coal seams.

The combined petrographic and geochemical datasets have been employed to examine both inter- and intra-seam variations at a regional scale, enabling meaningful correlations among different coal seams within the Sohagpur coalfield. These correlations help in understanding the spatial heterogeneity of coal properties and their relationship to depositional environment, peat-forming conditions, and post-depositional alterations. Maceral and microlithotype assemblages, in particular, have been used to reconstruct the evolutionary history of the coals and to infer the prevailing paleoenvironmental and paleoclimatic conditions during coal formation.

In addition to conventional coal characterization, the present study emphasizes the assessment of coalbed methane (CBM) potential and the feasibility of CO₂ sequestration within these coal seams. Detailed investigations of pore structure, microfracture development, and gas adsorption characteristics provide insights into the storage capacity, permeability, and gas retention behaviour of the coals. These parameters are critical for evaluating both methane generation and retention, as well as the suitability of the coal seams for long-term CO₂ storage, thereby linking traditional coal studies with contemporary energy transition and climate mitigation strategies.

Furthermore, integrating Rock-Eval pyrolysis data with petrographic observations enables evaluation of kerogen type, hydrocarbon generation potential, and the role of these coals as potential source rocks. Thermal maturity assessments based on vitrinite reflectance and pyrolysis parameters offer a coherent understanding of the maturation pathways of organic matter within the basin. The chapter also addresses the environmental implications of major, minor, and trace elements identified through geochemical analyses, highlighting their potential impact during coal utilization and post-mining processes.

Overall, this chapter provides a holistic synthesis of coal genesis, petrochemical evolution, gas adsorption behaviour, pore system development, and utilization potential of the Sohagpur coals.

6.2 Petro-chemical characterization of the coals of Sohagpur coalfield

The petrochemical characterization of the Sohagpur coals encompasses a comprehensive analysis of their qualitative and quantitative properties, including proximate and ultimate analyses, maceral composition, microlithotypes, mineral matter, and vitrinite reflectance. Geochemical characterization was carried out through several advanced analytical methods, including proximate analysis (measuring moisture, ash content, volatile matter, and fixed carbon), ultimate analysis (determining carbon, hydrogen, nitrogen, sulfur, and oxygen content), Rock-Eval pyrolysis (to assess the source rock potential), as well as elemental analysis of major, minor, and trace elements. Additionally, the identification of both organic and inorganic constituents was achieved using techniques such as X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR).

The study also explores the vertical distribution of key petrochemical components within the coal seam (from top to bottom), noting variations that suggests of enrichment or depletion process. These variations, both within individual seams and between different coal seams, provide important insights into the dynamic conditions in the basin during the coal formation, helping interpret the evolution of the coal deposit over time.

Several geological factors have influenced the properties of these coals, including the paleodepositional environment, lithostatic pressure, temperature, duration of heating, and post-tectonic transformations, such as igneous intrusions. These factors collectively leave distinct imprints on the coal's petrochemical signature, offering vital clues about its

genesis. The petrochemical properties, in turn, play a critical role in determining the coal's suitability for industrial uses.

The distribution patterns of petrographic components within the coal seam further indicate climatic changes and shifts in surface water cover during the coalification process. As the coalification process progresses, an increase in vitrinite content leads to a brightening of the coal's appearance. At the same time, a higher proportion of carbonaceous shale and dirt bands results in a duller, less reflective appearance. Vitrinite-enriched zones are typically associated with tropical, humid, and temperate climates that experienced wet conditions during peat accumulation. In contrast, zones enriched in inertinite suggest periods of intermittent dryness, intense oxidation, microbial degradation, and fire events, reflecting more arid conditions during coal formation.

As coalification advances, the carbon content steadily increases, while the oxygen and hydrogen content decrease, reflecting the progressive transformation of the peat into coal. The study takes great care to present the variation in the initial microconstituents of the coal, ensuring minimal sample preparation, and preserving the natural characteristics of the coal. Petrographic components are analyzed alongside mineral matter, and the proximate constituents are discussed based on their as-received values, providing a holistic view of the coal's chemical and physical makeup. This detailed petrochemical and geochemical analysis not only helps to understand the coal's formation and characteristics but also sheds light on its potential applications and industrial viability.

In the Sharda coal mine, the coal seam exhibits pronounced vertical heterogeneity in its petrochemical characteristics, reflecting changing depositional and post-depositional conditions during peat accumulation. The banded bright coal, forming the third band from the bottom, is characterized by relatively high moisture content. In contrast, ash yield is

comparatively elevated in the middle and lower bands, indicating increased mineral matter influx during these stages of deposition. Volatile matter content shows an inverse relationship with ash yield, with higher values in bands containing lower mineral matter. Fixed carbon content is higher in the upper part of the seam, decreases abruptly downward, and then increases again within the banded bright coal near the seam bottom. Banded dull coal displays lower carbon content compared to banded bright coal. At the same time, the bottom section records the highest carbon percentage, suggesting enhanced organic matter concentration and better preservation, particularly in vitrinite-rich intervals. Hydrogen content shows only minor variation throughout the seam, although slightly reduced values in the bottom section indicate a higher degree of aromaticity of the organic matter. Sulphur content follows a zigzag distribution, being higher in the upper part, decreasing downward, and increasing again within the banded dull coal, reflecting fluctuating sulphur incorporation during peat formation under varying microbial activity and mineral matter input. Nitrogen content remains relatively constant, consistent with its association with stable organic constituents, whereas oxygen content is higher in dull coal bands, indicating enhanced oxidation in these intervals. Megascopically, the seam is dominated by banded dull coal in the upper part, transitioning to well-developed banded coal toward the bottom, a variation closely linked to changes in maceral composition. The bottom band is enriched in inertinite macerals, suggesting intense oxidation and probable wildfire activity during peat accumulation. The reflectance values range from 0.65 to 0.84%, and the path followed by the fixed carbon % is shown in Figure 6.1. The banded bright coal has a higher reflectance than the other bands present in this seam.

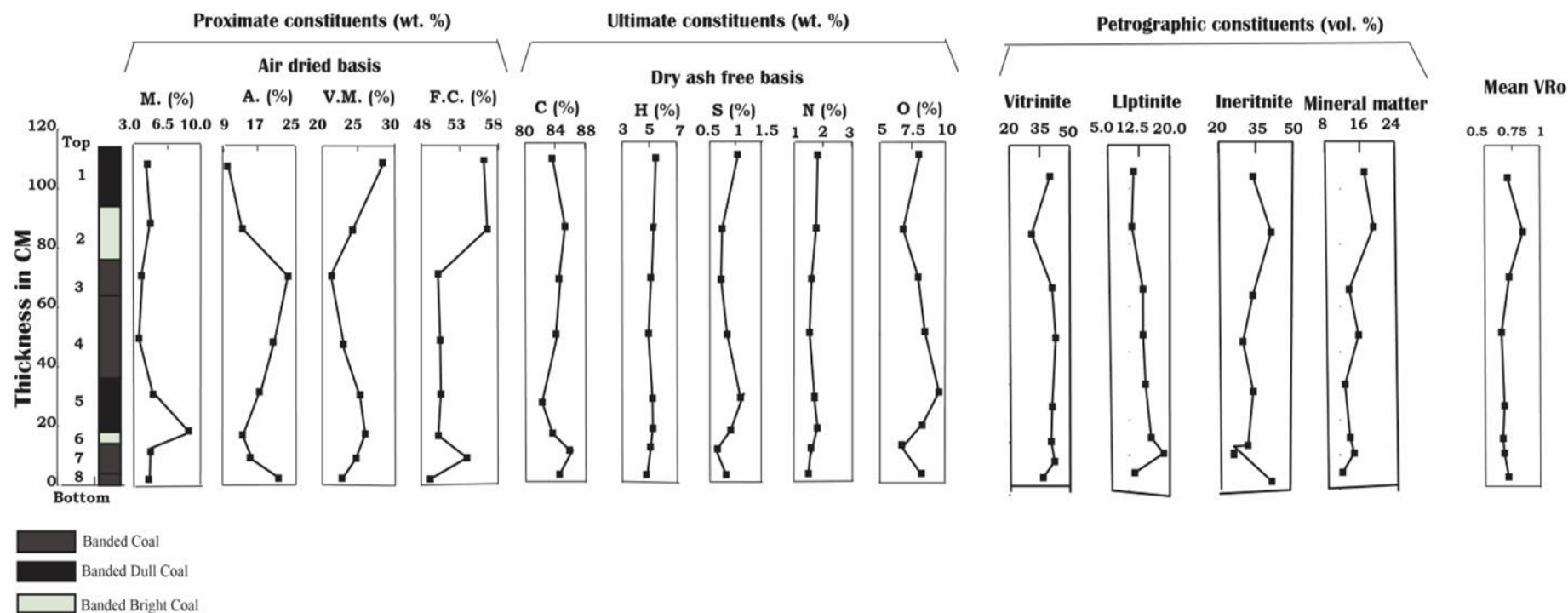


Figure 6.1 Petro-chemical characterization of the vertical seam profile of Burhar seam IV from the Sharda mine.

The Dhanpuri coal mine seam displays a systematic vertical variation in its petrochemical characteristics, reflecting changing depositional conditions during peat accumulation. Moisture content increases gradually toward the bottom of the seam, while the lower portion is marked by higher ash yield, indicating enhanced detrital and clastic influx during the later stages of peat deposition. This increase in mineral matter is accompanied by a corresponding decrease in volatile matter and fixed carbon contents in the lower bands, suggesting dilution of organic matter by inorganic constituents. Carbon content progressively decreases toward the bottom band, which is dominated by dull coal, and this trend is attributed to increased mineral matter concentration and comparatively poorer preservation of organic material. In contrast, hydrogen content is relatively higher in the bottom band, implying a greater abundance of hydrogen-rich functional groups, possibly related to lower coalification intensity or increased moisture retention. Sulphur content follows a zigzag distribution throughout the seam, reflecting fluctuating depositional conditions and variable sulphur fixation during peat formation. In contrast, nitrogen content remains relatively uniform. Oxygen content is elevated in the dull coal of the bottom band, indicating increased oxidation during deposition. Petrographically, the seam shows a clear transition from top to bottom, with the upper band characterized by low vitrinite content and relatively high inertinite abundance, suggesting oxidizing conditions and intermittent exposure of peat surfaces. Vitrinite content increases with depth, reflecting improved preservation of woody plant material under more reducing conditions, while the bottom band is enriched in mineral matter appears dull coal megascopically, indicative of enhanced clastic input during peat accumulation. The vitrinite reflectance values of this seam average at 0.77, while the top-to-bottom path of reflectance values shows that samples rich in vitrinite have a higher reflectance value, as shown in Figure 6.2.

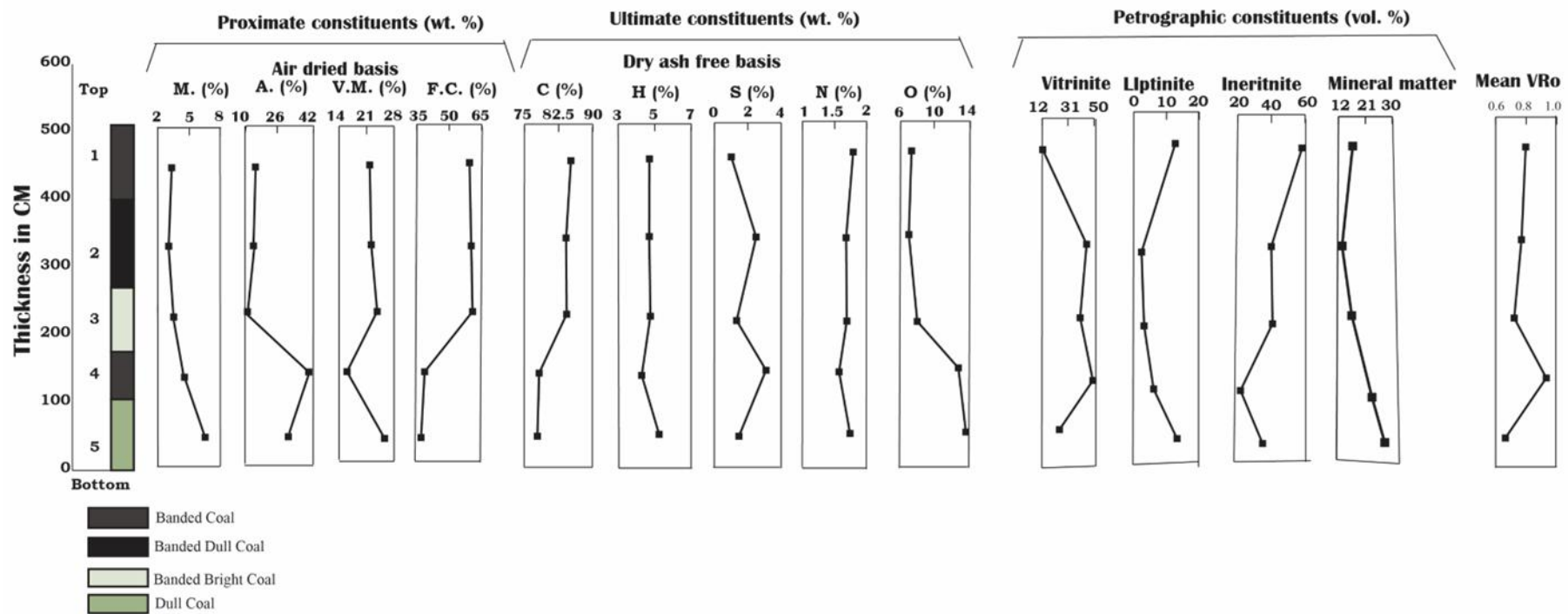


Figure 6.2 Petro-chemical characterization of the vertical seam profile of Burhar seam VI Top from the Dhanpuri mine.

In the Rajendra coal mine, the coal seam exhibits distinct vertical variations in petrochemical characteristics, reflecting fluctuating depositional and post-depositional conditions during peat accumulation. Moisture content shows an overall increasing trend toward the bottom of the seam, while the banded coal layer exhibits relatively higher ash yield, indicating localized enrichment in mineral matter. Volatile matter content is higher in the banded bright coal, suggesting improved preservation of reactive organic components, whereas fixed carbon content is comparatively elevated in both the uppermost and lowermost bands, pointing to variability in organic matter concentration and coalification intensity across the seam profile. Carbon content is lowest in the middle band and higher in the upper and lower sections, implying greater organic matter degradation or increased mineral matter influx in the middle part of the seam. Hydrogen content decreases slightly with depth, consistent with progressive coalification. Sulphur content increases toward the banded coal in the lower section, possibly reflecting enhanced sulphide mineral formation or greater sulphur incorporation under more reducing conditions, while nitrogen content is also elevated in the lower band, indicating better preservation of nitrogen-bearing organic compounds. Oxygen content is lowest in the upper band and highest in the middle band, suggesting enhanced oxidation in the middle interval. Petrographically, the seam is characterized by a vitrinite-rich middle band, containing more than 60% vitrinite macerals, indicative of optimal peat preservation under waterlogged reducing conditions. In contrast, the upper and lower bands are enriched in inertinite macerals, reflecting episodes of oxidation, peat degradation, and fluctuating water table conditions during seam development. The vitrinite reflectance values of these coal ranges from 0.54 to 0.66, and the middle band rich in vitrinite maceral group shows the higher values in comparison to other bands, as shown in Figure 6.3.

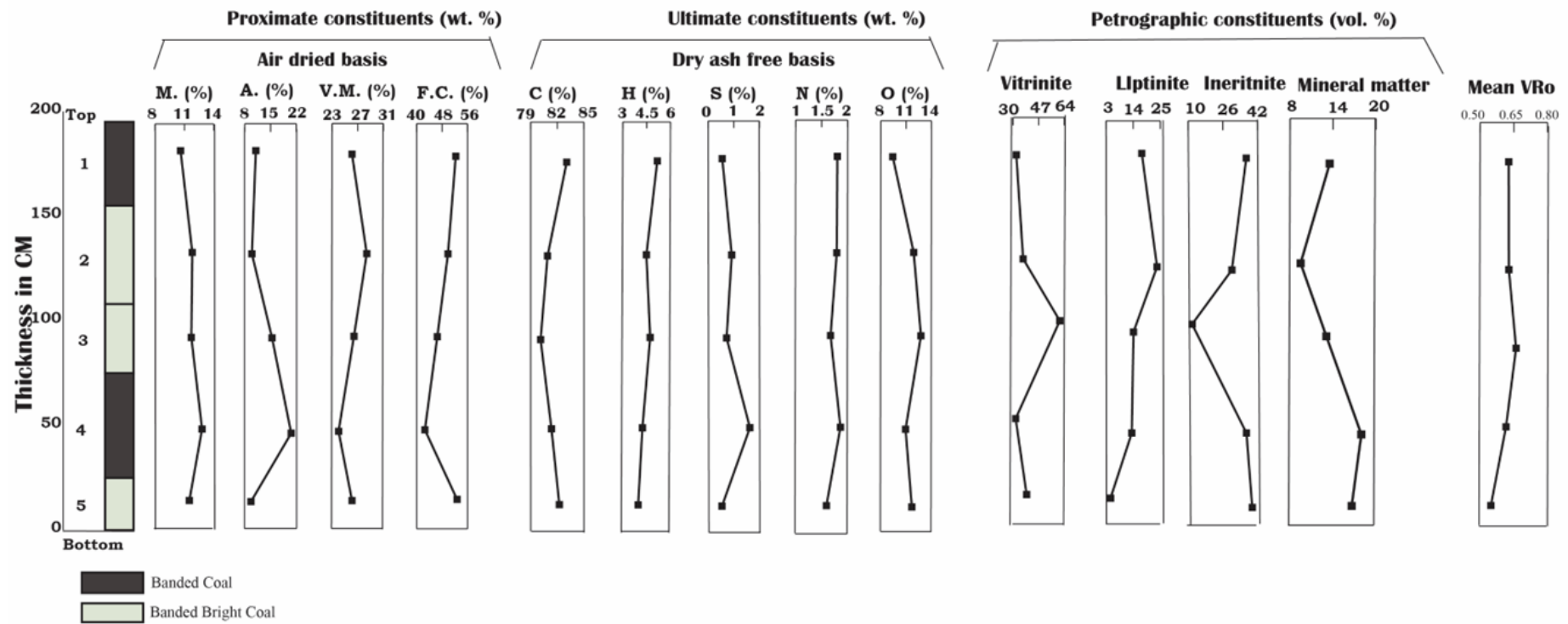


Figure 6.3 Petro-chemical characterization of the vertical seam profile of Burhar seam VI Bottom from the Rajendra coal mine.

Khairaha Seam VI exhibits distinct vertical variations in its petrochemical attributes, reflecting changing depositional conditions during peat accumulation. The bottom bands are characterized by relatively lower moisture content but higher ash yield, indicating enhanced mineral matter input in this interval. Volatile matter and fixed carbon contents attain their lowest values in the bottom band, suggesting significant dilution of organic matter and comparatively poorer organic concentration. Carbon content increases markedly in the middle section of the seam, where banded bright coal occurs, reflecting improved preservation of organic matter. Hydrogen content reaches its minimum in this band, indicating relatively higher aromaticity of the organic matter, whereas elevated hydrogen values in the bottom band point to lower coal rank or the increased moisture retention. Sulphur content is also higher in the bottom band, possibly resulting from sulphur enrichment during the later stages of peat accumulation under favourable reducing conditions. Nitrogen content shows an overall decreasing trend upward but increases locally within the banded dull coal of the bottom band, suggesting localized enrichment of nitrogen-bearing organic compounds. Oxygen content decreases toward the middle band and subsequently increases toward the bottom, rendering the top and bottom bands relatively oxygen-rich and indicative of enhanced oxidation in these intervals. Petrographically, the seam displays a zigzag vertical distribution of macerals, with the top and middle bands enriched in vitrinite, reflecting relatively stable and reducing depositional environments. In contrast, the pronounced increase in inertinite macerals below the middle band suggests a shift toward more oxidizing conditions and/or increased fire activity during the later stages of peat accumulation. The vitrinite reflectance values of these coals range from 0.49 to 0.67%, and the values follow the same zigzag path showing higher values at the bottom second band and then decreasing toward top and then again increasing in top band, as shown in Figure 6.4.

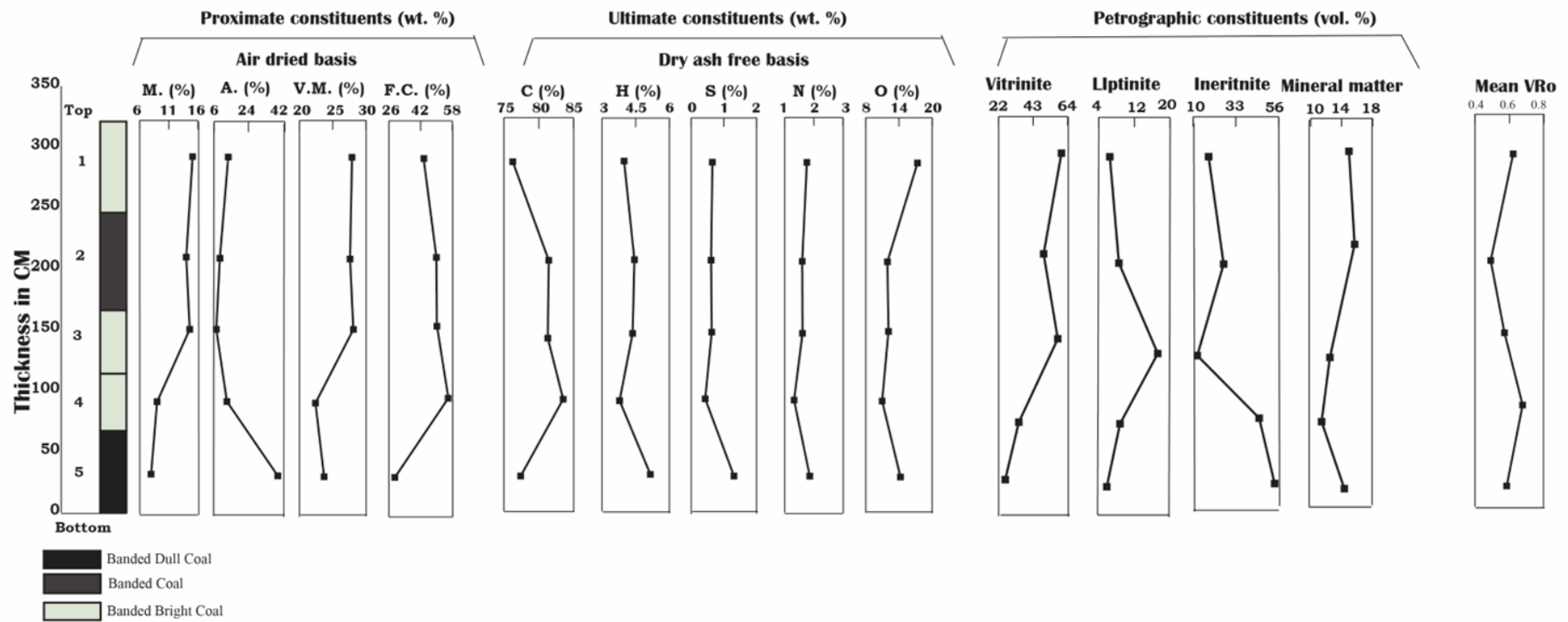


Figure 6.4 Petro-chemical characterization of the vertical seam profile of Burhar seam VI Bottom from the Khairaha coal mine.

Khairaha Seam VII shows pronounced vertical variability in its petrochemical characteristics, reflecting changing depositional conditions during peat accumulation. The upper and lower bands exhibit relatively higher moisture content, whereas the middle band shows lower moisture and the highest ash yield, indicating substantial mineral matter input during this phase of deposition. Correspondingly, volatile matter and fixed carbon contents are reduced in the middle band, consistent with its dull coal character and elevated inorganic dilution. A marked decrease in carbon content is observed in the banded dull coal of the middle section, reflecting enhanced incorporation of mineral matter and oxidation. Hydrogen and sulphur contents show similar declining trends in this interval, suggesting diminished preservation of organic matter. Nitrogen content remains nearly uniform throughout the seam, indicating limited sensitivity to variations in depositional conditions. Oxygen content attains its maximum in the middle band, further confirming intensified oxidation and an increase in inorganic matter concentration. Petrographically, the central band is dominated by banded dull coal with a high abundance of inertinite macerals, indicating significant oxidation of organic matter during peat formation. In contrast, both the overlying and underlying bands show an increased proportion of vitrinite relative to inertinite, implying comparatively improved preservation conditions under more reducing environments in adjacent stratigraphic intervals. The vitrinite reflectance values of this seam range from 0.61 to 0.66% and show minimal changes throughout the seam as shown in Figure 6.5.

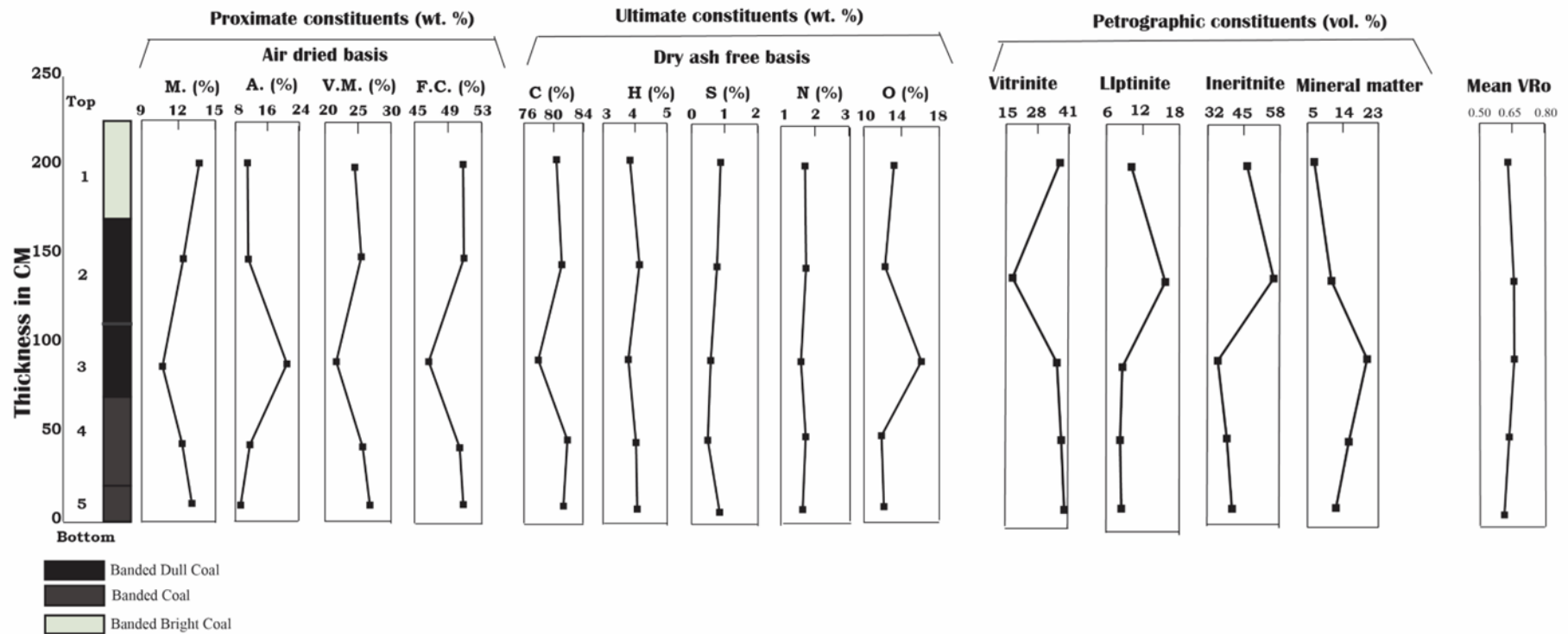


Figure 6.5 Petro-chemical characterization of the vertical seam profile of Burhar seam VII Top from the Khairaha coal mine.

Damini Seam VI exhibits pronounced site-specific variations in its petrochemical characteristics, reflecting localized differences in depositional and post-depositional conditions during peat accumulation. At the first site of Burhar seam VI Bottom, a decrease in moisture content is observed in the middle band, accompanied by an increase in ash yield, while volatile matter and fixed carbon contents decrease correspondingly, indicating enhanced mineral matter input and dilution of organic material in this interval. At the second site of Burhar seam VI Bottom, moisture content decreases toward the bottom of the seam, whereas ash yield increases with depth. Geochemically, the first site shows decreasing carbon and hydrogen contents with depth, suggesting progressive enrichment in mineral matter and/or degradation of organic matter, while a sudden increase in sulphur content in the basal section points to localized sulphur fixation under reducing conditions. Nitrogen content remains relatively uniform throughout the seam, whereas oxygen content attains its highest value in the middle band, indicating enhanced oxidation during that depositional phase. In contrast, the second site shows higher carbon and hydrogen contents in the middle section, suggesting improved preservation of organic matter during this interval. At this site, sulphur content decreases with depth, nitrogen content peaks in the middle band, and oxygen content reaches its minimum in the same interval, consistent with reduced oxidation and conditions for favourable peat preservation. Petrographically, Damini Seam VI is dominated by dull coal bands throughout the seam profile, reflecting high inertinite macerals and mineral matter abundance. However, the middle band is distinguished by comparatively lower inertinite content relative to the upper and lower bands, indicating a brief phase of reduced oxidation and comparatively better preservation of peat during seam development. The vitrinite reflectance values of these sites range from 0.73 to 0.97% and 0.76 to 1.0%, respectively and show higher values at the bottom bands as shown in Figure 6.6.

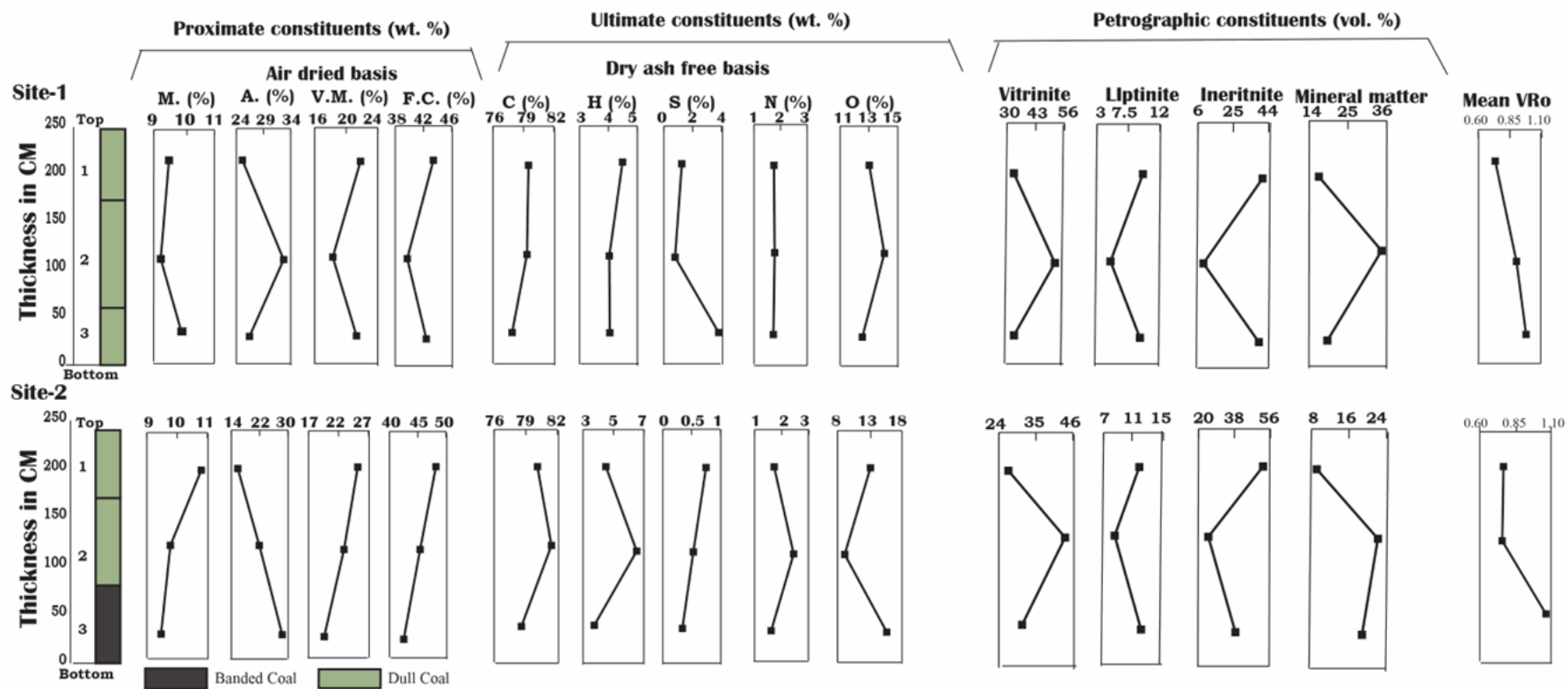


Figure 6.6 Petro-chemical characterization of the vertical seam profile of Burhar seam VI Bottom from Damini coal mine.

Burhar seam V from the Damini coal mine exhibits distinct vertical variations in its petrochemical characteristics reflecting changes in depositional conditions during peat accumulation. Moisture content increases in the middle band of the seam, while ash yield shows a corresponding decrease, indicating reduced mineral matter input and enhanced organic matter preservation in this interval. Volatile matter and fixed carbon contents show trends similar to moisture content throughout the seam profile, suggesting a strong relationship between moisture retention and the preservation of organic constituents. Elemental analysis reveals that carbon, hydrogen, and sulphur contents increase upward toward the middle band and then decrease toward the bottom, indicating to optimal peat preservation and relatively stable, reducing conditions during the middle stage of seam development. In contrast, nitrogen and oxygen contents decrease toward the middle band but increase in the upper and lower sections, reflecting enhanced oxidation and greater inorganic influence at the seam boundaries. Megascopically, the upper band is dominated by dull coal with high mineral matter content, indicating increased detrital input during the early phase of peat deposition. With increasing depth, mineral matter content decreases, marking a transition to more organic-rich peat accumulation under diminished clastic influence. The vitrinite reflectance values of coals from this seam range from 0.58 to 0.80%, showing the minimum values at the middle band, while higher values at the bottom and top band, as shown in Figure 6.7.

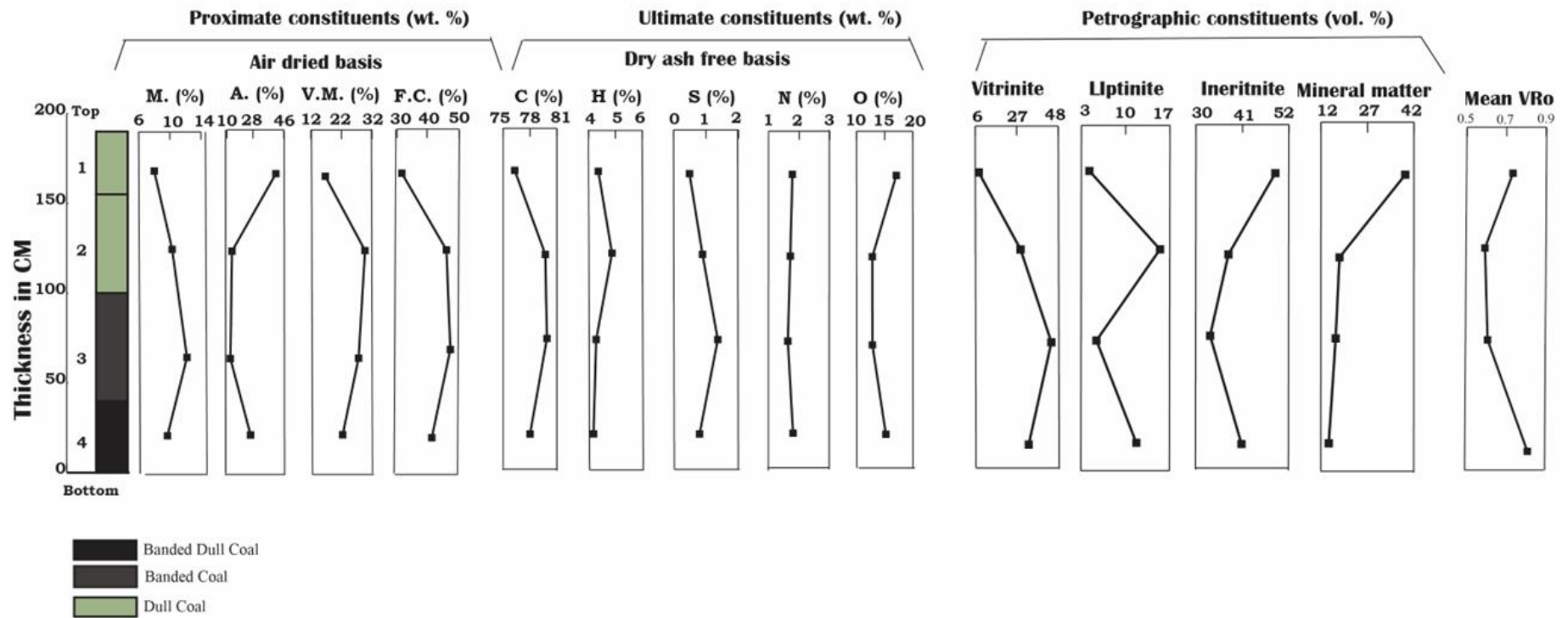


Figure 6.7 Petro-chemical characterization of the vertical seam profile of Burhar seam V from Damini coal mine.

The Burhar seam VII Top from Bangwar coal mine exhibits pronounced vertical variability in its petrochemical characteristics, reflecting fluctuating depositional conditions during peat accumulation. Moisture content is relatively low in the upper band, then increases and abruptly decreases toward the bottom of the seam. Ash yield is highest in the upper band, indicating significant mineral matter influx during the early stages of seam development. Volatile matter and fixed carbon contents exhibit a zigzag pattern of decrease and increase throughout the seam profile, suggesting alternating phases of organic matter preservation and dilution by inorganic constituents. Carbon content reaches its maximum in the bottom banded coal and its minimum in the middle dull coal band, reflecting variations in organic matter concentration and the degree of oxidation. Hydrogen content also follows a zigzag trend, with higher values in the upper band, a decline in the middle section, a subsequent increase, and a final decrease toward the bottom, indicative of fluctuating coalification intensity and preservation conditions. Sulphur content is relatively higher in the middle and lower sections, suggesting enhanced sulphur incorporation during these phases of peat accumulation, while oxygen content attains its maximum in the dull coal band, confirming increased oxidation. Petrographically, the seam is composed of alternating banded and dull coal lithotypes, with inertinite macerals dominating over vitrinite and liptinite, indicating pervasive oxidation of peat material and likely frequent exposure of the peat surface during deposition. The vitrinite reflectance values of this seam range from 0.59 to 0.71%, the bottom band have higher values in comparison to other bands, while the middle bands have the lower values, as shown in Figure 6.8.

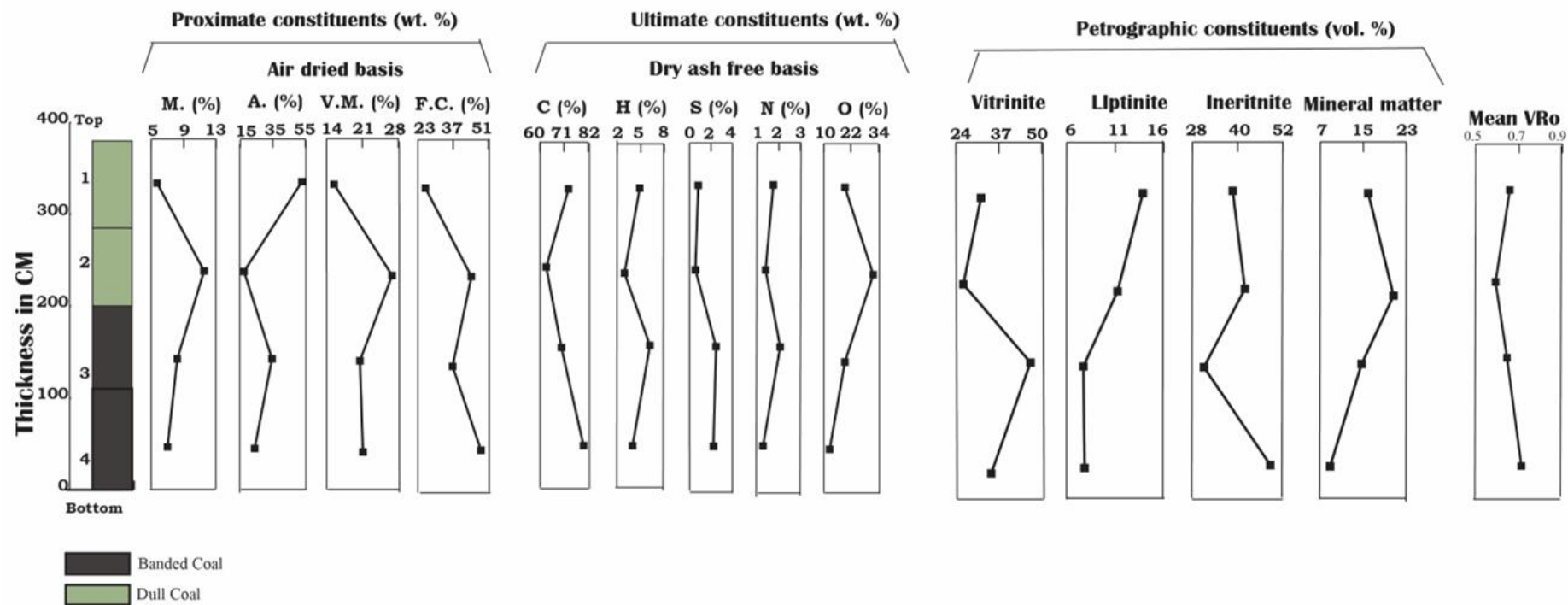


Figure 6.8 Petro-chemical characterization of the vertical seam profile of Burhar seam VII Top from Bangwar coal mine.

The Burhar seam VI Top from Amalai coal mine displays distinct vertical variations in petrochemical characteristics, reflecting fluctuating depositional and diagenetic conditions during peat accumulation. Moisture content is higher in the upper and lower bands, whereas the middle band, dominated by dull coal, exhibits lower moisture content. This middle interval shows the highest ash yield, indicating a significant influx of mineral matter, and corresponds with lower volatile matter and fixed carbon contents, reflecting dilution of organic material by inorganic constituents. A pronounced drop in carbon content within the dull coal band is accompanied by similarly low hydrogen values, indicative of substantial organic matter degradation. Sulphur content is elevated in the lower section, likely due to sulphur fixation under reducing conditions, whereas nitrogen content remains relatively uniform throughout the seam. Oxygen content peaks in the middle dull coal band, confirming enhanced oxidation during this depositional phase. Petrographically, the seam exhibits a pronounced zigzag pattern in maceral distribution: the top band is vitrinite-rich, followed by a sharp decline, then a gradual increase toward the middle band, with this cyclical pattern continuing downward. Such alternating increases and decreases in vitrinite concentration reflect repeated fluctuations in depositional conditions, water table levels, and oxidation states, resulting in alternating phases of organic matter preservation and degradation throughout the seam. The vitrinite reflectance values of these coals range from 0.60 to 0.81%, showing that the top and bottom bands have lower values in comparison to the middle bands of the seam as shown in Figure 6.9.

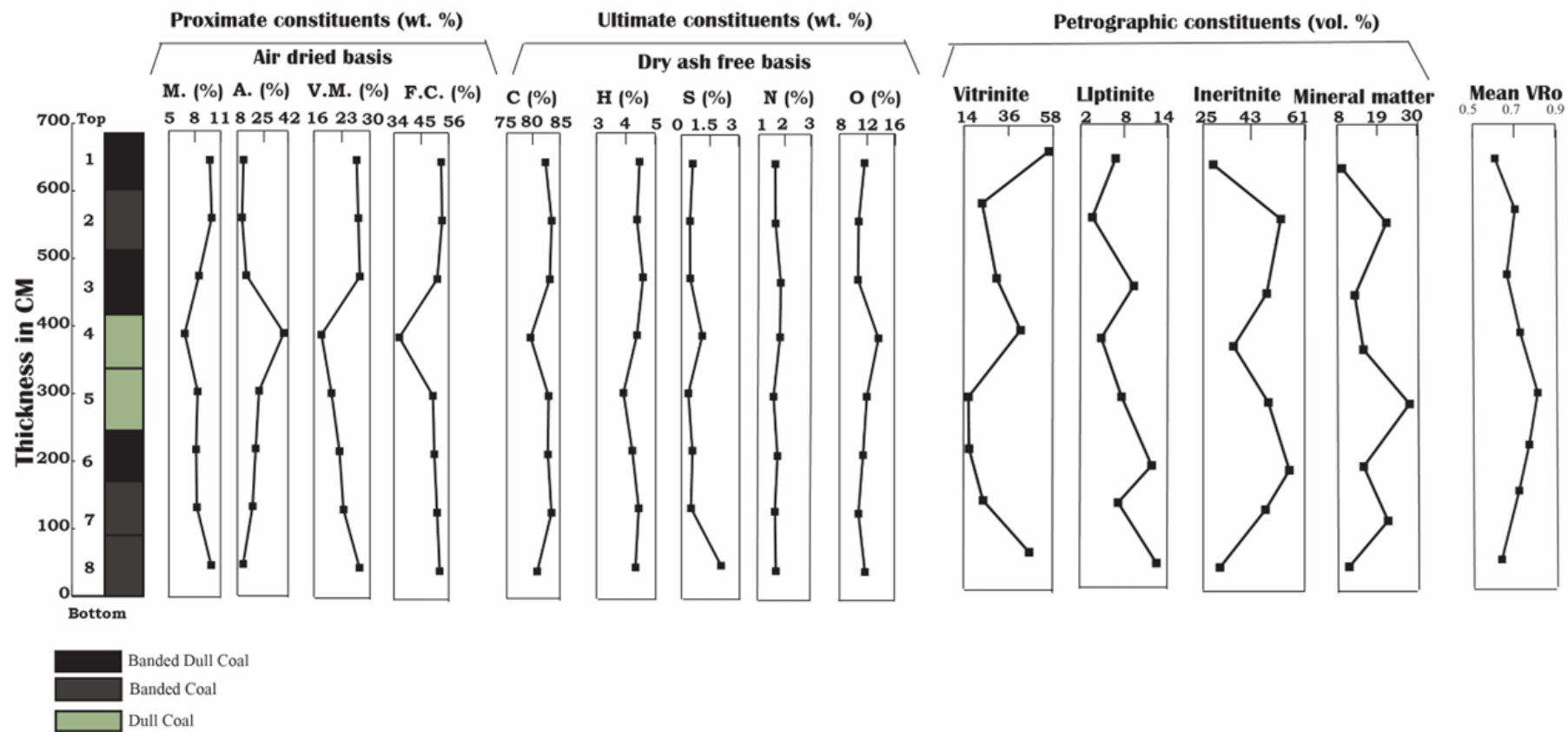


Figure 6.9 Petro-chemical characterization of the vertical seam profile Burhar seam VI Top from Amalai coal mine.

6.2.1 Distribution of group macerals on mineral matter-free basis in different coal seams

Across the studied coal seams, maceral composition shows significant spatial variability, reflecting differences in depositional environments, organic matter preservation, and oxidation conditions. In the Sharda Burhar seam IV, vitrinite is the dominant maceral, averaging 47.76% on a mineral-matter-free (mmf) basis. Similarly, the Rajendra and Khairaha VI seams are vitrinite-rich, with mean vitrinite contents of 46.67% and 52.97%, respectively. In contrast, the Dhanpuri seam is dominated by inertinite macerals, averaging 48.07% (mmf basis), suggesting a higher contribution from oxidized or degraded organic matter. The Khairaha VII seam also shows inertinite dominance, with 49.76% (mmf), reflecting relatively drier or more oxidizing peat-forming conditions. Damini VI exhibits marked site-specific variation within the same seam: the first site is vitrinite-rich (53.16% mmf), whereas the second site is dominated by inertinite (45.64% mmf), highlighting localized changes in depositional or post-depositional conditions. The Damini V, Bangwar, and Amalai seams are all inertinite-dominated, with mean inertinite contents of 53.45%, 47.13%, and 53.09% (mmf), respectively. These variations indicate that maceral distribution in these seams is strongly influenced by local paleoenvironmental factors, water table fluctuations, oxidation level, and the preservation potential of organic matter during peat accumulation, as shown in Figure 6.10.

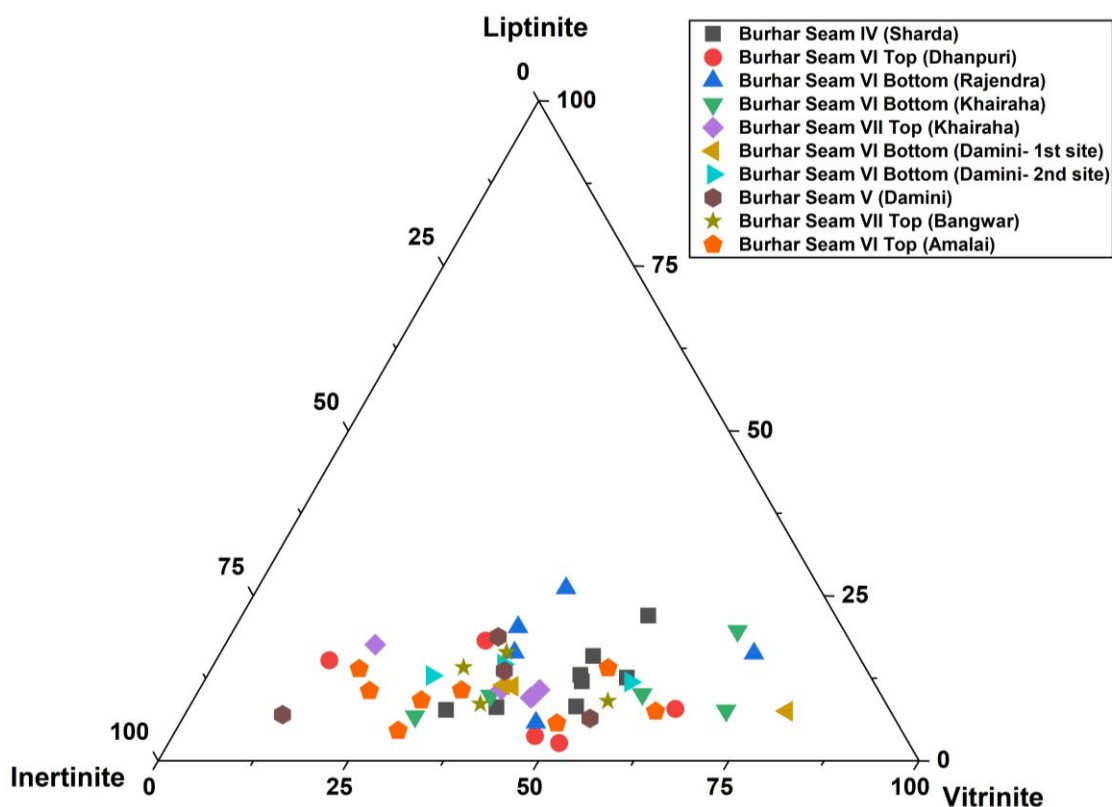


Figure 6.10 Distribution of group macerals on mmf basis.

6.2.2 Distribution of microlithotype with carbominerite in different seams

The microlithotype composition of the studied coal seams, determined as monomaceral, bimaceral, trimaceral, and carbominerite types, shows significant spatial variability across the different mining blocks. The Sharda mines exhibit a dominant monomaceral content with an average value of 57.12% (ranges from 43.35 to 68.22%), accompanied by bimaceral at an average 17.33% (ranges from 7.53 to 36.78%), trimaceral at an average 8.36% (ranges from 3.48 to 11.38%), and carbominerite at an average 17.20% (ranges from 11.83 to 27.22%). In Dhanpuri, monomaceral averages 48.31% (ranges from 12.34 to 74.47%), bimaceral at an average 13.28% (ranges from 8.62 to 19.80%), and trimaceral at an average 3.65% (ranges from 0.63 to 11.62%), while carbominerite is notably high at an average 34.76% (ranges from 13.08 to 64.25%). The Rajendra seam records monomaceral at an average 47.99% (ranges from 20.70 to 66.89%), bimaceral at 24.66%

(15.44–38.48%), trimaceral at an average of 10.11% (ranges from 1.12 to 22.16%), and carbominerite at an average of 17.23% (ranges from 12.39 to 25.59%). Khairaha VI contains the highest monomaceral proportion at an average 65.71% (ranges from 59.75 to 73.84%), with bimaceral at an average 11.73% (ranges from 9.38 to 15.92%), trimaceral at an average 5.47% (ranges from 3.49 to 7.47%), and carbominerite at an average 17.09% (ranges from 13.08 to 25.50%). Khairaha VII has monomaceral with an average of 50.93% (ranges from 39.33 to 63.72%), bimaceral at an average 18.05% (ranges from 11.95 to 23.81%), trimaceral at an average 6.66% (ranges from 3.54 to 10.86%), and carbominerite at an average 24.37% (ranges from 11.81 to 40.29%). The Damini VI (1st site) shows the lowest monomaceral value of 30.36% (ranges from 20.10 to 49.36%), the highest carbominerite content of 51.11% (ranges from 24.47 to 76.24%), and bimaceral at an average 16.38% (lies between 2.13 and 26.79%) and trimaceral at 2.15% (0.00–5.96%). Similarly, Damini VI (2nd site) contains 31.09% monomaceral, an average (ranges from 20.51 to 49.83%), average concentration of bimaceral is 12.31% (ranges 9.24 to 13.92%), trimaceral at an average 4.53% (ranges from 2.25 to 5.94%), and concentration of carbominerite is higher at an average 52.07% (ranges from 34.98–63.48%). The Damini V seam has monomaceral at an average 47.05% (ranging from 30.27 to 66.97%), concentration of bimaceral is low with an average 6.40% (3.51–8.71%), trimaceral at an average 7.58% (ranging from nil to 20.96%), and elevated carbominerite at an average 38.97% (ranging from 18.62 to 66.22%). Bangwar is dominated by monomaceral with an average 58.66% (ranging from 54.00 to 67.88%), an average concentration of bimaceral of 58.66% (ranging from 10.52 to 17.19%), trimaceral at an average 10.83% (ranging from 4.97 to 24.25%), and carbominerite at an average 16.67% (ranging from 11.00 and 23.42%). The Amalai seam contains monomaceral at an average 49.03% (ranging from 45.53 to 56.60%), bimaceral at an average concentration of 13.11%

(ranging from 3.53 to 27.36%), trimaceral at an average 6.26% (ranging from 0.36 to 23.53%), and a relatively high carbominerite content with an average concentration of 31.60% (ranging from 16.95 to 48.97%). Overall, monomaceral content varies widely from 30.36% in Damini VI (1st site) to 65.71% in Khairaha VI, while bimaceral content generally ranges from ~6% to 25%, and trimaceral proportions show considerable fluctuation, being highest in Rajendra (10.11%) and Bangwar (10.83%).

6.2.3 Distribution of microlithotype on carbominerite-free basis in different seams

The microlithotype composition on carbominerite-free basis of various coal seams across different mines, categorized into three groups: Vitrite+Clarite, Durite+Inertite, and Intermediates, highlighting substantial spatial and vertical variability as shown in Figure 6.11. The Sharda seam generally shows a balanced composition, with Vitrite+Clarite ranging from about 30% to 65%, Durite+Inertite between 5% and 54%, and Intermediates roughly 17% to 30%, reflecting moderate preservation of organic matter with some oxidation. In contrast, the Dhanpuri seam shows a strong dominance of Durite+Inertite, reaching up to 78%, in lower bands, while Vitrite+Clarite varies widely, sometimes as low as 7.8%, suggesting significant oxidation and peat degradation alongside occasional organic-rich phases. Rajendra seam is characterized by notably high Vitrite+Clarite contents peaking at 86%, coupled with lower Durite+Inertite (as low as 7.5%), and moderate Intermediates, implying favourable reducing conditions and good organic matter preservation. Khairaha VI shows a similar pattern with consistently high Vitrite+Clarite (up to 85%) and low Durite+Inertite (~6–19%), reinforcing a trend of vitrinite-rich peat deposits. Conversely, Khairaha VII shows a more mixed values assemblage with Durite+Inertite frequently exceeding 50%, indicating more oxidizing conditions and higher inertinite content, along with moderate Vitrite+Clarite and

Intermediates. The Damini VI seam at the first site is Durite+Inertite-dominated (above 58%), with relatively low Vitrite+Clarite (~10–36%) and low to moderate Intermediates, highlighting oxidizing depositional conditions, whereas the second site shows a similar trend but with slightly higher Intermediates, suggesting localized variation within the same seam. Damini V follows a comparable pattern with Durite+Inertite dominance (up to 66%) but shows higher variability in Vitrite+Clarite and Intermediates, indicating fluctuating preservation and mineral matter input. Bangwar coal exhibits relatively balanced proportions with Vitrite+Clarite often exceeding 25% and Durite+Inertite around 44–53%, reflecting mixed depositional conditions. Amalai mine seam is unique in showing extremely high Durite+Inertite values (up to ~91%), very low Vitrite+Clarite in some intervals (~4%), and moderate Intermediates, underscoring strong oxidation and organic matter degradation processes.

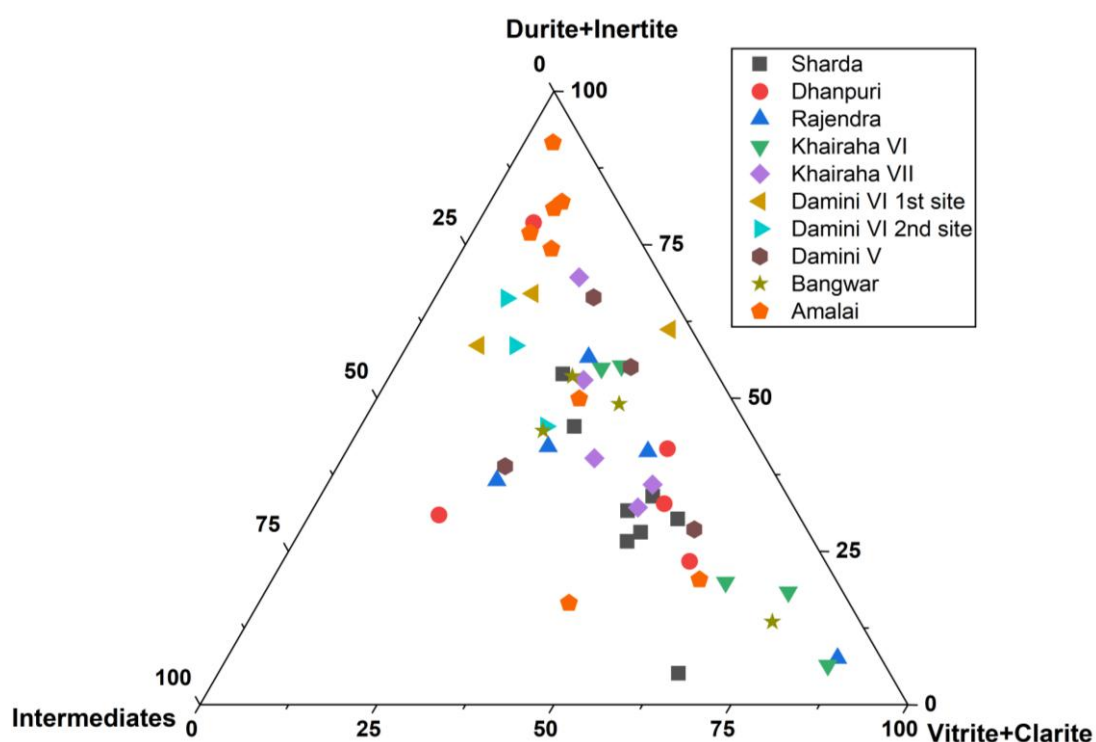


Figure 6.11 Distribution of microlithotype on carbominerite free basis.

6.2.4 Seam-wise variation of maceral and mineral matter

The distribution of maceral and mineral matter across the studied coal seams demonstrates significant seam and site-specific variability, reflecting differences in depositional environments, peat preservation, and oxidation conditions. Vitrinite, representing the primary humic organic component, dominates in seams such as Khairaha VI (avg. 45.61%, ranging 26.03–60.26%) and Rajendra (avg. 40.12%, 31.72–61.03%), suggesting optimal preservation of woody and gelified plant material under relatively reducing conditions. Liptinite content is generally low across all seams, averaging between 7–14%, with Rajendra showing the highest mean (14.72%), indicating a moderate contribution from resins, spores, and cuticular material. In contrast, lower liptinite values in seams like Dhanpuri (avg. 7.49%) and Amalai (7.94%) suggest minimal preservation of these components. Inertinite, indicative of oxidized or fire-affected organic matter, is most abundant in Dhanpuri (avg. 38.98%, max 58.15%), Damini V (40.13%, max 48.76%), Khairaha VII (43.36%, max 55.72%), and Amalai (43.4%, max 56.35%), reflecting intense oxidation, possible wildfire influence, and poor preservation in these intervals. Seams with higher vitrinite content, such as Khairaha VI and Sharda, consistently show lower mineral matter (avg. 13–14%), whereas inertinite-dominated like Damini VI 1st site (avg. 23.47%, max 34.54%) and Damini V (22.09%, max 39.17%), exhibit significantly higher ash content, suggesting greater detrital influx and dilution of organic matter. Within individual seams, the ranges are notable: Sharda shows vitrinite ranging from 26.91% to 46.85% and inertinite from 21.22% to 46.73%, highlighting internal heterogeneity likely due to alternating depositional conditions and fluctuating water table levels. Similarly, Khairaha VII shows a wide inertinite range (35.53–55.72%), and moderate vitrinite (17.55–38.72%), suggesting periods of oxidative stress during peat accumulation. The Bangwar seam shows relatively balanced proportions of vitrinite

(34.77% avg.) and inertinite (40.06%), reflecting intermediate preservation, while Amalai exhibits the highest variability, with vitrinite from 16.16% to 55.86% and inertinite from 27.98% to 56.35%, indicating strongly cyclic depositional controls.

6.2.5 Seam-wise variation of proximate constituents (wt. %)

The proximate analysis of the studied coal seams reveals considerable variability in moisture, ash, volatile matter, and fixed carbon as well as depositional conditions, and mineral matter influx. Moisture content ranges from a low of 3.04% in Dhanpuri to a high of 15.1% in Khairaha VI, with most seams averaging 5–12%, indicating generally moderate to high water retention in younger, less coalified seams. Ash content varies widely, from a minimum of 7.13% in Khairaha VI to a maximum of 52.84% in Bangwar, with average values ranging from 12.79% in Khairaha VII to 32.11% in Bangwar, highlighting differences in detrital input and mineral matter dilution across seams. Volatile matter content also shows seam-specific trends: higher averages are observed in Sharda (25.44%) and Khairaha VI (25.94%), indicating better preservation of reactive organic components, while lower averages occur in Dhanpuri (21.86%) and Bangwar (20.96%), suggesting higher rank or dilution by mineral matter. Fixed carbon, representing the concentrated combustible fraction, varies from a minimum of 26% in Bangwar to a maximum of 60.78% in Dhanpuri, with seam averages ranging between 38.8% in Bangwar to 52.15% in Sharda, reflecting the balance between organic matter preservation and ash dilution. Seams such as Rajendra, Khairaha VI, and Khairaha VII exhibit higher moisture and moderate ash content, consistent with better peat preservation under reducing conditions, whereas coal seams from Bangwar and Damini VI 1st site have high ash and lower fixed carbon, indicating significant detrital input and partial oxidation during peat accumulation. Overall, the proximate data highlight that coal quality is strongly influenced by the interplay of depositional environment, mineral influx,

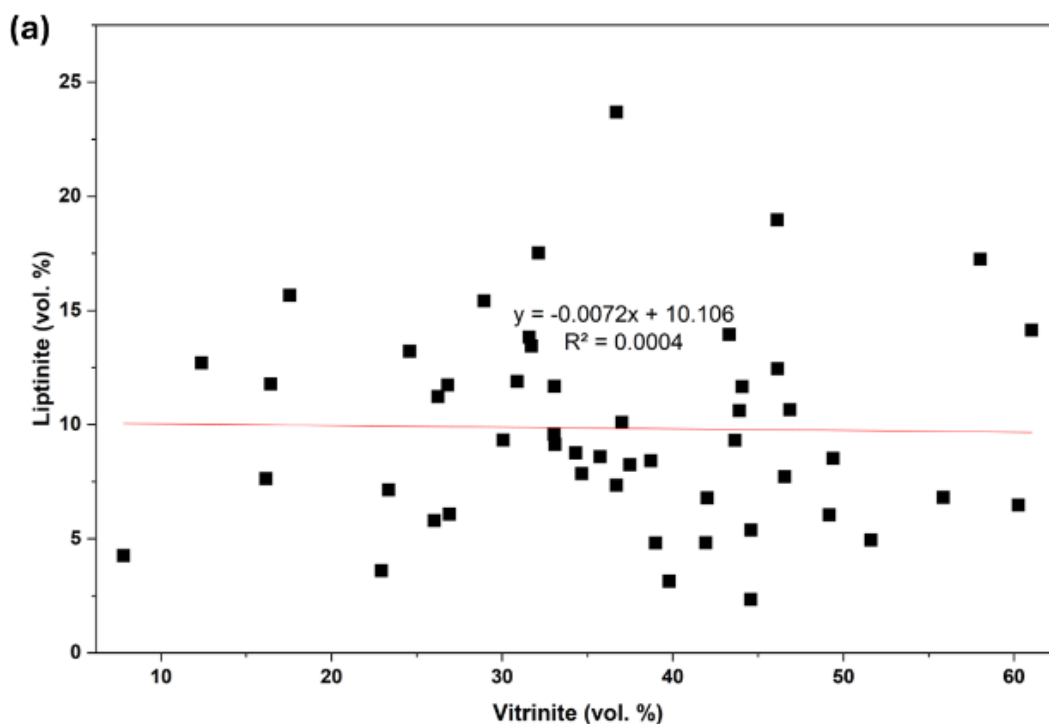
and coalification, with vitrinite-rich, low-ash seams showing higher fixed carbon and volatile matter. In contrast, inertinite-rich or mineral-rich seams display reduced combustible content and higher ash levels.

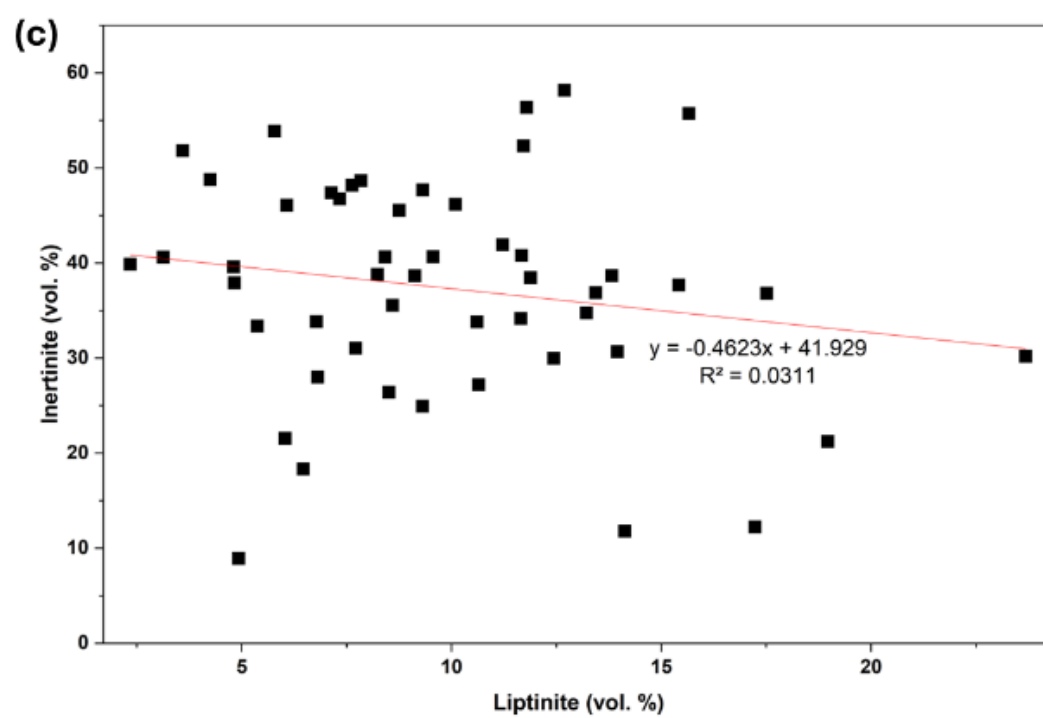
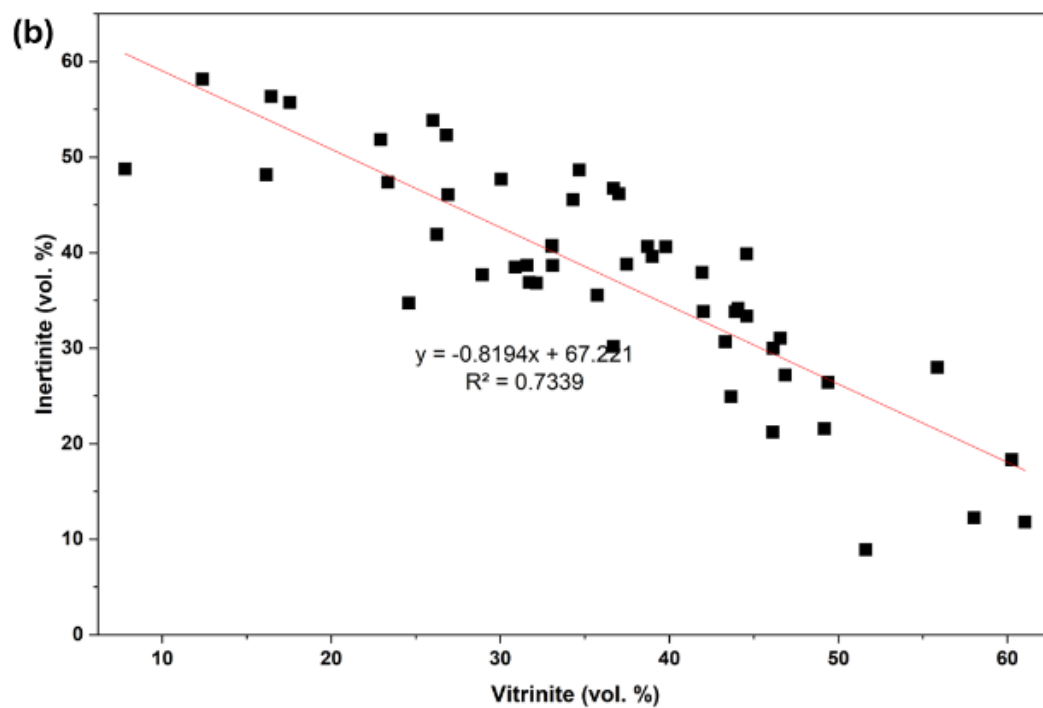
6.2.6 Seam-wise variation of ultimate constituents (wt. %) on dry ash-free basis

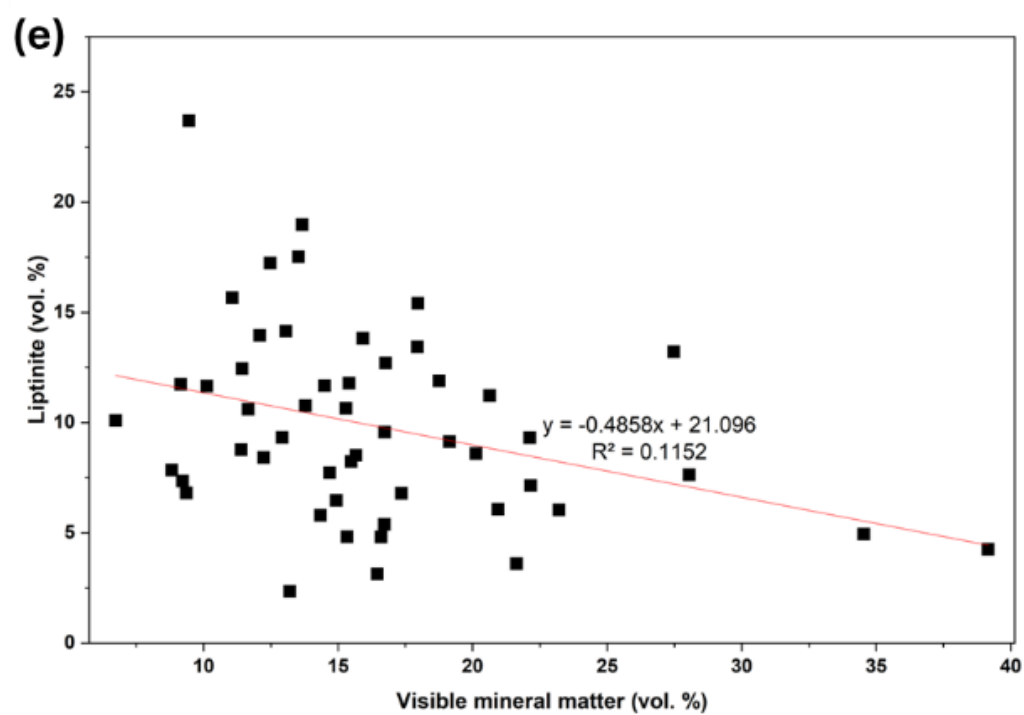
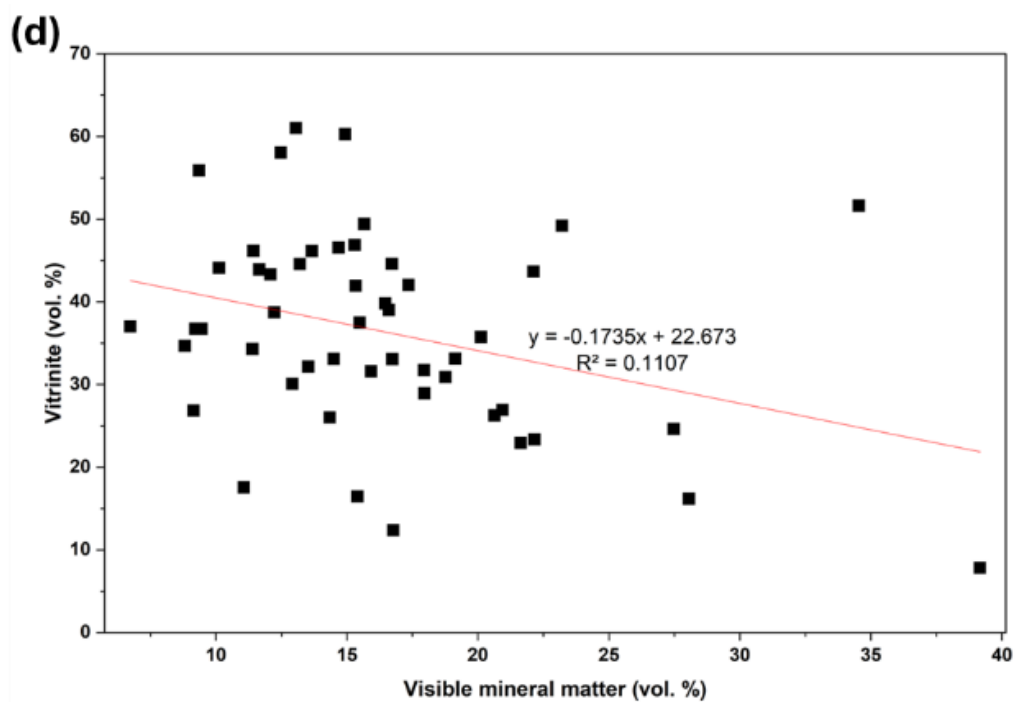
The ultimate analysis of the studied coal seams shows distinct variations in elemental composition, organic matter preservation, and depositional conditions. Carbon content is highest in Sharda (84.29% average) and Amalai (81.67%), indicating better coalification and organic concentration, while Bangwar shows the lowest average carbon (71.47%), reflecting higher mineral matter dilution and lower rank. Hydrogen content varies moderately across seams, with averages between 3.97% in Khairaha VII and 5.16% in Sharda, suggesting variation in volatile organic compounds and coal maturity. Sulphur content is generally low, with the highest averages observed in Damini VI 1st site (1.95%) and Dhanpuri (1.88%), likely due to sulphur fixation under reducing conditions or pyrite enrichment, while Khairaha seams and Amalai remain comparatively low (<1%). Nitrogen content is relatively uniform across seams (1.61–1.92%), indicating limited variability in nitrogen-bearing organic matter. Oxygen content exhibits the widest range, with the lowest average in Sharda (8.03%) and the highest in Bangwar (20.92%), reflecting differences in oxidation, mineral matter association, and organic degradation. Maximum and minimum values within each seam further highlight intra-seam variability; for example, Bangwar ranges from 62.99% to 79.94% carbon and 12.62% to 32.15% oxygen, showing significant heterogeneity in organic matter preservation and mineral dilution.

An attempt was made to examine the relationships between coal petrographic components using scatter plots. The relationship between vitrinite and liptinite shows no

significant correlation (R^2 value of 0.0004), as shown in Figure 6.12a. In contrast, vitrinite and inertinite exhibit a negative correlation, where an increase in inertinite corresponds to a decrease in vitrinite, likely due to the conversion of vitrinite into inertinite during the formation of the inertinite maceral group, as illustrated in Figure 6.12b. Similarly, inertinite and liptinite show a weak negative correlation, with an R^2 value of 0.0311 (Figure 6.12c). Furthermore, all three maceral groups: vitrinite, liptinite, and inertinite demonstrate negative correlations with visible mineral matter, as depicted in Figures 6.12d, 6.12e, and 6.12f, suggesting that increasing mineral matter is associated with a reduction in organic maceral concentration.







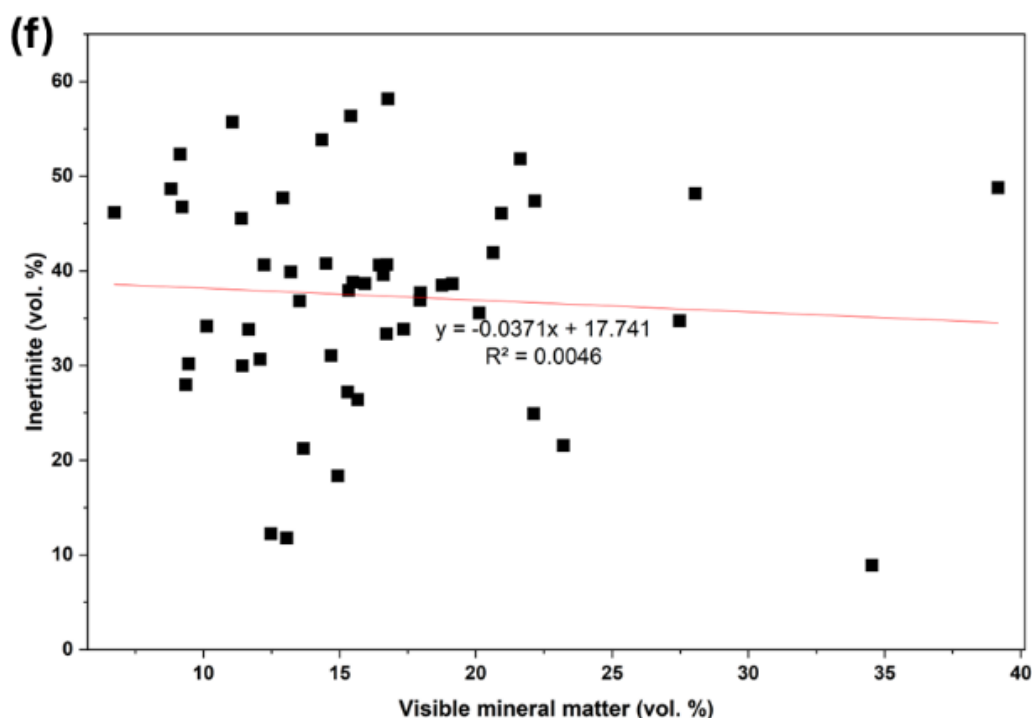
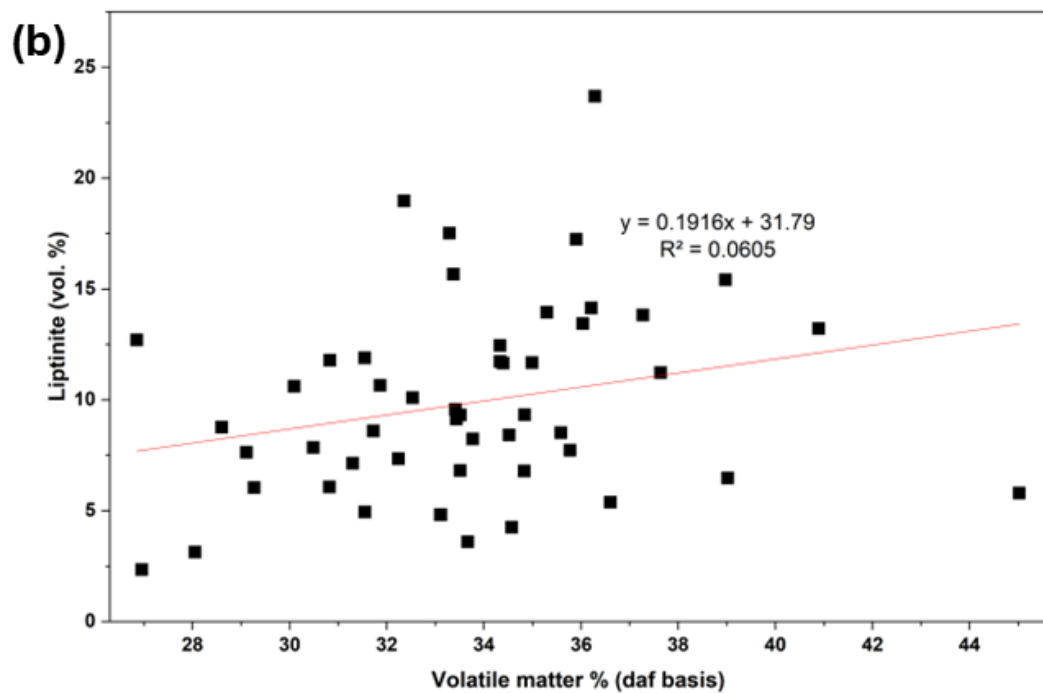
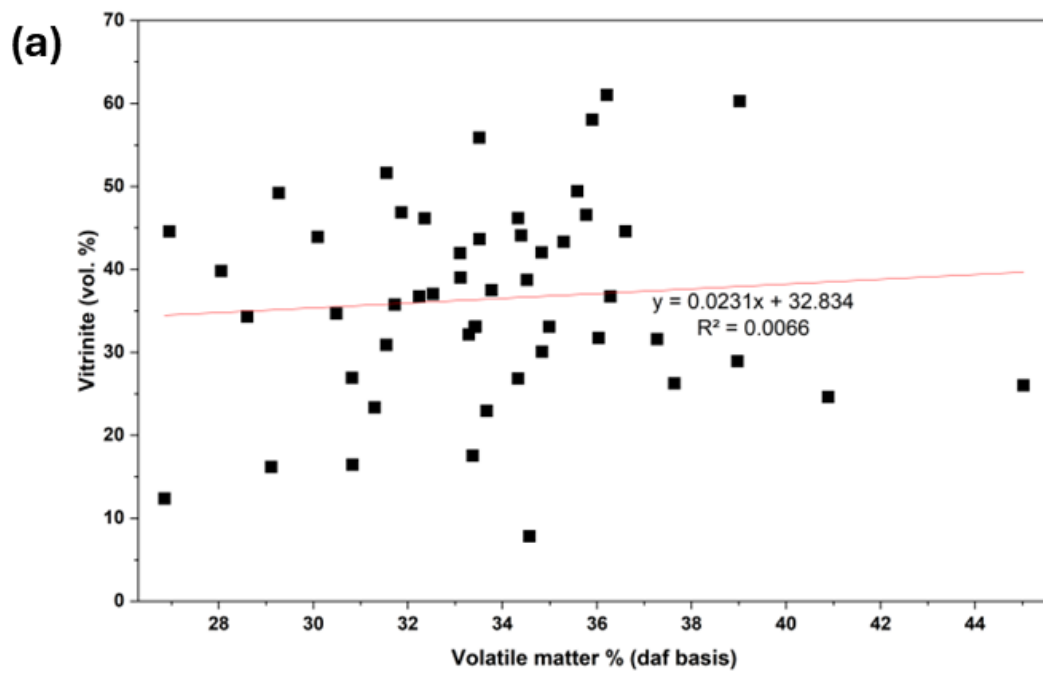
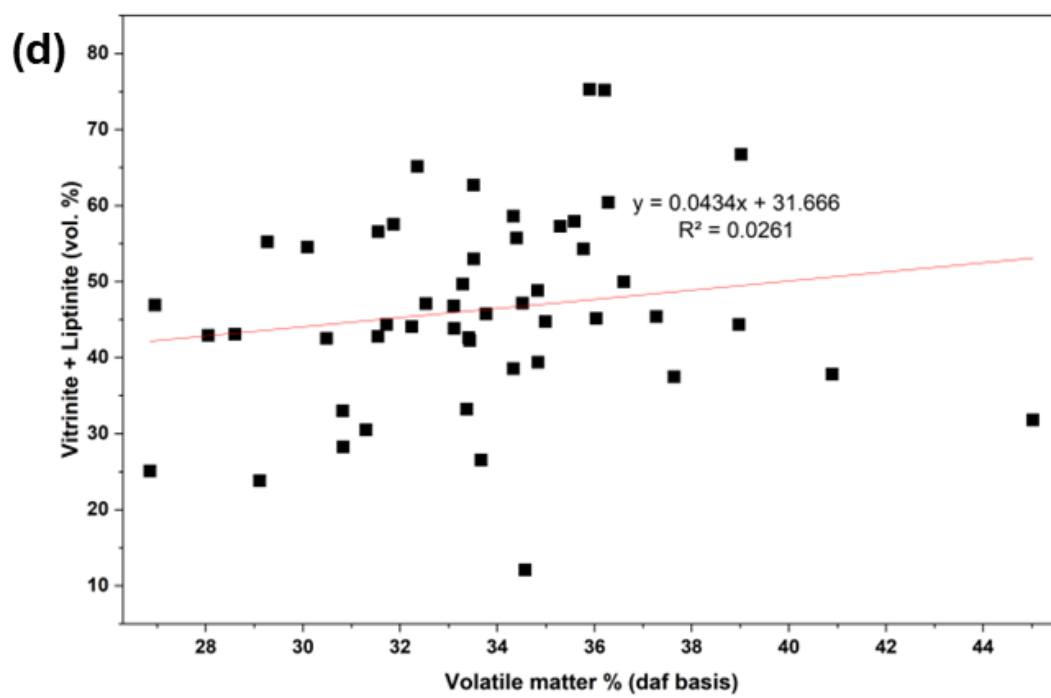
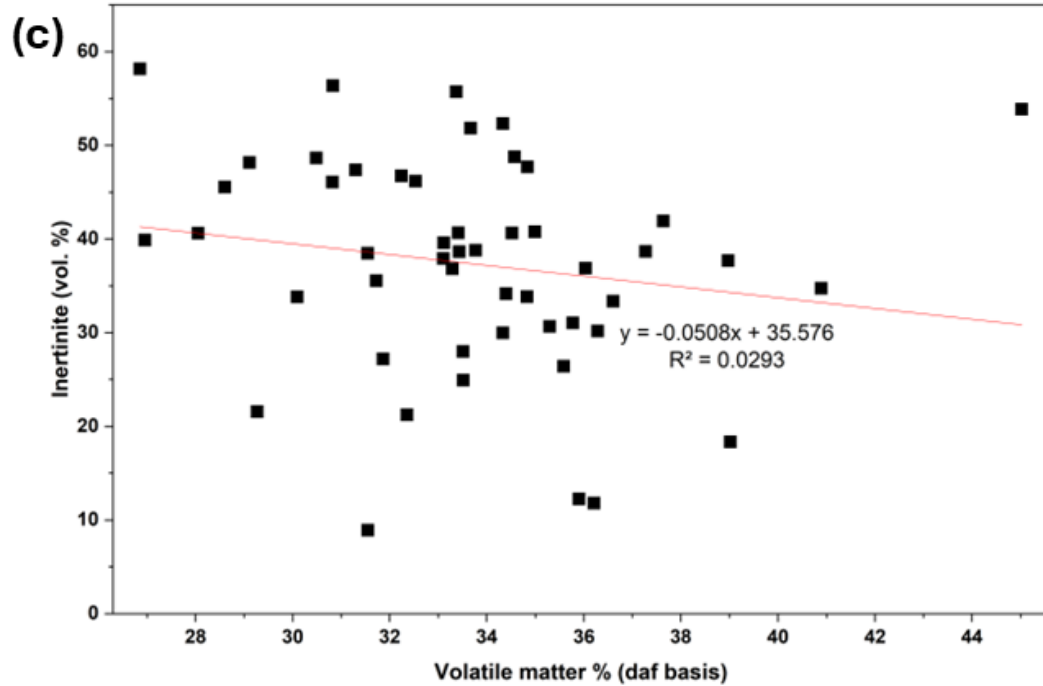


Figure 6.12 Interrelationship among micropetrographic (vitrinite, liptinite, inertinite, and visible mineral matter) constituents for coals of Sohagpur coalfield.

An attempt was made to investigate the interrelationships between micropetrographic constituents (vitrinite, liptinite, inertinite, and their combinations) and the proximate constituent, specifically volatile matter, on a dry, ash-free (daf) basis. The analysis reveals that vitrinite and liptinite exhibit a positive correlation with volatile matter, whereas inertinite shows a negative correlation with volatile matter (Figure 6.13a, b, c). This trend can be attributed to the chemical nature of the macerals: vitrinite and liptinite are rich in labile hydrogen and carbon structures, which decompose more readily during thermal maturation, contributing to higher volatile matter. In contrast, inertinite is highly aromatic and carbon-rich, with condensed structures that are more resistant to thermal degradation, resulting in lower volatile matter. When combinations of maceral groups are considered, the vitrinite + liptinite combination shows a positive correlation with volatile matter, while vitrinite + inertinite and liptinite + inertinite combinations display negative correlations (Figure 6.13d, e, f). This can be explained by the relative influence of inertinite in the combinations: the higher the proportion of inertinite, the more refractory

the coal, leading to lower volatile yields, whereas the vitrinite + liptinite combination enhances coal reactivity.





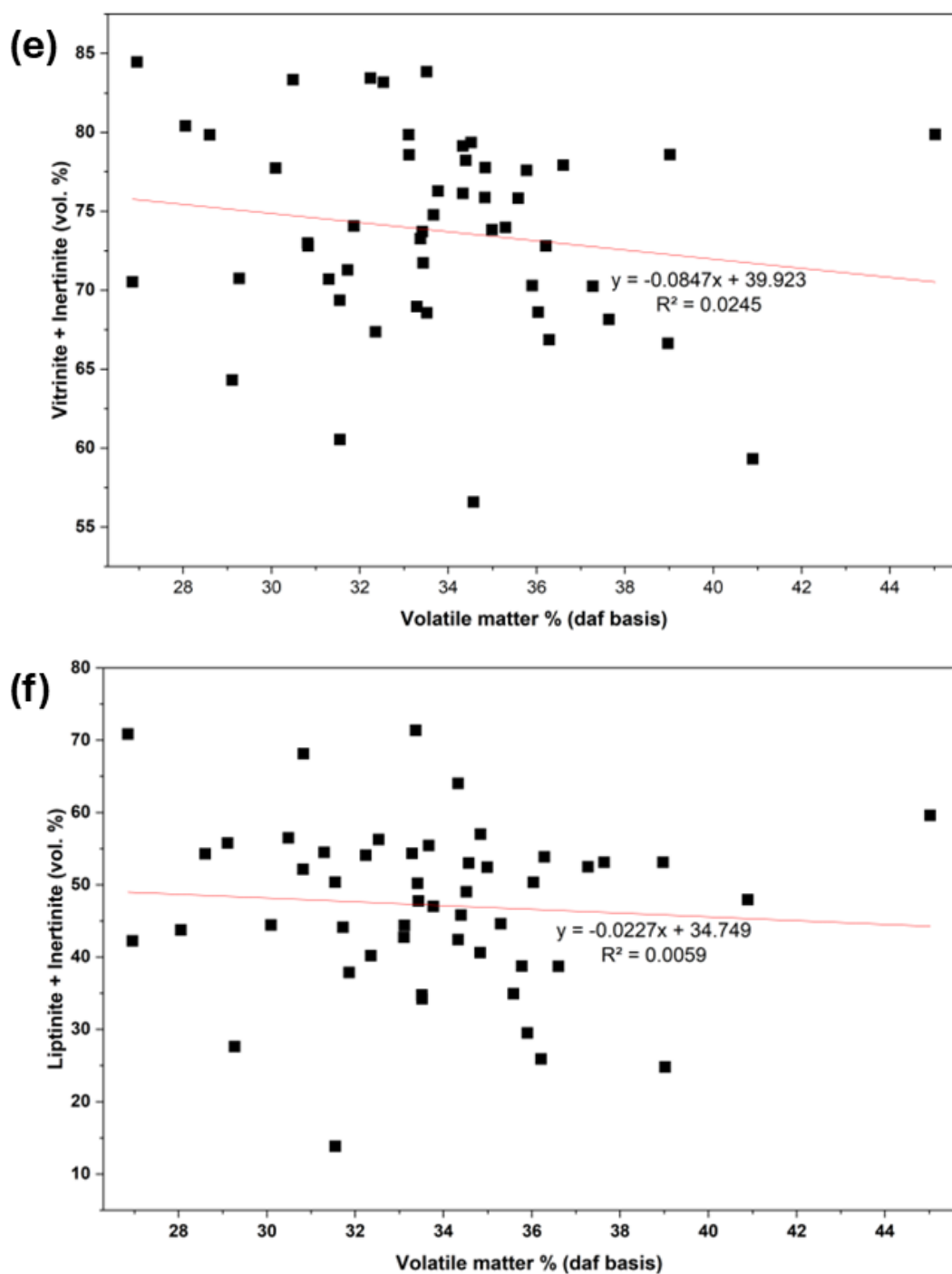


Figure 6.13 Interrelationship between proximate constituent (volatile matter %, daf basis) and micropetrographic components.

A scatter plot of volatile matter percentage (daf basis) versus mean vitrinite reflectance values for the Sohagpur coalfield is presented in Figure 6.14. The observed negative correlation indicates that as vitrinite reflectance increases, volatile matter decreases, suggesting that coal rank and maceral composition influence coal reactivity. Higher vitrinite reflectance corresponds to more thermally mature and carbon-rich coal, which

inherently contains lower proportions of volatile matter. This trend highlights the role of coalification in reducing volatile matter content and demonstrates the controlling influence of maceral composition and rank on the coal's proximate characteristics.

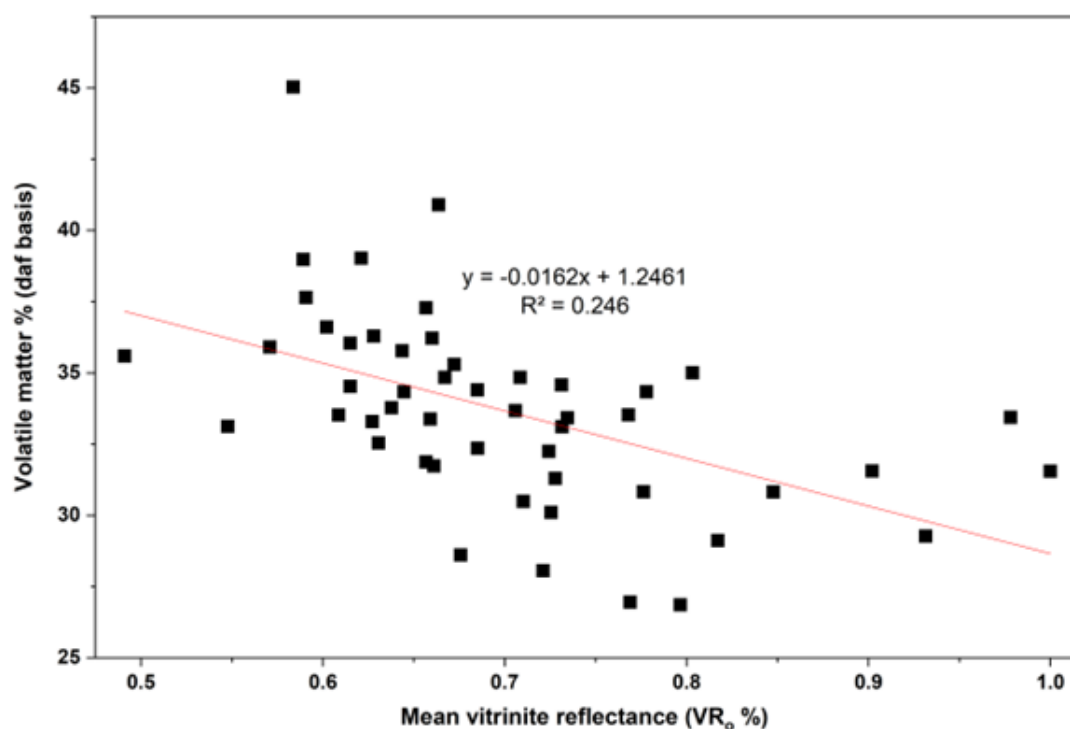
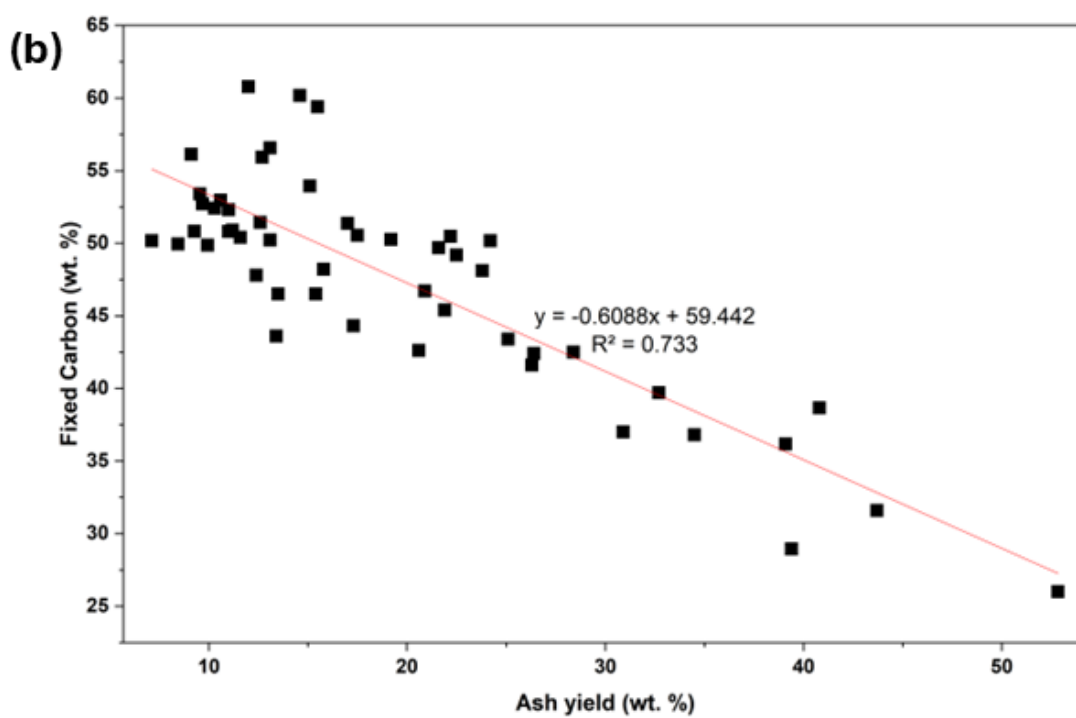
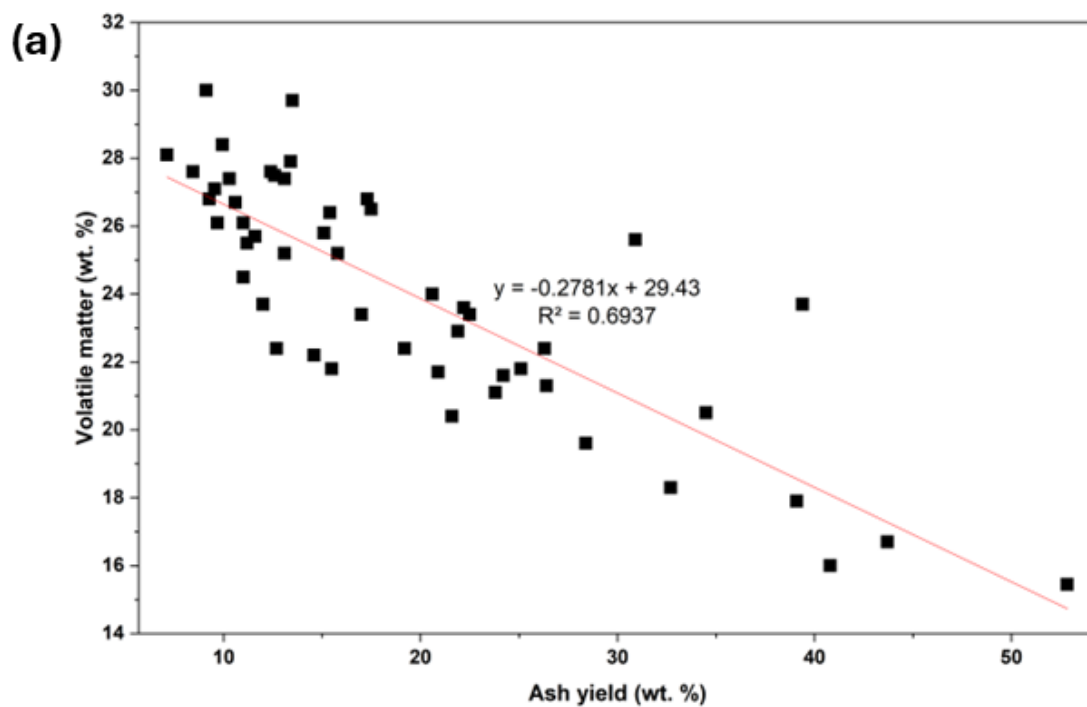


Figure 6.14 Interrelationship between vitrinite reflectance and volatile matter (daf basis) for coals of Sohagpur coalfield.

Scatter plots showing the relationships between ash yield (%) and volatile matter, fixed carbon, mineral matter, and carbominerite are presented in the Figure 6.15. The results show a negative correlation between ash yield and both volatile matter and fixed carbon (Figures 6.15a and 6.15b), indicating that higher ash content dilutes the combustible organic fraction of the coal. In contrast, ash yield shows a positive correlation with mineral matter and carbominerite (Figures 6.15c and 6.15d).



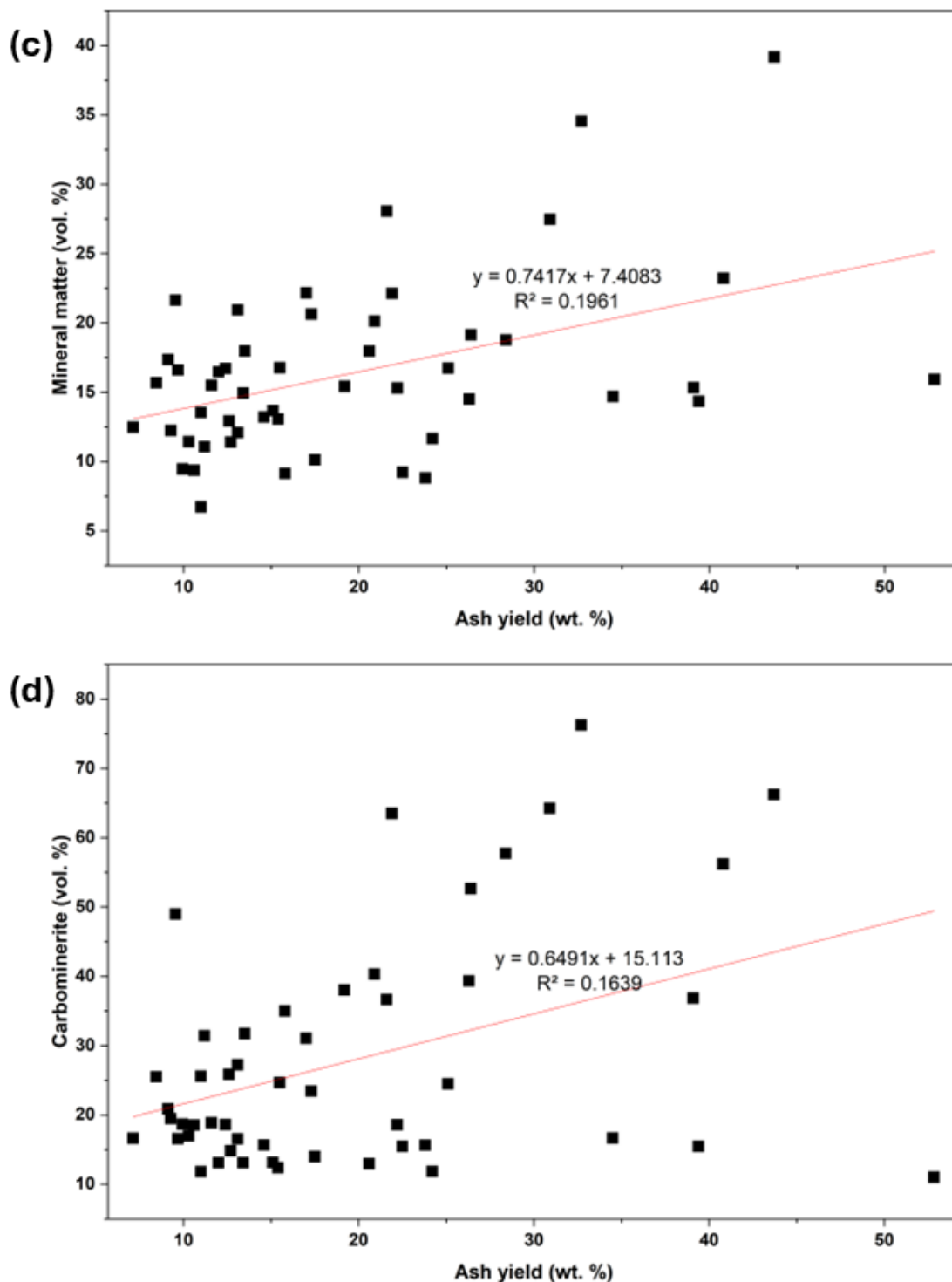


Figure 6.15 Interrelationship between ash yield (wt. %) with volatile matter (wt. %), fixed carbon (wt.%), mineral matter (vol. %), and carbominerite (vol. %).

6.3 Kerogen type

Kerogen is a complex, high-molecular-weight organic material that is insoluble in aqueous alkaline solutions as well as in most common organic solvents (Tissot and Welte,

1984). It originates from the degradation and transformation of diverse biological precursors, including algae, pollen, bacteria, higher plants, and amorphous organic matter. Kerogen is typically dispersed within fine-grained sedimentary rocks such as shales and mudstones. During burial and increasing thermal maturation, kerogen undergoes thermal cracking, a process that progressively breaks down its macromolecular structure. This transformation results in the generation of hydrocarbons, initially producing liquid hydrocarbons (oil) and, with further maturation, gaseous hydrocarbons (natural gas).

One of the most widely accepted approaches for kerogen characterization is the van Krevelen method (van Krevelen, 1961), which is based on the atomic hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios of organic matter. Using this classification scheme, kerogen is divided into four principal types. Type I kerogen is characterized by an H/C ratio greater than 1.25 and an O/C ratio less than 0.05. It is typically derived from protein- and lipid-rich precursors deposited in anoxic lacustrine environments and is composed mainly of alginite, amorphous organic matter, cyanobacteria, and algae; consequently, it is highly oil-prone. Type II kerogen exhibits H/C ratios ranging from 1.0 to 1.25 and O/C ratios between 0.03 and 0.18. This type primarily originates from marine plankton and algae and has the potential to generate both oil and gas. Type III kerogen, with an H/C ratio less than 1.0 and an O/C ratio between 0.03 and 0.30, is mainly derived from terrestrial higher plants and is predominantly gas-prone. Type IV kerogen is distinguished by an H/C ratio of less than 0.5 and consists largely of inert organic matter, with limited potential for hydrocarbon generation, typically producing only dry gas. The original van Krevelen diagram has been subsequently refined and modified by several researchers (McIver, 1967; Welte, 1969; Alpern et al., 1972; Jones and Edison, 1978). When the H/C and O/C ratios of Sohagpur coals are plotted on the modified van Krevelen

diagram of Jones and Edison (1978), the results indicate that these coals correspond to Type III kerogen, as shown in Figure 6.16.

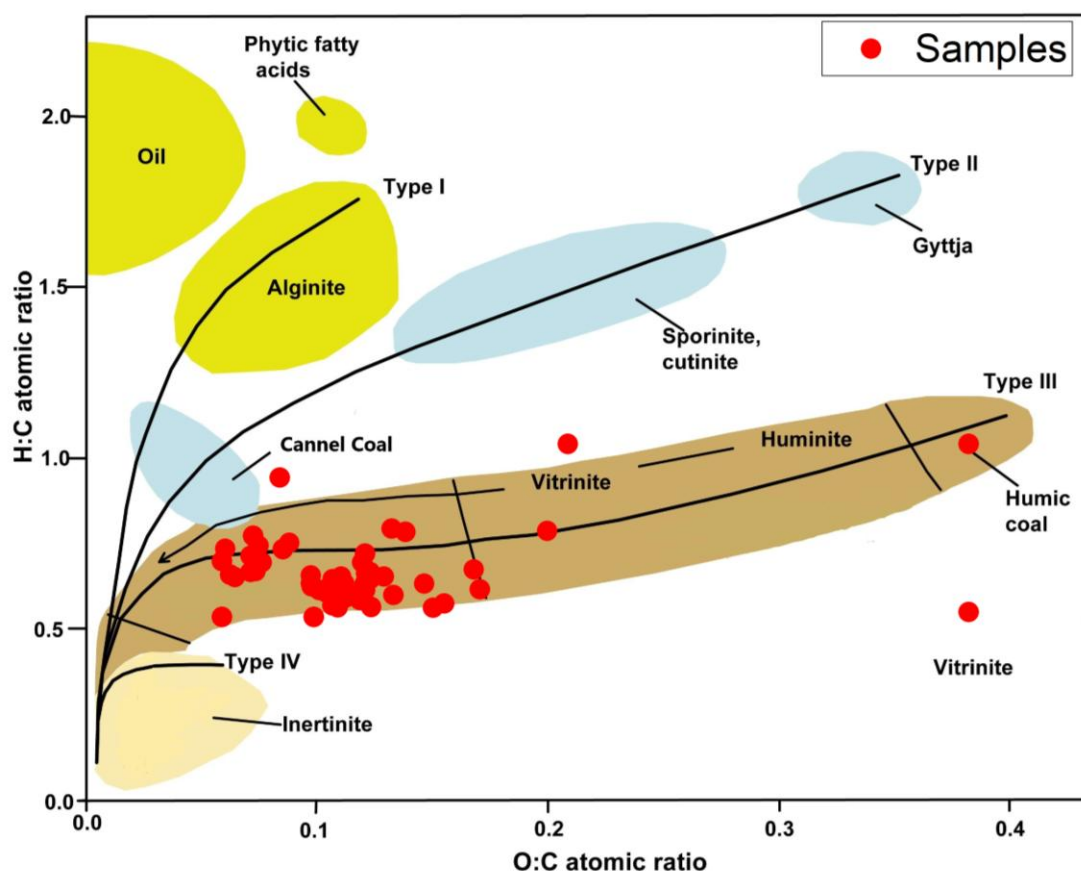


Figure 6.16 The kerogen type in the coals of Sohagpur coalfield (after Jones and Edison, 1978).

The results are further supported by the kerogen characterization scheme based on maceral composition proposed by Cornford (1979). The dominance of vitrinite and inertinite macerals, coupled with the relatively low abundance of liptinite macerals in these coals, indicates that the organic matter is predominantly Type III kerogen. In contrast, coal bands enriched in inertinite macerals are classified as Type IV kerogen due to their inert nature and limited hydrocarbon-generating potential, as shown in Figure 6.17.

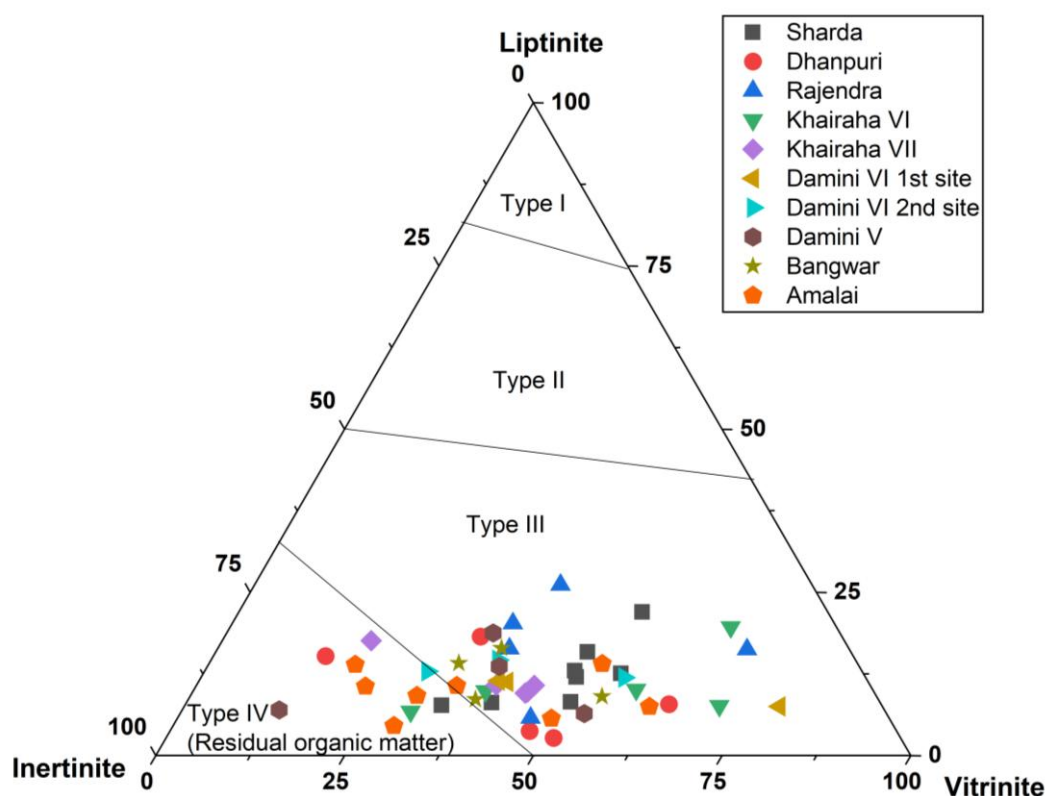


Figure 6.17 Type of kerogen present in coal seams of Sohagpur coalfield (after Cornford, 1979).

The cross-plot of hydrogen index (HI) versus oxygen index (OI) places these coals between Type II and Type III kerogen, indicating the potential for generating mixed liquid and gaseous hydrocarbons, as shown in Figure 6.18 a. This inference is attributed to the relatively high hydrogen index values observed in these coals. The same interpretation is further supported by the kerogen classification scheme proposed by Petersen (2005), which integrates vitrinite reflectance and HI, as well as by the classification based on HI and T_{max} developed by Van Koeverden et al. (2011). Additionally, a cross-plot of S_2 versus total organic carbon (TOC) reinforces this conclusion, showing that most of the coals are predominantly gas-prone Type III kerogen, while some coal bands plot within the mixed Type II–III kerogen field, suggesting their capability to generate both liquid and gaseous hydrocarbons, as shown in Figure 6.18 b.

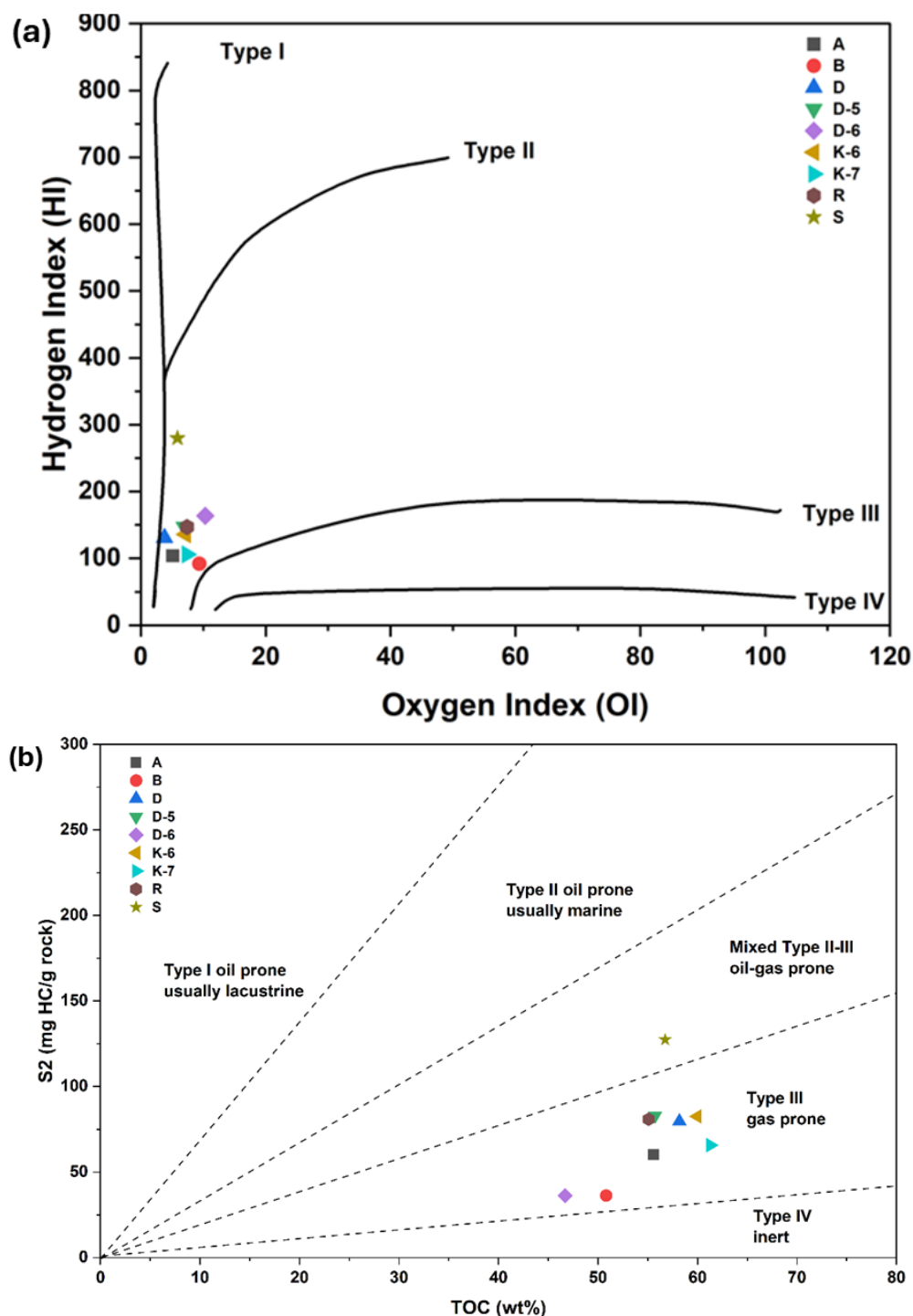


Figure 6.18 (a) Kerogen type based on the hydrogen index (HI) versus oxygen index (OI) values showing Sohagpur coals fall in the kerogen type III (after Peters 1986), and (b) Plot of remaining hydrocarbon potential (S2) versus TOC for coals of Sohagpur coalfield (after Langford and Blanc-Valleron, 1990).

Where A: Amalai, B: Bangwar, D: Dhanpuri, D-5: Damini V, D-6: Damini VI, K-6: Khairaha VI, K-7: Khairaha VII, R: Rajendra, and S: Sharda.

6.4 Coal rank, thermal maturity, and organic matter evolution/hydrocarbon potential

Post-depositional subsidence significantly influences the physicochemical evolution of coalification, commonly referred to as the “maturation” or “rank” of organic matter. As subsidence and sediment accumulation progress, temperature and pressure increase in accordance with the geothermal gradient and the thickening overburden. During this process, lignite undergoes progressive physicochemical transformation to form sub-bituminous coal, bituminous coal, semi-anthracite, anthracite, and ultimately meta-anthracite. Throughout diagenesis, catagenesis, and metagenesis, organic matter experiences substantial alterations, including changes in its micro-constituents (Smith and Cook, 1980; Chandra and Chakrabarti, 1989), the loss of CO and CO₂ (Kopp and Bennett, 2001), the expulsion of volatile compounds (Hayatsu et al., 1988; Kopp et al., 2000; Murchison, 2004), and other associated transformations. These processes collectively modify the petrographic and physicochemical characteristics of the organic matter (Gorbanenko and Ligouis, 2014; Varma et al., 2018; Acharyya, 2019). A variety of parameters are employed as indicators of organic matter maturity, including fluorescence intensity (particularly for low-rank coals), carbon content, volatile matter, moisture content, calorific value, spore colour or Thermal Alteration Index (TAI), vitrinite/huminite reflectance, production index (PI), and $T_{\max}$ (°C) derived from Rock-Eval pyrolysis (Wilkins et al., 1992). Among these, vitrinite reflectance is the most widely used and reliable indicator of thermal maturity. The organic constituents of coal have the potential to generate liquid and gaseous hydrocarbons. A source rock is defined as one that has generated, or has the capacity to generate, significant quantities of hydrocarbons. Based on hydrocarbon-generating potential, organic matter is classified as immature, mature, or over-mature. The source rock potential of any unit is assessed through quantitative and qualitative evaluation of its organic content, kerogen type, bitumen

content, and thermal maturity. Rock-Eval pyrolysis is a robust and widely applied technique for determining organic matter maturity and estimating the quantity of distillable hydrocarbons generated from source rocks.

6.4.1 Vitrinite reflectance interpretation /Assessment of maturity based on vitrinite reflectance

Vitrinite reflectance (R_o) is a key parameter widely used to assess the thermal maturity of coals. In peat-forming environments, vitrinite reflectance provides valuable insight into the degree of coalification that occurs following the deposition and burial of plant-derived organic material (Taylor et al., 1998).

As coalification progresses, R_o values systematically increase with rising temperature and pressure, making this parameter a reliable indicator of coal rank and maturation history. The vitrinite reflectance values of the studied coal samples range from 0.59 to 0.88 (Table 5.1). When plotted against standard coal rank classification charts, these values correspond to the bituminous rank. According to the ASTM coal classification scheme, R_o values within this range are characteristic of high volatile bituminous coals (Figure 6.19). Therefore, the coals from the Sohagpur coalfield are classified as bituminous in rank, reflecting a moderate level of thermal maturation.

Rank		Reff Rm Oil	V.M. d.a.f. %	Carbon d.a.f. %	Bed Moisture	Cal. Value Btu/lb (Kcal/kg)	Rank Ref oil	Rank VM daf%	Applicability of different rank parameter		
German	USA								Carbon d.a.f.	VM, d.a.f.	H, d.a.f.
Torf	Peat	0.2	68								
			64								
Welch	Lignite	0.3	60	60	75						
			56		35	7200 (4000)					
Matt	Sub C	0.4	52								
	Bitu B		48	71	25	9900 (5500)					
Glanz	A	0.5	44								
	C	0.6	40	77	8-10	12600 (7000)					
Flam											
Gas flamm	B	0.7	32								
	High Volt. Bituminous	0.8									
Gas	A	1.0	28								
	Mid. Volt. Bituminous	1.2	24	87		15500 (8650)					
Fett		1.4									
	Low Volt. Bituminous	1.6									
Ess		1.8	16								
	Semi Anthracite	2.0	12								
Marger			8	91							
Anth.	Anthracite	3.0	4			15500 (8650)					
Meta Anth.	Meta Anth	4.0									

Figure 6.19 Rank of the Sohagpur coals based on the vitrinite reflectance (R_0) in the schemes representing the different stages of coalification according to ASTM and DIN classification (modified after Stach et al., 1982).

6.4.2 Rank effects on proximate and ultimate parameters

Coal rank exerts a significant control on both proximate and ultimate analysis parameters, reflecting the progressive physicochemical changes that occur during coalification. As coal rank increases, systematic variations in moisture, volatile matter, fixed carbon, and elemental composition are observed due to increasing temperature and pressure during burial and maturation.

In proximate analysis, low-rank coals such as lignite and sub-bituminous coal are characterized by high inherent moisture and volatile matter content, along with relatively low fixed carbon. With increasing rank toward bituminous and anthracitic coals, moisture content decreases markedly as pore water is expelled during compaction and thermal alteration. Volatile matter also shows a general decline due to the progressive release of gaseous compounds and low-molecular-weight hydrocarbons, while fixed carbon content

correspondingly increases. These trends reflect the increasing aromatization and condensation of the organic structure as coalification advances.

Ultimate analysis parameters also display strong rank-dependent trends. Carbon content increases progressively with rank, indicating enrichment of carbon through the loss of oxygen- and hydrogen-rich functional groups. Conversely, hydrogen and oxygen contents decrease due to dehydrogenation and decarboxylation reactions, including the expulsion of H₂O, CO, and CO₂. Nitrogen and sulfur contents may show variable behaviour depending on depositional environment and post-depositional processes, although they generally exhibit less systematic variation compared to carbon, hydrogen, and oxygen. As a result of these compositional changes, the atomic H/C and O/C ratios decrease with increasing rank, reflecting the transition from aliphatic-rich structures to more condensed aromatic frameworks.

6.4.3 Vitrinite reflectance and $T_{\max}$ maturity interpretation / Maturity of Sohagpur coals based on R_o and $T_{\max}$

Thermal maturity of the studied coals has been evaluated using vitrinite reflectance (R_o), $T_{\max}$ obtained from Rock-Eval pyrolysis, and the production index (PI), which together provide a robust framework for assessing the coalification stage and hydrocarbon-generating potential of organic matter (Peters, 1986; Taylor et al., 1998). The vitrinite reflectance values range from 0.59 to 0.88, while $T_{\max}$ values vary between 423.5 °C and 445 °C. These maturity parameters indicate that the coals have attained a moderate to relatively high level of thermal evolution, corresponding primarily to the bituminous coal rank.

Vitrinite reflectance is widely regarded as the most reliable indicator of coal and organic matter maturity (Taylor et al., 1998). R_o values between 0.6 and 0.7 are typically associated with the onset of the oil window, whereas values ranging from 0.7 to 1.0

correspond to peak oil generation and the transition toward early thermogenic gas generation (Peters and Cassa, 1994; Tissot and Welte, 1984). The R_o values observed in the present study suggest that most coal samples lie within the early to peak oil window, with some samples approaching the early gas window. This indicates progressive coalification driven by increased burial temperature and pressure, consistent with regional subsidence and geothermal conditions.

The T_{max} values further support this interpretation. T_{max} values around 435 °C are indicative of early thermal maturity, while values approaching 440–445 °C reflect a more advanced maturity stage, as shown in Figure 6.20. The T_{max} range observed in the studied coals, therefore, confirms a maturity gradient spanning from early mature to mature stages of hydrocarbon generation. The overall consistency between R_o and T_{max} values indicates that the organic matter has undergone sufficient thermal stress to generate hydrocarbons, primarily gaseous in nature due to the dominance of Type III kerogen (Espitalié et al., 1985; Peters, 1986).

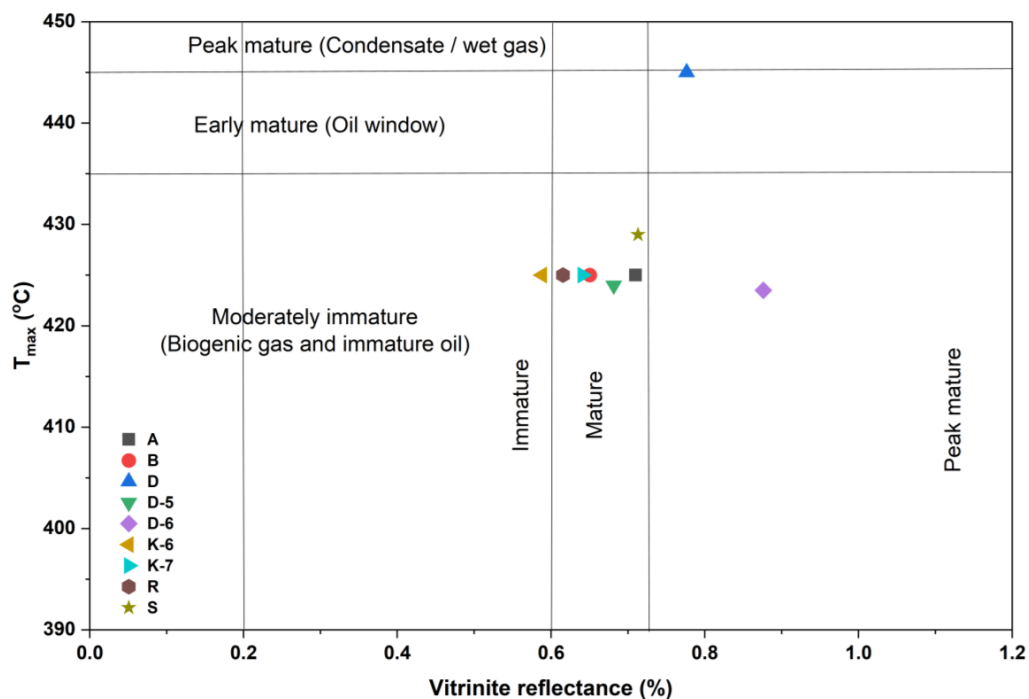


Figure 6.20 Plot of vitrinite reflectance and T_{max} showing the maturity levels (after Peters and Cassa 1994).

The production index values are consistently low, ranging from 0.01 to 0.07. Low PI values indicate that only a small fraction of generated hydrocarbons has been expelled from the source rock and that most hydrocarbons remain retained within the coal matrix. This suggests a system characterized by limited expulsion efficiency, which is typical for coals and carbonaceous shales where hydrocarbons are strongly adsorbed onto organic surfaces. The low PI values, therefore, reinforce the interpretation that the coals are thermally mature but have largely retained their generated hydrocarbons in situ.

6.4.3.1 Implications for Hydrocarbon Generation

The maturity parameters indicate that the studied coals are predominantly gas-prone, consistent with their classification as Type III kerogen (Tissot and Welte, 1984; Peters and Cassa, 1994). At the lower end of the maturity range ($R_o \approx 0.6\text{--}0.7$; $T_{\max} \approx 423\text{--}430\text{ }^{\circ}\text{C}$), minor generation of liquid hydrocarbons may occur; however, the overall hydrocarbon potential is dominated by thermogenic gas generation. As maturity increases toward R_o values of $\sim 0.8\text{--}0.9$ and $T_{\max}$ values above $435\text{ }^{\circ}\text{C}$, the cracking of residual liquid hydrocarbons and kerogen enhances methane generation.

The relatively low PI values imply that the generated hydrocarbon have not been efficiently expelled, which is a characteristic feature of coal-bearing systems. Instead, hydrocarbons, particularly methane, remain trapped within the coal matrix or migrate only over very short distances. This behaviour enhances the significance of coals as unconventional gas reservoirs rather than as conventional oil source rocks.

6.4.3.2 Implications for Coalbed Methane (CBM) Generation

The maturity range identified in this study is highly favourable for coalbed methane (CBM) generation. Vitrinite reflectance values between 0.6 and 1.0 are widely recognized as optimal for thermogenic methane generation in coals (Rice, 1993). The studied coals

fall squarely within this window, indicating that substantial amounts of thermogenic methane were likely generated during coalification. At this stage of maturity, methane generation results from both the breakdown of kerogen and the cracking of earlier-generated hydrocarbons. The dominance of vitrinite macerals further enhances CBM potential, as vitrinite-rich coals typically develop abundant microporosity during coalification. This microporous structure provides extensive surface area for methane adsorption, which is critical for CBM storage (Laxminarayana and Crosdale, 1999).

6.4.3.3 Adsorption Dominance and Gas Storage Mechanism

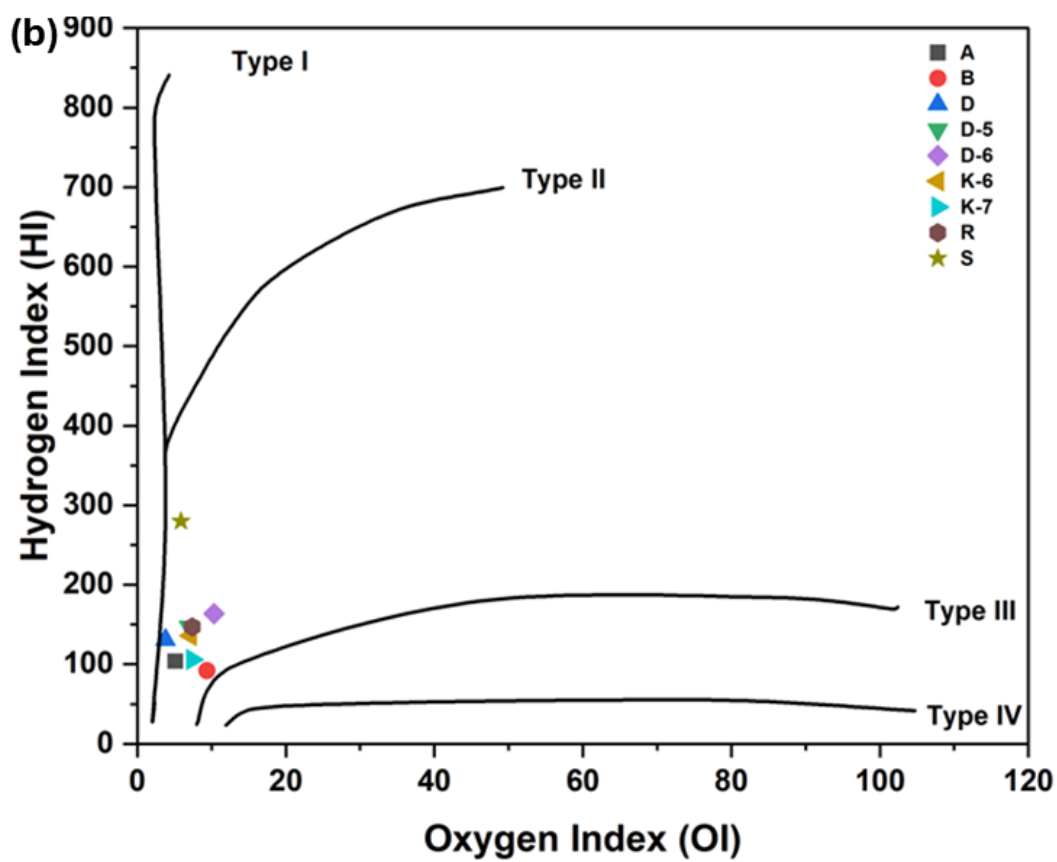
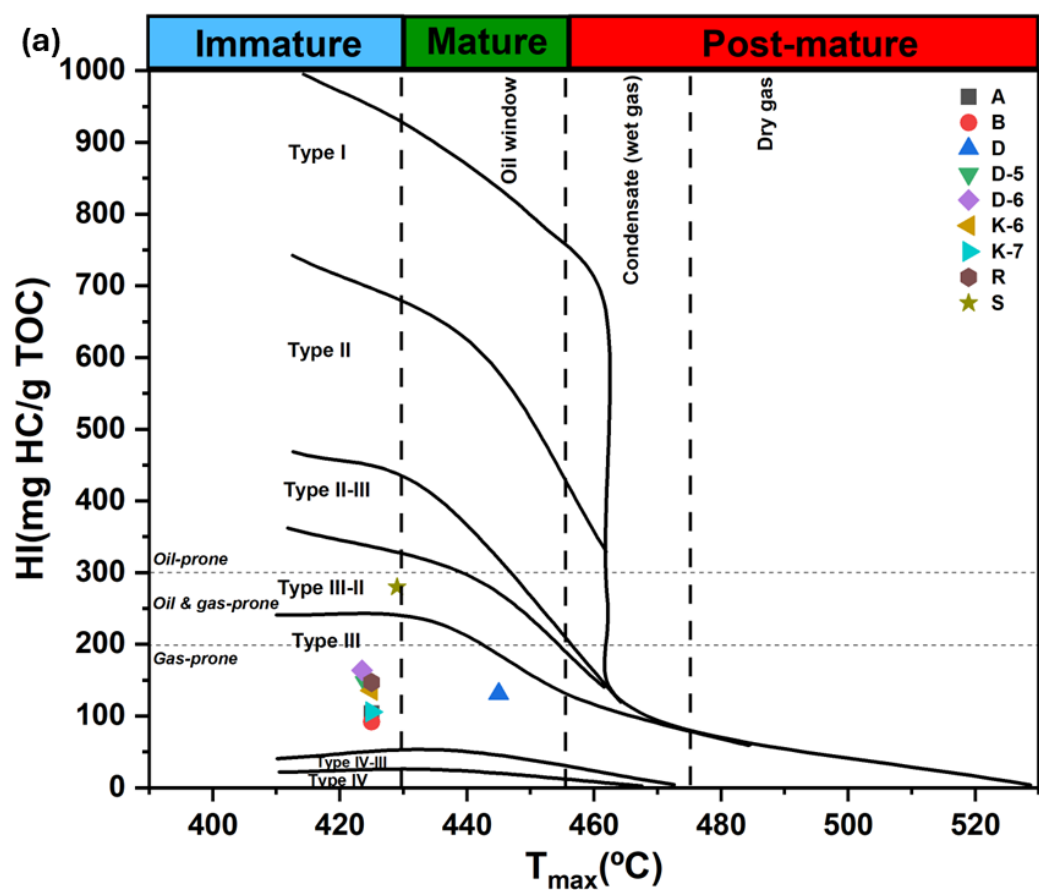
The combination of moderate to high thermal maturity and low PI values strongly suggests that adsorbed gas dominates over free gas in the studied coals. In coal reservoirs, methane is primarily stored by adsorption onto the internal surfaces of organic matter rather than as free gas in pore spaces. The observed maturity level promotes the development of well-connected micropores, particularly within vitrinite macerals, thereby enhancing adsorption capacity. At R_o values of approximately 0.6–0.9, adsorption capacity is typically high, while permeability remains relatively low. This results in strong gas retention within the coal matrix and limited natural expulsion. Consequently, methane remains adsorbed until pressure is reduced by natural uplift or by anthropogenic activities such as drilling and dewatering.

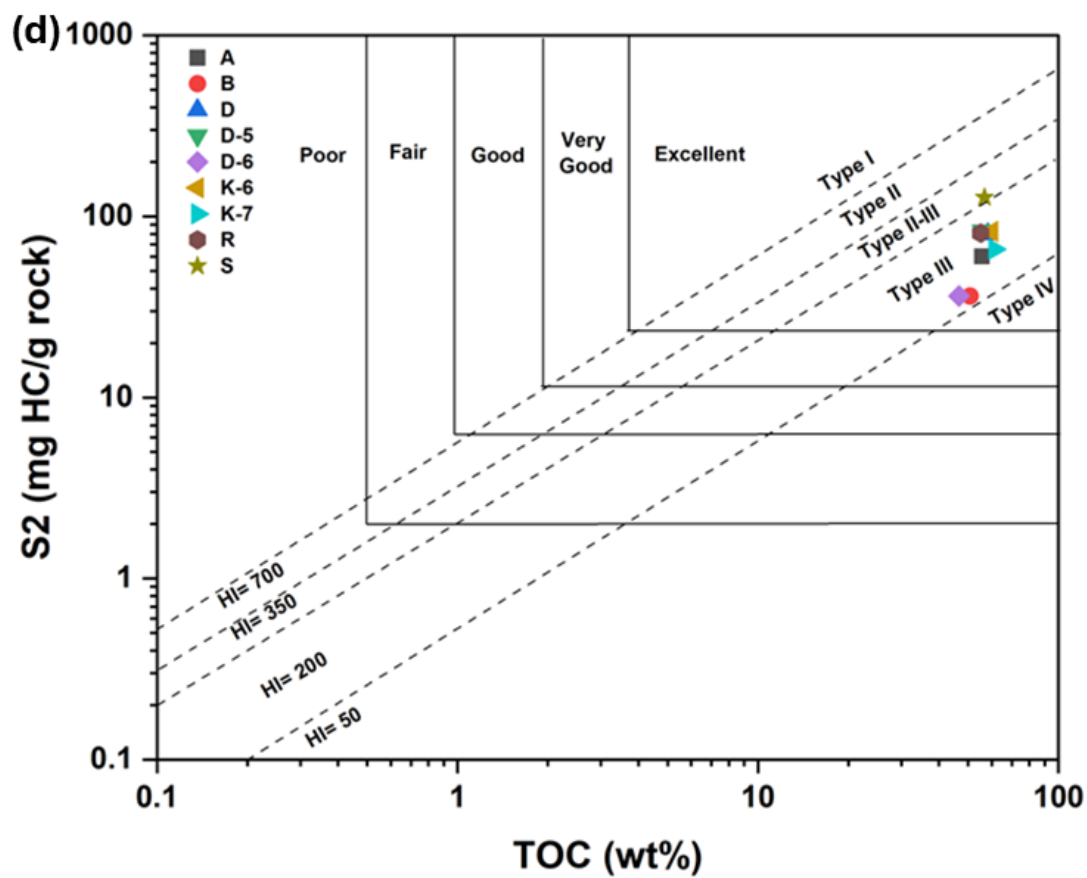
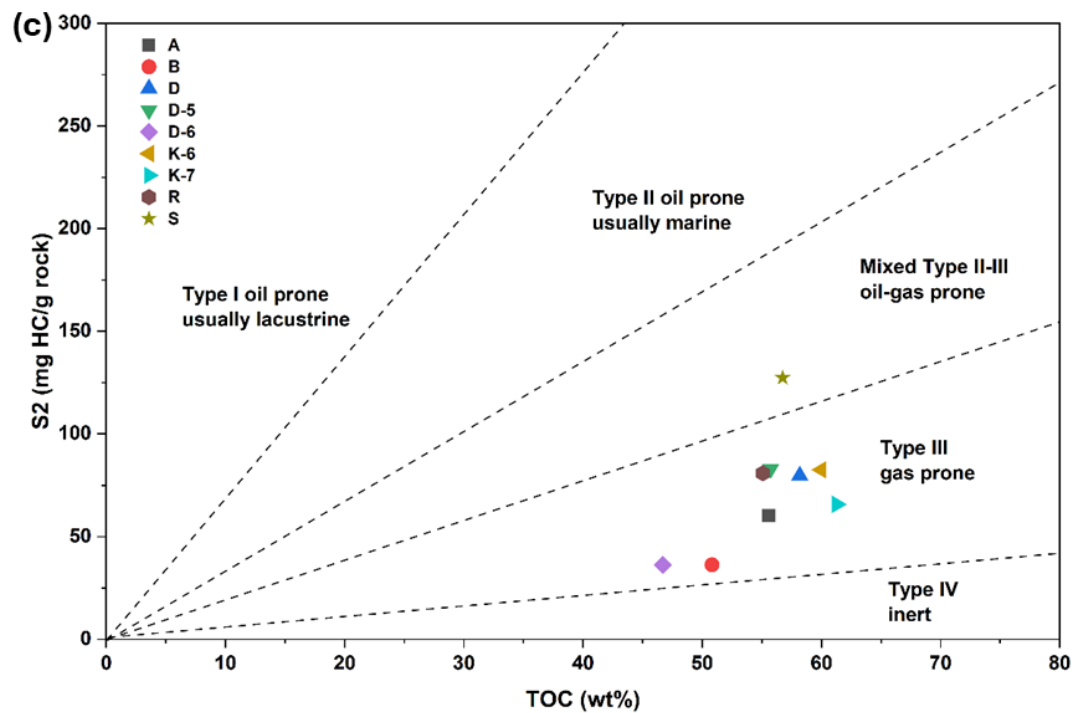
6.4.4 Geochemical indicators for hydrocarbon generation

The kerogen type of a coal plays a fundamental role in determining its hydrocarbon-generating potential. In the studied coal samples, kerogen characterization was performed using Rock-Eval pyrolysis parameters as shown in Table 6.1, including Hydrogen Index (HI), Oxygen Index (OI), S1, S2, T_{max} , and Total Organic Carbon (TOC) (Peters, 1986; Tissot & Welte, 1984). Most of the coal samples exhibit HI values between 92 and 164 mg HC/g TOC, with OI values ranging from 3.8 to 10.3 mg O₂/g TOC. These values

correspond to Type III kerogen, which is derived predominantly from terrestrial plant material and is primarily gas-prone (Tissot & Welte, 1984; Peters & Cassa, 1994). One coal sample, however, displays a HI of 280 mg HC/g TOC and an OI of around 6 mg O₂/g TOC, indicating Type II kerogen, derived from a mixed organic source, such as algal or liptinitic material, capable of generating both oil and gas. This classification aligns with the coal's maceral composition, as high vitrinite content generally correlates with Type III kerogen, as shown in Figure 6.21, which is favourable for methane generation (Cornford, 1979; Rice, 1993).

Thermal maturity of the coal samples is reflected in the $T_{\max}$ values, which range from 423.5 °C to 445 °C. According to standard hydrocarbon generation windows (Espitalié et al., 1985; Peters, 1986), $T_{\max}$ values between 423–430 °C correspond to early mature stages, whereas values above 435 °C indicate peak oil window or early thermogenic gas generation. The coal sample with Type II kerogen falls within the early to peak oil window, suggesting a potential for limited liquid hydrocarbon generation along with gas, whereas the remaining Type III coals are within the early gas window, indicating that thermogenic methane generation dominates. Vitrinite reflectance data ($R_o = 0.59\text{--}0.88$) support this interpretation, indicating bituminous coal rank and confirming that the coals have reached sufficient thermal maturity for significant hydrocarbon generation (Taylor et al., 1998).





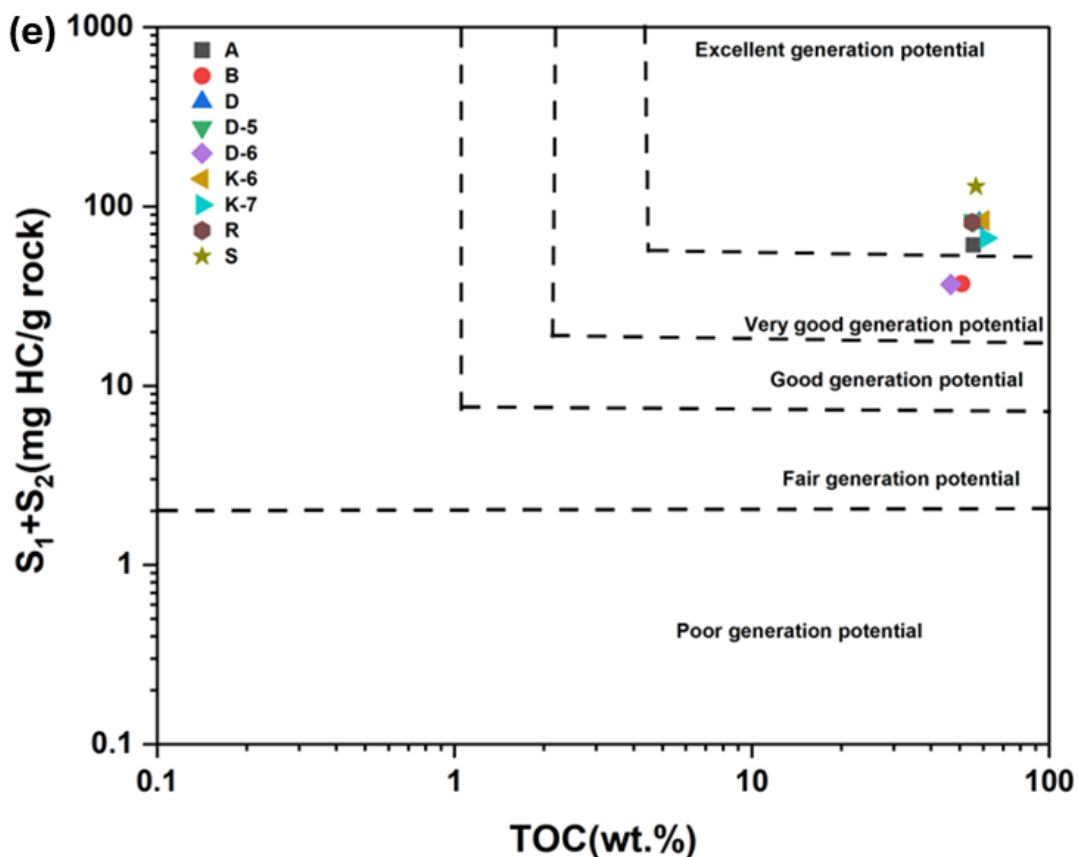


Figure 6.21 (a) $T_{\max}$ and HI (b) HI vs OI (c) TOC vs S2 plot shows that coals from Sohagpur fall in the Kerogen Type III (d) TOC vs S2 and (e) TOC vs S1+S2 shows that these coals have excellent generation potential.

The Hydrogen Index (HI) provides a direct measure of hydrocarbon potential. Type III coals in this study, with HI values below 200 mg HC/g TOC, are gas-prone, whereas the Type II coal sample, with HI ~280 mg HC/g TOC, represents mixed oil- and gas-prone kerogen (Tissot & Welte, 1984). Oxygen Index (OI) values are relatively low (3.8–10.3 mg O₂/g TOC), indicating the progressive loss of oxygen-containing functional groups during coalification, consistent with decarboxylation and dehydration processes (Hayatsu et al., 1988).

The hydrocarbon-generating potential is also evidenced by S2 values, which reflects hydrocarbons generated during the thermal cracking of kerogen. S2 ranges from 36 mg HC/g rock in the lower-HI coals to 127 mg HC/g rock in the high-HI sample, confirming significant thermogenic hydrocarbon generation potential. S1 values, representing free

hydrocarbons, are low (0.48–1.97 mg HC/g rock), indicating that most generated hydrocarbons remain adsorbed within the coal matrix rather than expelled to conventional petroleum systems (Peters, 1986; Rice, 1993).

The Production Index (PI) of these coals, ranging from 0.01 to 0.07, indicates limited expulsion of hydrocarbons from the coal matrix. Low PI values suggest that although hydrocarbons have been generated, they are largely retained in situ, consistent with the behaviour of thermogenic gas in coal systems (Peters & Cassa, 1994; Rice, 1993). This retention is particularly relevant to coalbed methane (CBM) potential, as methane is predominantly stored by adsorption onto the microporous surfaces of organic matter, especially within vitrinite-rich macerals (Levine, 1993).

Table 6.1 Geochemical indicators for hydrocarbon generation obtained from Rock Eval pyrolysis.

Sample name	TOC (wt. %)	S1 (mg HC/g rock)	S2 (mg HC/g rock)	S3 (mg HC/g rock)	T _{max} (°C)	HI	OI	CaCO ₃ (wt. %)	PI
Amalai	55.6	0.94	60.11	3.1	425	104	5.125	5.44	0.03
Bangwar	50.82	0.74	36.31	3.74	425	92	9.4	5.47	0.07
Dhanpuri	58.18	1.44	79.7	2.26	445	131	3.8	4.97	0.04
Damini V	55.75	0.48	83.07	4.26	424	147	7	5.99	0.01
Damini VI	46.68	0.52	36.25	3.38	423.5	163.67	10.33	17.85	0.04
Khairaha VI	59.99	0.75	82.57	4.74	425	136	7.2	7.05	0.02
Khairaha VII	61.3	0.69	65.69	4.94	425	106	7.4	6.44	0.02
Rajendra	55.09	0.67	80.84	4.31	425	147	7.4	5.45	0.02
Sharda	56.75	1.97	127.37	2.05	429	280	5.88	13.07	0.03

The distinction between thermogenic and biogenic hydrocarbon generation is critical. Biogenic methane forms at shallow depths and low temperatures (<50 °C) through microbial activity, producing predominantly methane. Thermogenic gas, on the other hand, is generated at higher temperatures (>100 °C) by the thermal cracking of kerogen and previously generated hydrocarbons (Rice, 1993). In the studied coals, T_{max} values above 423 °C and corresponding R_o values confirm that methane generation is

predominantly thermogenic, with minimal biogenic contribution due to the coal's advanced thermal maturity.

6.4.5 Organic petrography evidence for thermal evolution / Evidence from organic petrography regarding thermal evolution

The degree of thermal maturation in coals is closely reflected in changes in maceral morphology, vitrinite reflectance distribution, and the relative abundance of maceral groups, particularly the increase in inertinite content. The dataset shown in Table 6.2 span a range of mean vitrinite reflectance values from 0.59% to 0.88%, indicating coals within the bituminous to high volatile bituminous rank, consistent with moderate thermal maturity (Taylor et al., 1998).

Table 6.2 Mean vitrinite reflectance and petrographic constituents values of Sohagpur coals.

Sample Name	Mean R _o %	Petrographic constituents (vol. %)			
		Vitrinite	Liptinite	Inertinite	Mineral Matter
Sharda	0.71	41.24	10.76	34.21	13.79
Dhanpuri	0.78	34.11	7.49	38.98	19.42
Rajendra	0.62	40.12	14.72	31.04	14.12
Khairaha VI	0.59	45.61	9.35	31.27	13.77
Khairaha VII	0.64	33.3	10.2	43.36	13.13
Damini VI (1st Site)	0.87	39.26	7.88	29.39	23.47
Damini VI (2nd Site)	0.88	33.79	10.98	38.56	16.68
Damini V	0.68	28.6	9.18	40.13	22.09
Bangwar	0.64	34.77	10.15	40.06	15.02
Amalai	0.71	31.62	7.94	43.4	17.04

6.4.5.1 Changes in Maceral Morphology and Reflectance

Vitrinite reflectance (R_o%) is the most widely accepted quantitative measure of coal maturity, as it increases with temperature and time during coalification. The reflectance values observed here (0.59 to 0.88%) correspond to a maturation stage in which vitrinite undergoes significant chemical and structural alterations, leading to increased reflectance.

This increase signifies progressive aromatization and loss of volatile components within the vitrinite macerals, reflecting bituminous coal rank (Taylor et al., 1998).

The variation in reflectance within samples is often accompanied by changes in vitrinite morphology, such as the development of fine fracturing, shrinkage cracks, and transition from cellular to more regular textures and to fused forms, as shown in Figure 6.22. These morphological transformations reduce the optical anisotropy and contribute to higher reflectance measurements (Taylor et al., 1998).

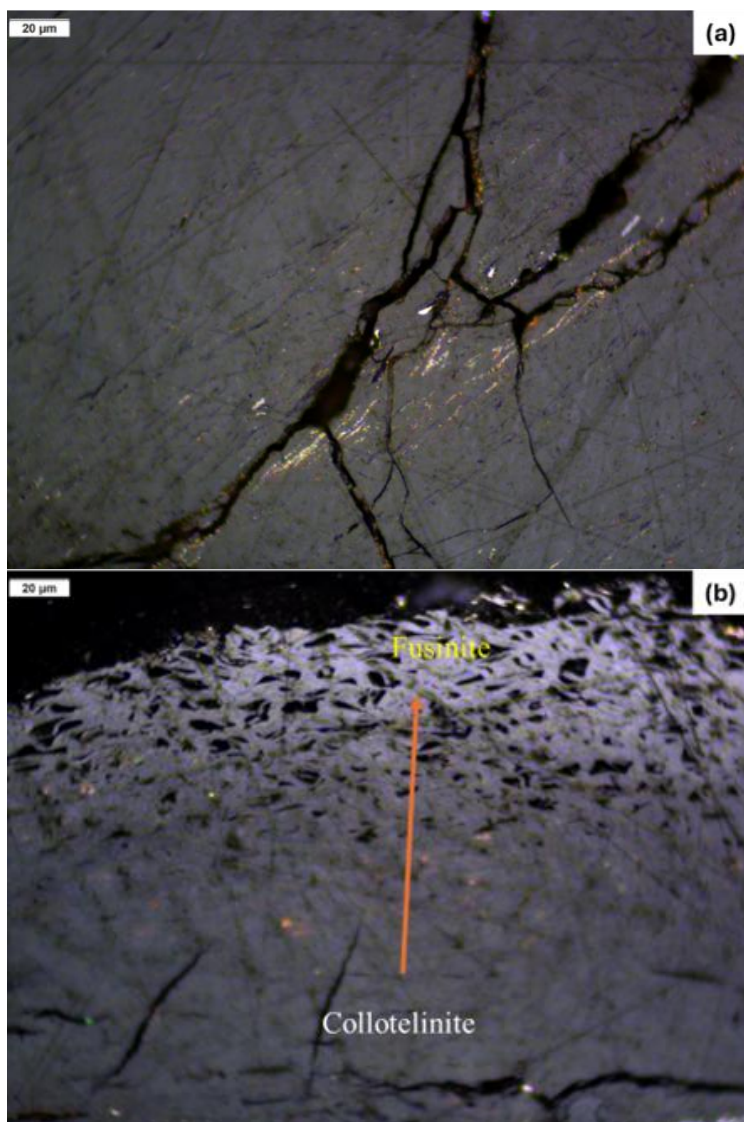


Figure 6.22 (a) Fractured and shrinkage cracks in collotelinite sub maceral (b) transition from the collotelinite to fusinite sub macerals.

6.4.5.2 Increase in Inertinite Content with Maturation

Inertinite volume in these coals ranges from 29% to 43%. This increase can be attributed to the progressive chemical alteration and partial degradation of vitrinite and liptinite macerals during thermal maturation, which converts some reactive organic matter into more inert, condensed structures classified as inertinite. The relative decrease in vitrinite content alongside an increase in inertinite suggests selective degradation and transformation of the more volatile macerals (vitrinite and liptinite) into inertinite macerals during maturation.

6.4.5.3 Changes in Liptinite and Mineral Matter

Liptinite content generally decreases slightly with increasing maturity, which is consistent with its higher reactivity and earlier loss of volatiles during coalification (Taylor et al., 1998). Mineral matter does not directly affect the maturation, as it is a component of detrital influx.

6.4.6 FT-IR based structural chemistry

Fourier Transform Infrared Spectroscopy (FT-IR) is a powerful tool for analyzing the molecular structure of coal, providing detailed insights into the functional groups and chemical bonding present across different coal ranks (Painter et al., 1985; Chen et al., 2015). As coal rank increases, the FT-IR spectra reveal systematic changes in the relative intensities of absorption bands corresponding to aromatic and aliphatic structures, and to oxygen-containing functional groups. These molecular changes have direct implications for adsorption characteristics, especially in the context of coalbed methane (CBM) and CO₂ sequestration.

6.4.6.1 Aromaticity vs. Aliphaticity with Coal Rank

One of the most significant chemical transformations during coalification is the progressive increase in aromaticity, accompanied by a decrease in aliphatic structures, as

shown in Figure 6.23 (Mazumdar 1988; Zheng et al., 2018). FT-IR spectra typically show absorption bands near 1600 cm^{-1} (aromatic C=C stretching) becoming more prominent with increasing rank, indicating enhanced condensation of aromatic rings (Painter et al., 1981). In contrast, aliphatic C–H stretching vibrations appearing near $2900\text{--}2800\text{ cm}^{-1}$ gradually diminish as the coal matures, reflecting the loss of aliphatic side chains and crosslinking of the molecular network. This aromatic enrichment is directly linked to the increasing coal rank, reflecting a thermally driven dehydrogenation and cyclization process (Chen et al., 2015).

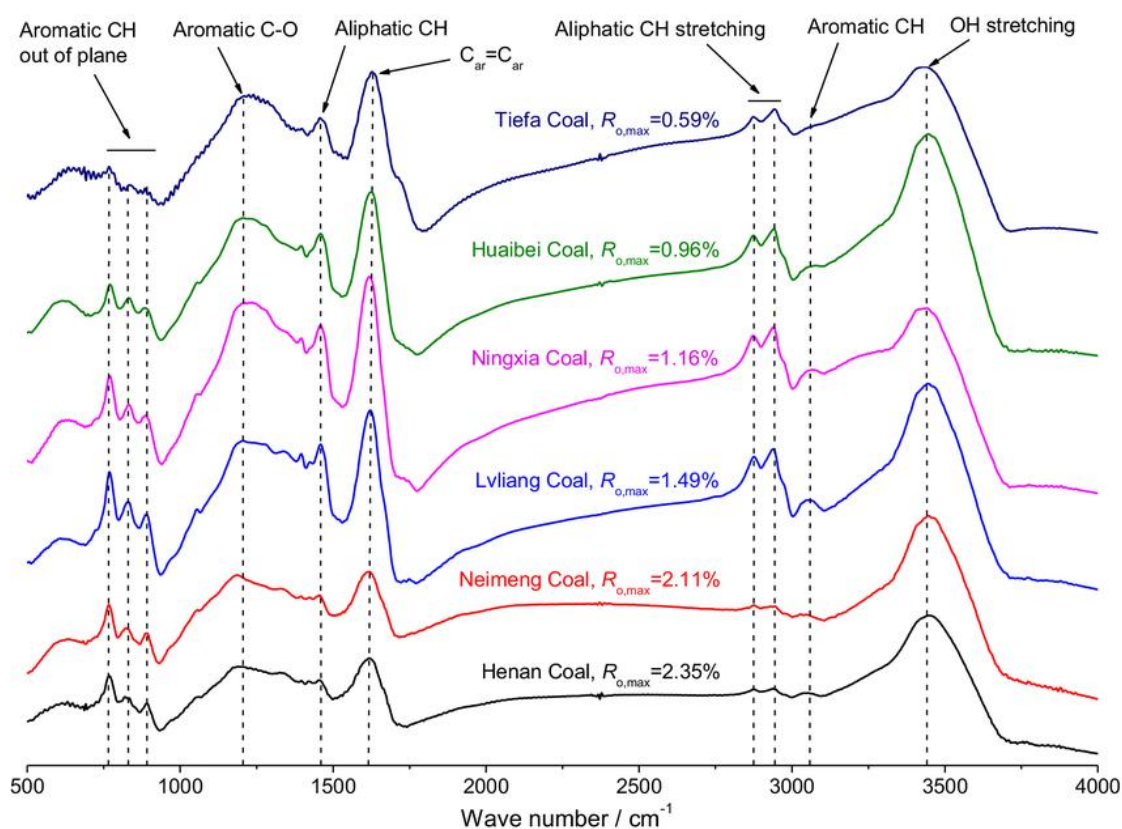


Figure 6.23 FT-IR spectra of various coal ranks (Zheng et al., 2018).

The shift towards aromaticity increases the rigidity and planarity of the coal matrix, reducing the flexibility of the organic framework. This structural densification affects the porosity and adsorption sites, altering gas storage and diffusion properties

6.4.6.2 Oxygenated Functional Groups and Their Role in Adsorption and CO₂ Affinity

Oxygen-containing functional groups, such as hydroxyl (–OH), carbonyl (C=O), and carboxyl (–COOH) groups, are also clearly detected in the FT-IR spectra, typically in the ranges 3400–3600 cm^{–1} (–OH stretching), 1700 cm^{–1} (C=O stretching), and 1200–1300 cm^{–1} (C–O stretching) (Yao et al., 2011). These polar groups tend to decrease with increasing rank due to thermal decomposition and decarboxylation reactions (Chen et al., 2015; Zheng et al., 2018). However, in lower rank coals, their abundance is higher, which significantly influences the coal's hydrophilicity and affinity for polar gases like CO₂ (Maphala and Wagner 2012).

These oxygenated groups provide active adsorption sites via dipole–quadrupole and hydrogen bonding interactions, thereby enhancing the selective adsorption of polar molecules such as CO₂ relative to non-polar methane (Wang et al., 2017; Zhang et al., 2017). Thus, coals rich in oxygen functionalities exhibit stronger CO₂ adsorption capacities, making them promising candidates for CO₂ sequestration and enhanced CBM recovery via CO₂ injection (Zhang et al., 2017, 2021; Kishor et al., 2025a).

6.4.6.3 Functional groups chemistry with macerals and adsorption behaviour

The FT-IR derived chemical structure closely correlates with maceral composition, especially between vitrinite and inertinite macerals, which have distinct chemical and physical properties that affect adsorption behaviour (Chen et al., 2015). Vitrinite macerals are rich in aliphatic chains and oxygenated groups in lower rank coals, contributing to higher adsorption capacity through both physical adsorption in micropores and chemical affinity to polar gases (Zhang et al., 2017). As rank increases, vitrinite undergoes aromatization, reducing aliphatic content and oxygen functionality, which modifies its adsorption characteristics by favouring hydrophobic adsorption sites (Wang et al., 2017;

Zhang et al., 2017; Kishor et al., 2025b). Inertinite macerals, on the other hand, consist of highly aromatic, condensed carbon structures with fewer polar functional groups. Their rigid, condensed structure provides stable, microporous adsorption sites, but has lower chemical affinity for polar molecules compared to vitrinite. Increased inertinite content, often observed with higher rank coals, enhances physical adsorption due to greater microporosity but reduces chemical adsorption associated with oxygen functionalities, whereas liptinite maceral shows higher hydrophilicity and reduces the adsorption site preoccupied by water or hydrogen molecules.

6.4.7 Oil potential

Hedberg (1968) was among the earliest researchers to highlight the significant role of terrigenous organic matter in oil generation. This concept has since been reinforced by numerous studies (Durand and Paratte, 1983; Murchison, 1987a; Abdullah, 1999; Callejon and Bissada, 2001; Sykes and Snowdon, 2002; Abbassi et al., 2016; Takahashi et al., 2020). Globally, only a limited number of coalfields are recognized as source rocks for petroleum systems. Notable examples include the Surat Basin in Australia (Khorasani, 1987), the Ruhr Basin in northwest Germany (Littke et al., 1990), the Barito Basin in Southeast Kalimantan, Indonesia (Witts et al., 2012), and the Northeast Ordos Basin in China (Guoyi et al., 2010; Zhang et al., 2017). Coals rich in liptinite macerals possess high hydrogen content, making them efficient hydrocarbon expellers (Saxby, 1980; Saxby and Shibaoka, 1986; Erik and Sancar, 2010). Furthermore, synthetic crude oils derived from coal closely resemble crude oils produced from adjacent oilfields, suggesting a genetic link (Raja Rao, 1981). The coexistence of crude oil and coal within the same geological formations further supports this connection (Saikia and Dutta, 1980; Levine, 1993; Petersen et al., 2000; Qi, 2011; Petersen and Hertle, 2018). High wax content observed in certain crude oils may originate from terrigenous source materials

with similar wax-rich characteristics (Hunt, 1991). Several authors have provided guidelines for interpreting the source rock potential of coals based on petrochemical parameters. Peters (1986) developed a system for evaluating source rock potential using Rock-Eval pyrolysis data. Additionally, Sykes and Snowdon (2002) introduced parameters such as the bitumen index (BI), defined as S1/TOC (Killops et al., 1978), and the quality index (QI), defined as (S1 + S2)/TOC (Pepper and Corvi, 1995), for assessing the petroleum potential of coal-derived source rocks. Table 6.3 provides the values of bitumen and quality index values for Sohagpur coals.

Table 6.3 Bitumen and quality index of Sohagpur coals.

Sample name	TOC (wt. %)	S1 (mg HC/g rock)	S2 (mg HC/g rock)	Production index (PI)	Bitumen index (BI)	Quality index (QI)
Amalai	55.6	0.94	60.11	0.03	0.02	1.10
Bangwar	50.82	0.74	36.31	0.07	0.01	0.73
Dhanpuri	58.18	1.44	79.7	0.04	0.02	1.39
Damini V	55.75	0.48	83.07	0.01	0.01	1.50
Damini VI	46.68	0.52	36.25	0.04	0.01	0.79
Khairaha VI	59.99	0.75	82.57	0.02	0.01	1.39
Khairaha VII	61.3	0.69	65.69	0.02	0.01	1.08
Rajendra	55.09	0.67	80.84	0.02	0.01	1.48
Sharda	56.75	1.97	127.37	0.03	0.03	2.28

The production index values of these coals range from 0.01 to 0.07, while bitumen and quality index values range from 0.01 to 0.03 and 0.73 to 2.28. The bitumen index values (0.01–0.03) indicate a free hydrocarbons content, suggesting the coal samples are either immature or have retained most hydrocarbons within the kerogen. Meanwhile, the quality index values (0.73–2.28) indicate a moderate to good hydrocarbon generative potential, suggesting that these coals contains significant bound hydrocarbons capable of generating oil and gas upon further thermal maturation. Together, these indices highlight that the samples represent promising source rocks at an early to mid-maturity stage, with potential for both liquid and gaseous hydrocarbon generation as maturation progresses.

As per the guidelines of source rock generative potential (Peters, 1986), the geochemical parameters obtained by rock-eval pyrolysis indicate that the coals of the Sohagpur coalfield are an excellent source rock for hydrocarbon generation.

6.4.8 Indication of hydrocarbon generation

The potential for hydrocarbon generation in the studied coal samples is evaluated using an integrated set of geochemical parameters, including total organic carbon (TOC), Rock-Eval pyrolysis indices (S1, S2, T_{max}, Production Index), kerogen type, and petrographic maturity indicators, as shown in different crossplots in Figure 6.20. Together, these parameters provide strong evidence for the hydrocarbon-generating capability of the coals and the nature of hydrocarbons likely to be produced (Tissot and Welte, 1984; Peters, 1986). The TOC values observed in the coal samples indicate an abundance of organic matter, which is a fundamental prerequisite for effective hydrocarbon generation. Rock-Eval pyrolysis data further reveal appreciable S2 values, indicating the quantity of hydrocarbons generated by thermal cracking of kerogen. These elevated S2 yields suggest that the organic matter retains substantial hydrocarbon-generating potential. In contrast, relatively low S1 values indicate limited amounts of free hydrocarbons, implying that most hydrocarbons remain bound within the kerogen structure rather than having been expelled. This interpretation is supported by low production index (PI) values, which reflect minimal hydrocarbon expulsion and suggest an early to moderate stage of thermal evolution (Peters and Cassa, 1994). Kerogen characterization based on hydrogen index (HI) and oxygen index (OI) indicates that the organic matter is dominated by Type III kerogen, with localized occurrence of Type II kerogen. Type III kerogen, derived mainly from terrestrial plant material, is predominantly gas-prone, whereas Type II kerogen has the capacity to generate both liquid and gaseous hydrocarbons (Tissot and Welte, 1984; Peters and Cassa, 1994). The presence of Type II kerogen suggests that

limited liquid hydrocarbon generation is possible in specific intervals, although gas generation remains the dominant process overall. Thermal maturity indicators, including $T_{\max}$ and vitrinite reflectance (R_o), further confirm that the coals have reached maturity levels sufficient for hydrocarbon generation. $T_{\max}$ values correspond to the early to peak oil window, with some samples extending into the early gas generation stage (Espitalié et al., 1985; Peters, 1986). Vitrinite reflectance values corroborate this interpretation, indicating bituminous coal rank and confirming that the thermal conditions were adequate for initial thermogenic hydrocarbon generation (Taylor et al., 1998). Petrographic evidence also supports hydrocarbon generation, as increasing vitrinite reflectance and the relative enrichment of inertinite macerals reflect progressive coalification and thermal alteration of organic matter. These changes are consistent with the transformation of reactive organic components into more condensed, aromatic structures that can generate thermogenic hydrocarbons.

6.4.9 Oil yield

Coal macerals respond differently during liquefaction due to variations in their chemical composition, reactivity, and thermal behaviour. According to Cudmore (1977), efficient coal liquefaction requires a reactive maceral content exceeding 60%, as these macerals actively participate in bond cleavage and hydrogenation reactions. Additionally, Singh and Kumar (2017) emphasized that liquefaction and hydrogenation processes are most effective in coals with vitrinite reflectance (R_o) values below 0.8%, as higher reflectance indicates increased aromaticity and reduced reactivity. In the studied coals, vitrinite reflectance values range from 0.59 to 0.88, while the proportion of reactive macerals ranges from 46.55% to 63.78%. These parameters suggest that the coal samples exhibit moderate to good suitability for liquefaction, with samples closer to the optimal thresholds showing greater potential.

Among the maceral groups, liptinite contributes significantly to higher liquefaction yields due to its high hydrogen content and abundant aliphatic chains, which readily break down under thermal conditions. Vitrinite macerals also play a crucial role, as their thermoplastic nature allows them to soften, swell, and dissolve during heating, thereby enhancing the overall liquefaction efficiency. In contrast, inertinite macerals are highly aromatic, oxidized, and structurally condensed, making them comparatively inert and resistant to thermal decomposition. As a result, inertinite largely remains unreacted throughout the liquefaction process and contributes minimally to liquid product formation (Suárez-Ruiz and Crelling, 2008).

To evaluate the liquefaction behaviour of the coal samples, both conversion percentages and oil yield percentages were calculated. Two commonly used approaches for estimating conversion efficiency were proposed by Guyot (1978) and by Jin and Shi (1997). The method developed by Jin and Shi is based on the proportion of reactive macerals in the coal, whereas Guyot's method relies on the petrofactor, which integrates petrographic parameters that influence coal reactivity. In coal petrography, the combined proportion of liptinite and vitrinite maceral groups is referred to as reactive macerals, as these components actively participate in thermal decomposition and hydrogenation reactions during liquefaction.

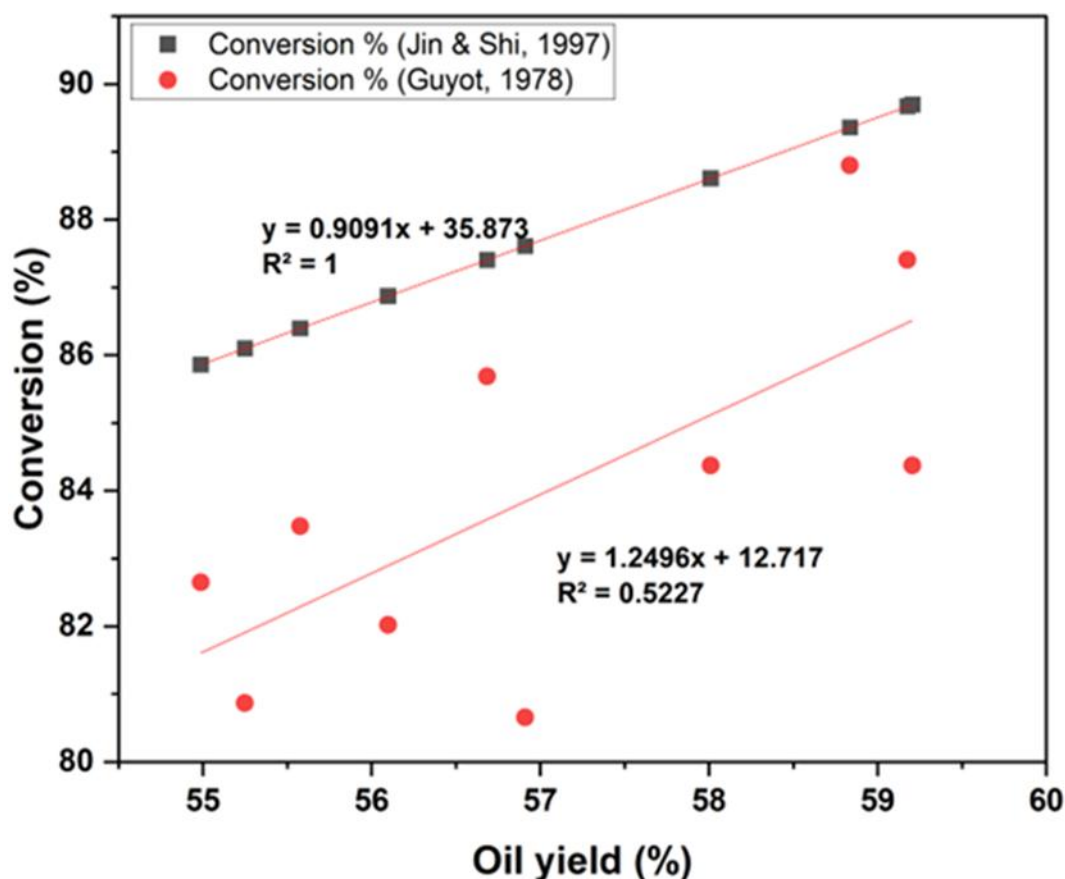


Figure 6.24 Interrelationship between the oil yield (%) and conversion (%) based on Guyot (1978) and Jin & Shi (1997).

The conversion percentages calculated using the approach proposed by Guyot (1978) and Jin and Shi (1997) demonstrate a direct relationship between oil yield and liquefaction efficiency, as shown in Figure 6.24. According to this method, higher oil yields correspond to greater conversion of coal organic matter into liquid hydrocarbons, indicating improved suitability of the coal for liquefaction. This trend reflects the influence of reactive macerals, particularly vitrinite and liptinite, which are rich in hydrogen and aliphatic constituents and therefore readily undergo thermal cracking and hydrogenation reactions during liquefaction. As the proportion of reactive macerals increases, a greater fraction of the coal matrix is transformed into liquid products, resulting in enhanced oil yields and higher conversion percentages. Consequently, the Jin and Shi (1997) conversion parameter effectively captures the coal reactivity and its

potential to produce liquid hydrocarbons, serving as a reliable indicator of liquefaction behaviour and efficiency.

6.5 Petro-chemical correlation

An attempt has been made to correlate the different coal seams of the Sohagpur coalfield on the regional scale based on the petrographic and geochemical constituents, as shown in Figures 6.25 to 6.31.

Among the investigated seams, Khairaha Seam VI is comparatively enriched in vitrinite, distinguishing it from the other seams. In contrast, inertinite content is notably higher in seams such as Khairaha Seam VII and Amalai, reflecting greater oxidation or charring of the original plant material during peat accumulation. The visible mineral matter content is highest in the Damini seams, indicating enhanced clastic input or post-depositional mineralization. An inverse relationship between liptinite and mineral matter is observed across the coal seams, suggesting that an increase in inorganic influx may have diluted hydrogen-rich organic components, as shown in Figure 6.25.

Microolithotype and carbominerite correlations further emphasize compositional differences among the seams. The dominance of vitrite microlithotypes in Khairaha Seam VI reflects the prevalence of vitrinite-rich organic matter and relatively favourable preservation conditions. Conversely, Damini Seam VI shows a higher abundance of carbargilite carbominerite, indicating a substantial association between organic matter and clay minerals. The mean inertite concentration is highest in the Amalai seam, consistent with its elevated inertinite maceral content. Additionally, vitrinertite microlithotypes are well developed in the Sharda seam, reflecting a mixed contribution of vitrinite and inertinite macerals as shown in Figure 6.26.

From a rank perspective, variations in vitrinite reflectance further support the regional correlation of seams. Damini Seam VI exhibits the highest vitrinite reflectance values, indicating a comparatively advanced stage of thermal maturation. In contrast, Khairaha Seam VI displays the lowest reflectance values, suggesting a lower level of coalification than to the other seams, as shown in Figure 6.27.

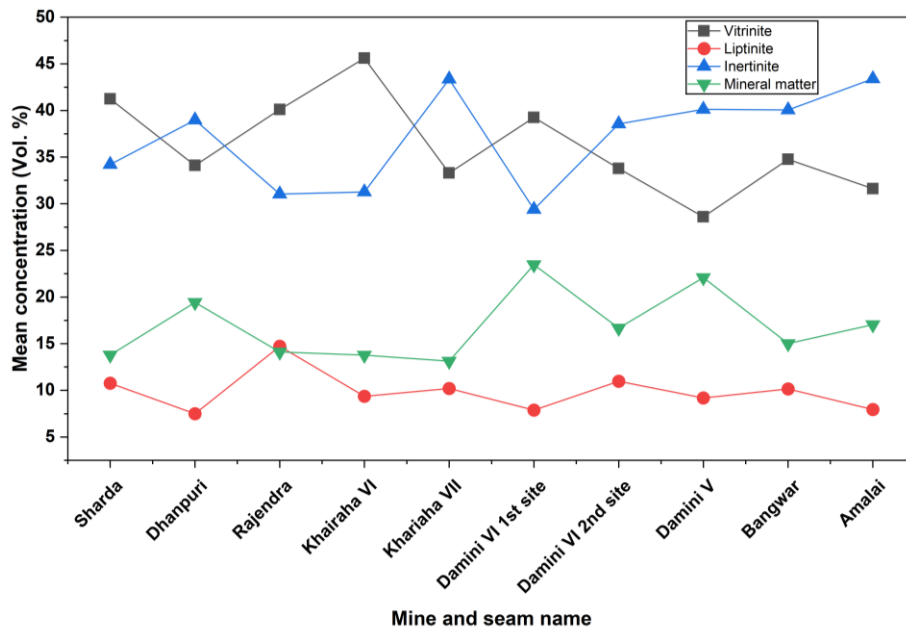


Figure 6.25 Variation of group macerals and visible minerals in the coals of different mines and seams of the Sohagpur coalfield.

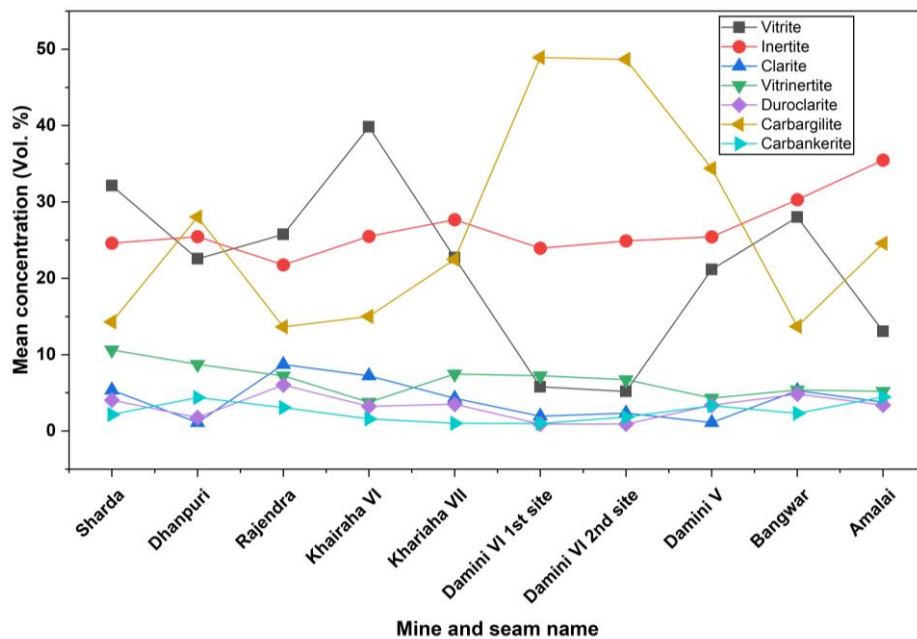


Figure 6.26 Variation of important microlithotype and carbominerite in the coals of different mines and seams of the Sohagpur coalfield.

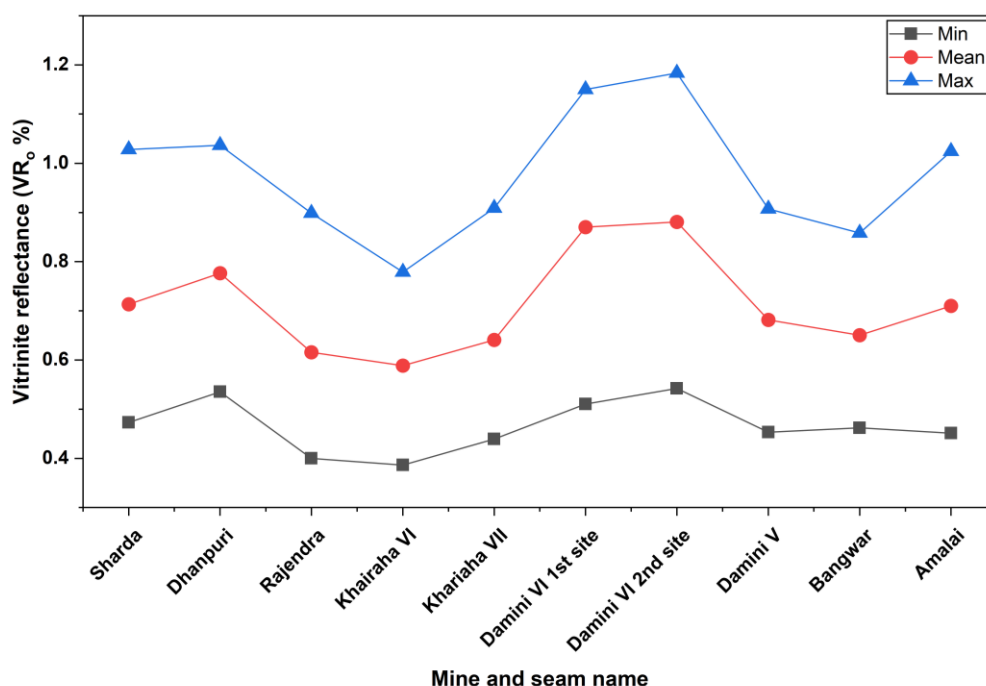


Figure 6.27 Variation of minimum, mean, and maximum vitrinite reflectance values in the coals of different mines and seams of the Sohagpur coalfield.

A comparative evaluation of the proximate analysis data for coals from different mines and seams of the Sohagpur coalfield reveals distinct variations. Among the studied coals, the Dhanpuri samples exhibit the lowest mean moisture content, indicating relatively advanced coalification and reduced inherent water retention. In contrast, the Bangwar coals show the highest mean ash yield, suggesting greater inorganic matter input or enhanced mineral admixture during deposition or post-depositional alteration. Volatile matter content displays only minor variations across the seams. The fixed carbon content is lowest in the Bangwar coals, consistent with their elevated ash content, as shown in Figure 6.28.

Ultimate analysis further highlights compositional similarities and differences among the coals. The concentrations of carbon, hydrogen, sulfur, nitrogen, and oxygen remain broadly comparable across most mines when expressed on a dry ash-free basis. However, the Bangwar coals deviate from this general trend, exhibiting the lowest carbon concentration and the highest oxygen content. This compositional signature suggests a

lower rank or greater oxidation of organic matter in the Bangwar samples, consistent with their higher ash yield and reduced fixed carbon content, as shown in Figure 6.29.

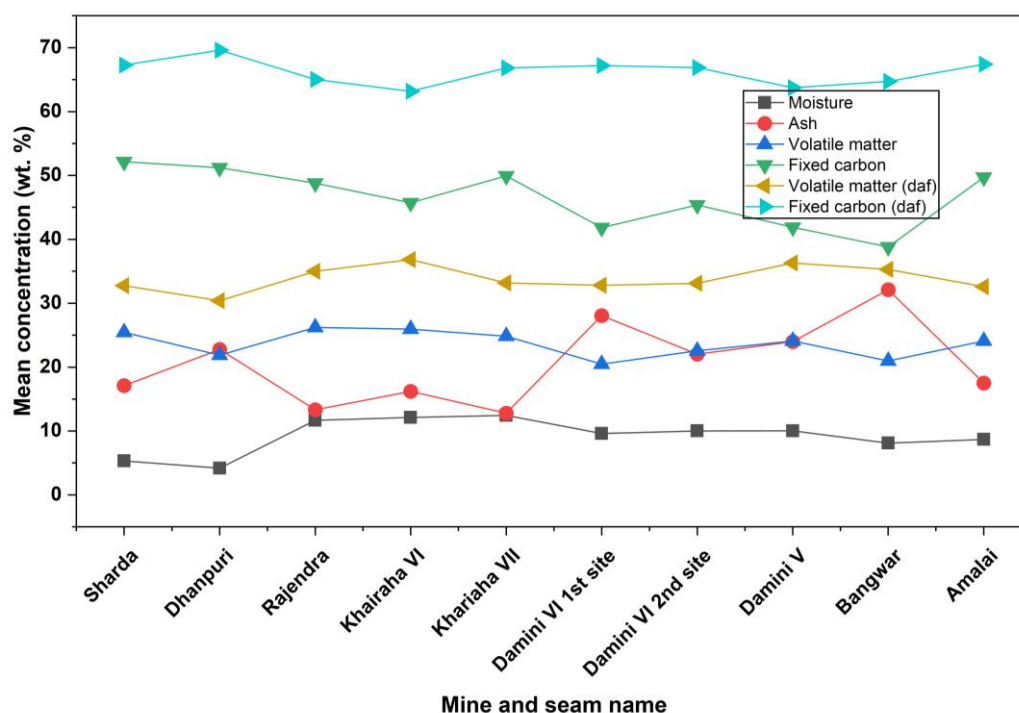


Figure 6.28 Variation of proximate constituents in the coals of different mines and seams of the Sohagpur coalfield.

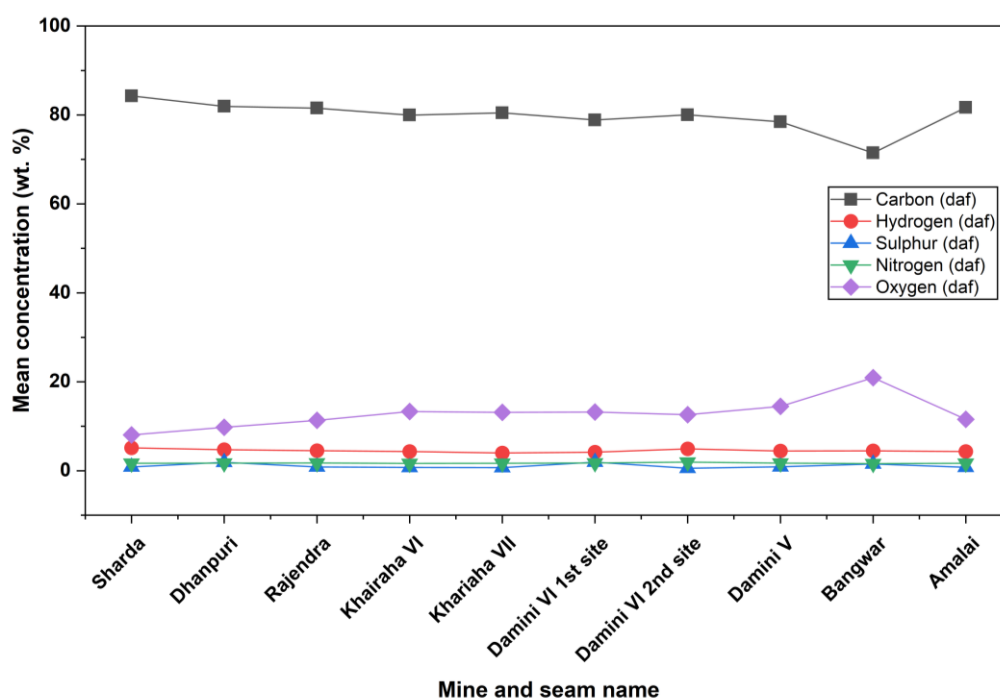


Figure 6.29 Variation of ultimate constituents in the coals of different mines and seams of the Sohagpur coalfield.

The distribution of major oxide concentrations across different coal seams indicates notable geochemical variability within the Sohagpur coalfield. The lowest concentrations of major oxides are observed in Khairaha Seam VII, suggesting minimal inorganic or detrital input in this seam. In contrast, coals from the Bangwar mine exhibit elevated concentrations of major oxides, a trend consistent with the higher ash yields observed in proximate analysis, as shown in Figure 6.30. This relationship highlights the strong control that mineral matter content exerts on the geochemical composition of the coals.

A similar pattern is observed in the distribution of major and minor elements across the studied coal seams. The Bangwar coals show enrichment in both major and minor elemental concentrations, reflecting enhanced mineral matter incorporation or post-depositional mineralization processes. Conversely, Khairaha Seam VII consistently records the lowest concentrations of these elements among the seams studied. The close correlation between elemental abundance and ash yield underscores the influence of inorganic constituents on the overall geochemical character of the coals, as shown in Figure 6.31.

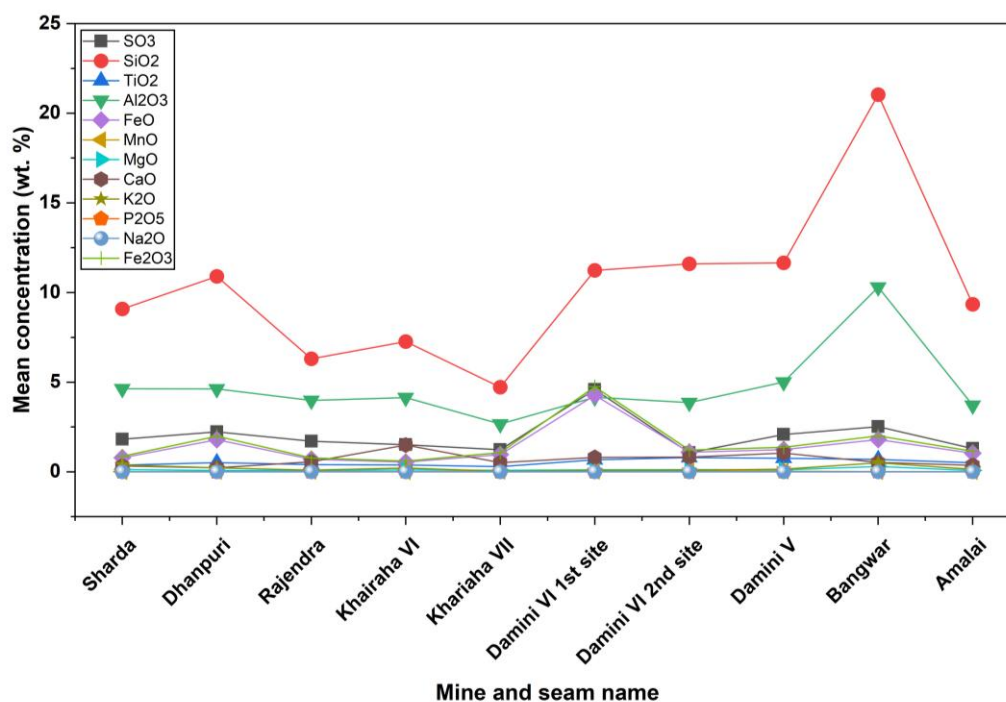


Figure 6.30 Variation of major oxides in the coals of different mines and seams of the Sohagpur coalfield.

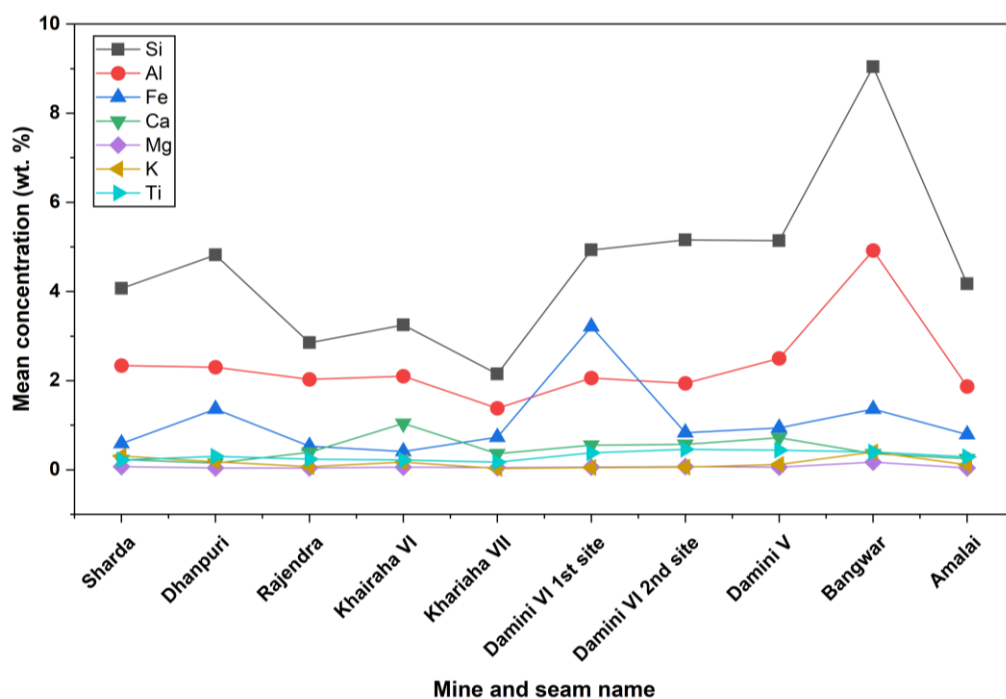


Figure 6.31 Variation of major and minor elements in the coals of different mines and seams of the Sohagpur coalfield.

6.6 Mineralogy and Inorganic Geochemistry

Mineral matter in coal originates from a combination of detrital input, authigenic mineral formation, and post-depositional alterations during burial and coalification. Detrital

minerals are introduced into peat swamps through fluvial influx, aeolian transport, and surface runoff, commonly comprising clay minerals, quartz, feldspars, and heavy minerals derived from the surrounding hinterland. Authigenic minerals, such as carbonates, sulphides, and some clay minerals, form within the peat or coal seam during early diagenesis through chemical precipitation and microbial activity. Additionally, post-depositional processes, including groundwater circulation and hydrothermal fluid interaction, may further modify the mineral assemblages within coal seams, influencing their inorganic geochemical signatures (Ward, 2002; Spears, 2013).

The distribution of mineral matter within coal seams is highly variable and is primarily controlled by depositional environment, proximity to sediment sources, and peat accumulation rates. Seams subjected to frequent flooding or increased clastic input typically show elevated ash yield and higher concentrations of major oxides and trace elements. Conversely, coals formed in relatively isolated, low-energy peat-forming environments tend to exhibit lower mineral matter content and reduced inorganic elemental concentrations. Vertical and lateral variations in mineral matter within coal seams reflect changes in hydrological conditions, sediment supply, and basin evolution during peat deposition (Diessel, 1992; Ward, 2002).

The significance of mineral matter in coal extends beyond its contribution to ash yield, as it strongly influences coal mineralogy, geochemical behaviour, and utilization characteristics. The abundance and type of minerals determine the concentrations of major oxides (e.g., SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO) and trace elements, which are largely hosted within clay minerals, carbonates, sulphides, and oxides. Elevated concentrations of silica and alumina are typically associated with clay-rich coals, while increased calcium and magnesium contents reflect the presence of carbonate minerals. Iron

enrichment often indicates the occurrence of pyrite or other iron-bearing phases, which may form under reducing conditions within the peat swamp (Dai et al., 2020).

From an inorganic geochemical perspective, mineral matter plays a critical role in controlling elemental mobility, adsorption behaviour, and environmental impact. The surface of clay minerals and organic matter can adsorb trace and rare earth elements, influencing their distribution and enrichment within coal seams. Inorganic geochemistry also provides valuable information on sediment provenance, depositional conditions, and post-depositional processes. Furthermore, mineral matter composition affects coal utilization, influencing ash fusion behaviour, slagging and fouling potential, and the release of environmentally sensitive elements during combustion or gasification (Ward, 2002; Dai et al., 2020).

6.6.1 Mineralogical interpretation using XRD

The mineral composition of coals from various seams and mines shows considerable variability, reflecting differences in depositional environment, sediment source, and diagenetic processes. The major minerals identified include quartz, kaolinite, muscovite, montmorillonite, vermiculite, illite, aragonite, dickite, albite, antigorite, and anatase, each contributing distinct physical and chemical properties to the coal.

Quartz is a common and stable silicate mineral, resistant to chemical weathering, often representing detrital input from surrounding source rocks. It is most abundant in Damini V (35.4%) and Dhanpuri (31.3%), indicating higher clastic influx or siliciclastic sediment contributions in these seams. In contrast, Rajendra seam shows the lowest quartz content (5.2%), implying less detrital quartz or more dilution by other minerals.

Muscovite, a mica group mineral rich in potassium and aluminium, is abundant in Sharda (57.5%), Rajendra (47.6%), and Amalai (50.4%) seams. Muscovite contributes to the

inorganic fraction with platy morphology and impacts the coal's mechanical strength and thermal behaviour during combustion or gasification.

Montmorillonite, a smectite group clay known for its swelling properties and high cation exchange capacity, is present only in trace amounts (below 1%) in Sharda and Dhanpuri. Although minor, its presence can affect coal's gas adsorption and reactivity, especially under varying moisture conditions.

Vermiculite, another clay mineral with swelling properties, is detected in trace amounts only in Dhanpuri (1.0%), indicating localized or minor alteration zones.

Illite, a non-swelling clay mineral, is relatively abundant in Bangwar (30.7%) and Dhanpuri (8.4%), indicating a more mature clay mineral assemblage derived from moderate weathering and diagenesis. Illite influences coal's adsorption characteristics and its interaction with hydrocarbons.

Aragonite and **dickite** are present mainly in Rajendra (18.7% and 12.9%, respectively) and Damini VI (16.8% aragonite). Aragonite, a form of calcium carbonate, indicates marine or lacustrine carbonate input and is often associated with biogenic activity or early diagenesis. The presence of carbonate minerals can affect coal reactivity and combustion behaviour by contributing to ash formation.

Kaolinite, a clay mineral formed by chemical weathering of feldspars under acidic conditions, is dominant in several seams, particularly Khairaha VII (59.3%) and Dhanpuri (54.2%). Its high concentration suggests intense weathering and a likely acidic depositional environment or post-depositional alteration. Kaolinite-rich coals tend to have lower cation exchange capacity and thereby influence coal's adsorption properties, especially for gases such as CO₂ and methane.

Albite, a sodium-rich feldspar, is noted in Rajendra (12.9%) and Khairaha VII (14.5%). Albite's presence reflects detrital input from feldspar-rich source rocks and contributes to the silicate mineral fraction in the coal.

Antigorite, a serpentine group mineral, is found significantly in Khairaha VII (14.5%). This mineral usually forms through low-grade metamorphic alteration of ultramafic rocks, and its presence suggests tectonic or hydrothermal influences.

Anatase, a titanium dioxide mineral known for its photocatalytic properties, is present in minor quantities in Damini V (1.4%), suggesting trace element incorporation possibly derived from volcanic or detrital sources.

6.6.2 Mineralogical interpretation using XRF

The major oxide composition of coal samples from different seams reflects significant variability, providing insight into the mineral matter content, depositional environment, and potential source material. These oxides are primarily associated with mineral matter in coal and influence both its geochemical behaviour and utilization characteristics.

Silicon Dioxide (SiO₂) concentrations range widely across the seams, with the highest value observed in Bangwar (21.04%) and comparatively lower values in Khairaha VII (4.72%) and Rajendra (6.3%). Silicon dioxide is predominantly hosted in quartz and clay minerals, indicating that Bangwar coal contains a significantly higher detrital quartz and silicate mineral input. This elevated silica content corresponds well with the higher ash yield and the abundance of clay minerals such as illite and kaolinite noted previously.

Aluminium Oxide (Al₂O₃), another indicator of clay mineral content, varies from about 2.67% in Khairaha VII to 10.3% in Bangwar. This reflects the abundance of aluminosilicate minerals such as kaolinite, illite, and muscovite, which are important in determining the coal's adsorption capacity and chemical reactivity. The highest Al₂O₃

concentration in Bangwar coincides with elevated SiO_2 , confirming the presence of significant clay minerals.

Iron Oxides (FeO and Fe_2O_3) concentrations provide clues about the presence of iron-bearing minerals such as pyrite and siderite. The Damini VI seam (first site) records the highest FeO (4.27%) and Fe_2O_3 (4.75%) contents, suggesting a notable presence of iron minerals, likely pyrite, formed under reducing conditions during coal deposition. Elevated iron oxides can influence sulfur content and play a key role in coal's environmental impact through acid mine drainage during oxidation.

Calcium Oxide (CaO) concentrations are particularly high in Khairaha VI seam (1.49%) and Damini V (1.04%), indicative of carbonate minerals such as calcite or aragonite. These carbonates can alter coal combustion behaviour, affecting ash melting and slagging properties. Their presence also points to occasional marine or lacustrine carbonate influx during peat formation or early diagenesis.

Magnesium Oxide (MgO) and **Manganese Oxide (MnO)** are present in relatively low concentrations across all seams, with slight enrichment in Bangwar (MgO 0.3%). These oxides often substitute into clay minerals or carbonate lattices and can affect trace element geochemistry and catalytic properties during coal conversion processes.

Titanium Dioxide (TiO_2), associated mainly with heavy minerals like rutile or anatase, ranges from 0.29% in Khairaha VII to 0.79% in Damini VI (second site). Although present in minor amounts, TiO_2 is a useful indicator of detrital input from volcanic or metamorphic sources.

Potassium Oxide (K_2O) and **Sodium Oxide (Na_2O)**, components of feldspar and mica minerals, show variable but generally low values. Bangwar exhibits the highest K_2O

(0.5%) content, consistent with the abundance of muscovite and illite from mineralogical data.

Phosphorus Pentoxide (P_2O_5) is generally low or absent, indicating minor phosphate mineral presence, which is common in many coals but usually not significant in bulk geochemistry.

Sulfur Trioxide (SO_3) content varies from 1.06% to 4.59%, with the Damini VI seam (first site) having the highest sulfur oxide levels. This correlates with the iron oxide data, suggesting a significant presence of sulfur-bearing minerals such as pyrite, which is important for environmental and combustion considerations.

6.6.2.1 Relation of major and minor elements with mineral matter

The concentration of major and minor elements such as silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), magnesium (Mg), potassium (K), and titanium (Ti) in coal samples strongly reflects the nature and abundance of mineral matter within the coal matrix. These elements serve as key proxies for identifying the of mineral phases and provide insight into the depositional environment and post-depositional alterations.

Silicon (Si) is predominantly found in quartz and silicate minerals such as clays. The data show that Bangwar has the highest Si concentration (9.04%), indicating a significant presence of quartz or silicate clay mineral, which correlates with high mineral matter and ash content. Other seams, such as Damini VI and Dhanpuri also show moderately high Si values (around 4.8 to 5.1%), reflecting their clay and quartz rich mineralogy. Conversely, Khairaha VII seam, with the lowest Si (2.15%), likely contains less silicate mineral matter, indicating cleaner coal or different depositional input.

Aluminium (Al) is mainly associated with aluminosilicate minerals such as kaolinite, illite, and muscovite. The Bangwar seam again records the highest Al content (4.92%),

confirming the abundance of clay minerals. Al content varies between 1.38 and 2.5% in other seams, consistent with variations in clay mineral content as supported by mineralogical analyses.

Iron (Fe) concentrations range widely, with the Damini VI seam (1st site) showing the highest Fe content (3.21%), which suggests substantial iron-bearing minerals such as pyrite or siderite. These iron minerals are often associated with sulfur and influence coal's environmental impact during oxidation and combustion. Lower Fe concentrations in Khairaha VI and Rajendra indicate fewer iron sulphide minerals, possibly resulting in lower sulfur content.

Calcium (Ca) values vary, with Khairaha VI seam (1.04%) and Damini V (0.72%) showing relatively elevated Ca levels, indicative of carbonate minerals such as calcite or aragonite. This points to a depositional environment with periodic carbonate influx or diagenetic carbonate precipitation. Other seams show lower Ca values, suggesting lesser carbonate mineral content.

Magnesium (Mg) concentrations are low but consistent, ranging from 0.04 to 0.17%. Mg often substitutes for other cations in clay minerals and carbonates, affecting coal reactivity and trace element behaviour.

Potassium (K) is mostly associated with clay minerals such as illite and muscovite. The highest K content is recorded in Bangwar (0.4%), reflecting its clay-rich nature, while other seams have relatively low K concentrations (0.03–0.31%), aligning with their mineralogy.

Titanium (Ti), an indicator of detrital heavy minerals such as rutile and anatase, ranges from 0.17 to 0.46%, with the Damini VI seam (2nd site) showing the highest value, suggesting higher detrital input or volcanic influence.

6.6.2.2 Occurrence and significance of major, minor, and trace elements in coals of Sohagpur coalfield

Coal combustion is a major contributor to trace element pollution in the environment. Numerous studies have highlighted the negative impacts of these trace elements on ecosystems and human health (Van Hook, 1979; Finkelman and Gross, 1999; Ren et al., 1999; Sajwan et al., 1999; Steinnes, 2010; Pokrovsky et al., 2012). Elements such as arsenic (As), lead (Pb), cadmium (Cd), and zinc (Zn) are particularly hazardous; their excessive exposure can lead to serious health problems (Sajwan et al., 1999; Mastalerz and Drobnik, 2007). For instance, lead exposure can result in mental retardation and kidney damage, while chromium inhalation has been linked to lung cancer. Arsenic contamination is associated with risks of lung and skin cancers. High copper intake can cause headaches, and in aquatic environments, copper concentrations above 1.0 mg/L are toxic to fish. Nickel and cobalt are potential carcinogens linked to lung and nasal cancers. Excessive zinc intake may damage digestive mucous membranes. Exposure to vanadium compounds can cause respiratory symptoms including coughing, wheezing, and chest tightness (Guidotti et al., 2008; Sajwan et al., 1999). The threshold limit values for vanadium pentoxide are 0.5 mg/m³ for dust and 0.05 mg/m³ for fumes (Calabrese et al., 1985).

The summarized toxicity and mode of occurrence of the selected trace elements are shown in Table 6.4. Co, Cr, V, and Zr are among the lithophile elements and may have an affinity with aluminosilicates (Sajwan et al. 1999).

Table 6.4 Environmental significance and mode of occurrence of selected trace elements present in the Coals of Sohagpur coalfield (Gluskoter 1975).

Elements	Average (ppm) in this study	Average (ppm) world coal) Finkelman 1999	Mode of occurrence in Coal (Wei et al., 2018)	Toxicity concerns (Guidotti et al. 2008) (Sajwan et al. 1999)
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V	65.07	22	In clays and organic association	Pulmonary irritant(rare)
Cr	73.63	15	Organic and clay association	Digestive tract cancers
Co	62.41	6.1	In Pyrite, some in accessory sulphides	Pulmonary, cardiac, and asthma sensitization
Ni	35.11	14	Unclear	Cancer risk, sensitization
Cu	28.60	16	Chalcopyrite	Neurotoxic
Zn	24.49	53	Sphalerite	Corrosion to the digestive mucous membranes
Rb	11.86	21	Clay minerals and feldspar	
Sr	29.69	130	Clay mineral and feldspar	
Zr	90.98	27	Organic association	
Pb	17.17	11	In Galena	Neurotoxic, renal systemic (protean)

The concentrations of environmentally sensitive trace and minor elements in these coals exceed the average global values reported by Finkelman (1999) (Table 6.4), highlighting their potential environmental and health hazards. Elevated levels of elements such as arsenic, lead, cadmium, and zinc can contribute to air, soil, and water contamination when these coals are burned for domestic use or in power plants. Prolonged exposure to these elements may lead to serious health consequences, including respiratory problems, neurological disorders, kidney damage, and even carcinogenic effects. Furthermore, emissions from coal-fired power plants can disperse these toxic elements over a wide area, increasing the risk to nearby communities. The high trace element content also underscores the need for proper coal handling, storage, and combustion practices, as well as the implementation of pollution control technologies such as flue gas desulfurization, electrostatic precipitators, and ash management strategies. These measures are critical to minimizing the release of harmful substance into the environment and protecting human health, particularly in regions where coal is a primary energy source. Overall, the elevated trace element content in these coals emphasizes the importance of careful monitoring and management to mitigate environmental contamination and associated health risks (Finkelman, 1999; Sajwan et al., 1999; Mastalerz and Drobniak, 2007).

6.6.3 Distribution and variation of major and minor elements along the seam profile

The vertical variation of major and minor elements across different coal bands reflects changes in detrital input, peat-forming conditions, mineral matter concentration, and post-depositional processes. In general, banded dull coal, which is richer in mineral matter and inertinite, shows higher concentrations of inorganic elements compared to banded bright coal, which is vitrinite-rich and organically dominated.

In the Sharda coal mine, elevated Si in the middle banded dull and lower banded bright coal suggests an increased siliciclastic influx, likely from detrital quartz and clay minerals during periods of higher clastic supply. The enrichment of Al and Fe in the middle band further supports enhanced input of clay mineral and iron-bearing minerals under more oxidizing or fluctuating depositional conditions. The relatively stable Ca and consistently low Mg indicate limited carbonate precipitation, while low K in banded bright coal reflects reduced illitic clay content. The increase in Ti in the bottom band suggests episodic heavy mineral input or volcanic detritus, as shown in Figure 6.32a.

In the Dhanpuri coal mine, higher Si and Al in the lower banded dull coal indicate a shift toward clay-rich sedimentation during the later stages of peat accumulation. The zigzag pattern of Fe reflects fluctuating redox conditions controlling iron mobility and pyrite formation. The increase in K and Ti in lower dull bands points to enhanced illite and heavy mineral concentration associated with increased detrital influx, as shown in Figure 6.32b.

The Rajendra coal mine shows enrichment of Si, Al, and Fe in banded bright coal within the middle and lower sections, suggesting intermittent clastic input even during vitrinite-dominated peat accumulation. Lower Ca values in deeper bands indicate minimal carbonate contribution, while relatively constant Mg suggests limited diagenetic

alteration. Elevated K and Ti in the middle band reflect localized clay and detrital mineral enrichment, as shown in Figure 6.32c.

In Khairaha Seam VI, the bottom banded bright coal shows elevated Si, Al, and Fe, suggesting late-stage detrital influx into the peat swamp. Low Ca suggests limited carbonate precipitation, whereas elevated Mg, K, and Ti indicate clay-rich mineral matter. The cyclic variation of K and Ti from top to bottom reflects repeated depositional cycles and fluctuating sediment supply, as shown in Figure 6.32d.

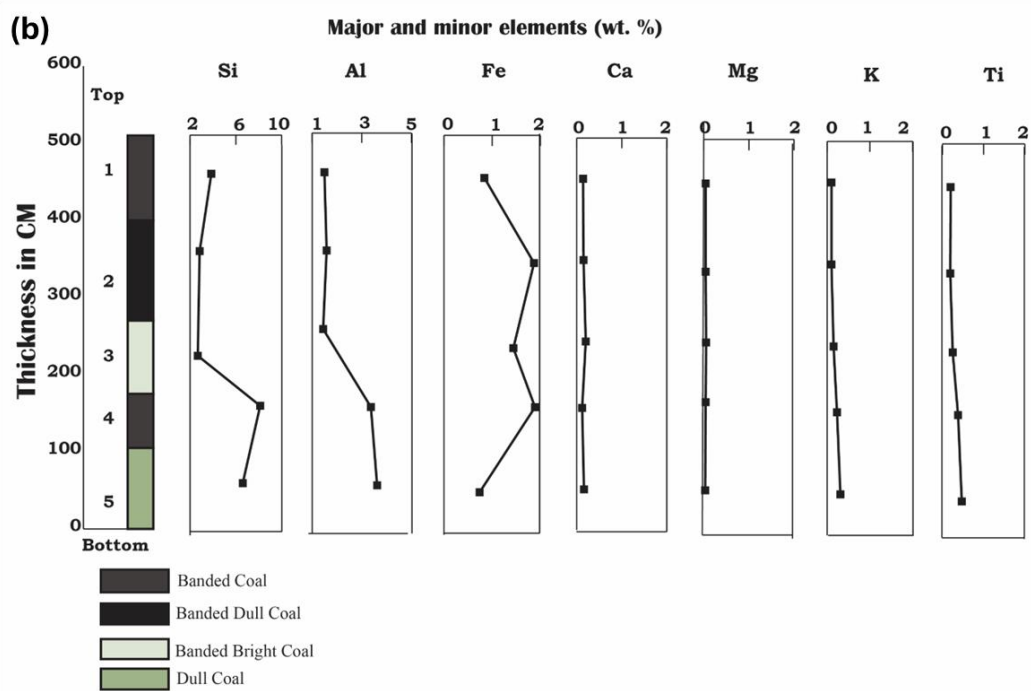
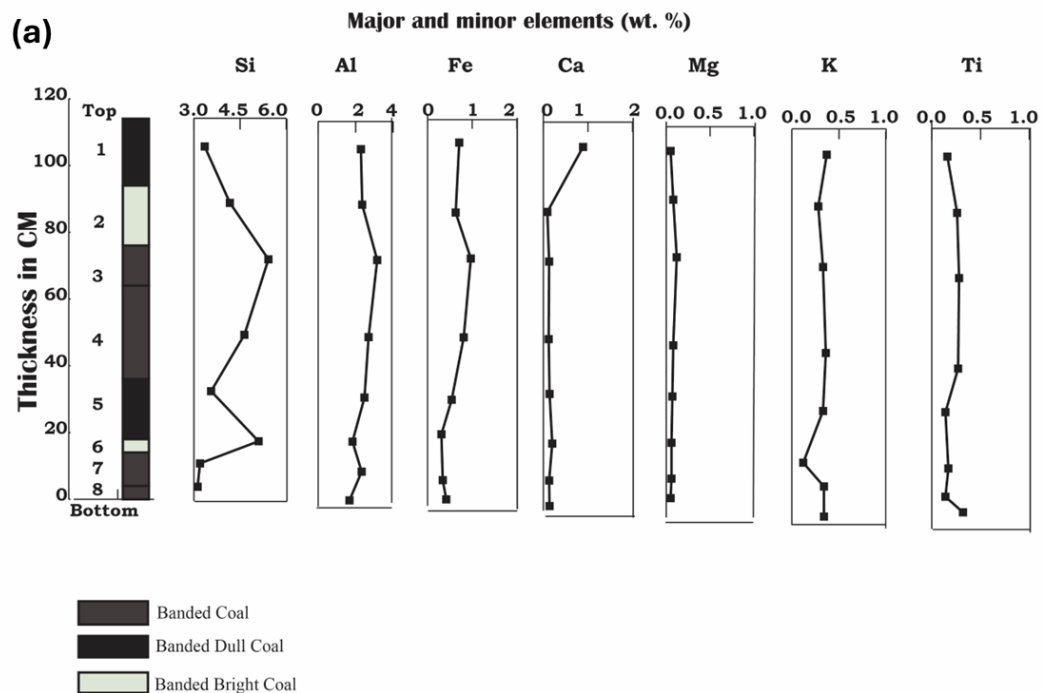
In Khairaha Seam VII, enrichment of Si and Al in the second-last band suggests localized clastic influx, while low Fe implies reduced sulphide mineral formation under less reducing conditions. The relatively uniform Ca, Mg, and K indicate stable geochemical conditions, whereas higher Ti in the upper seam reflects greater detrital input during early peat formation as shown in Figure 6.32, e.

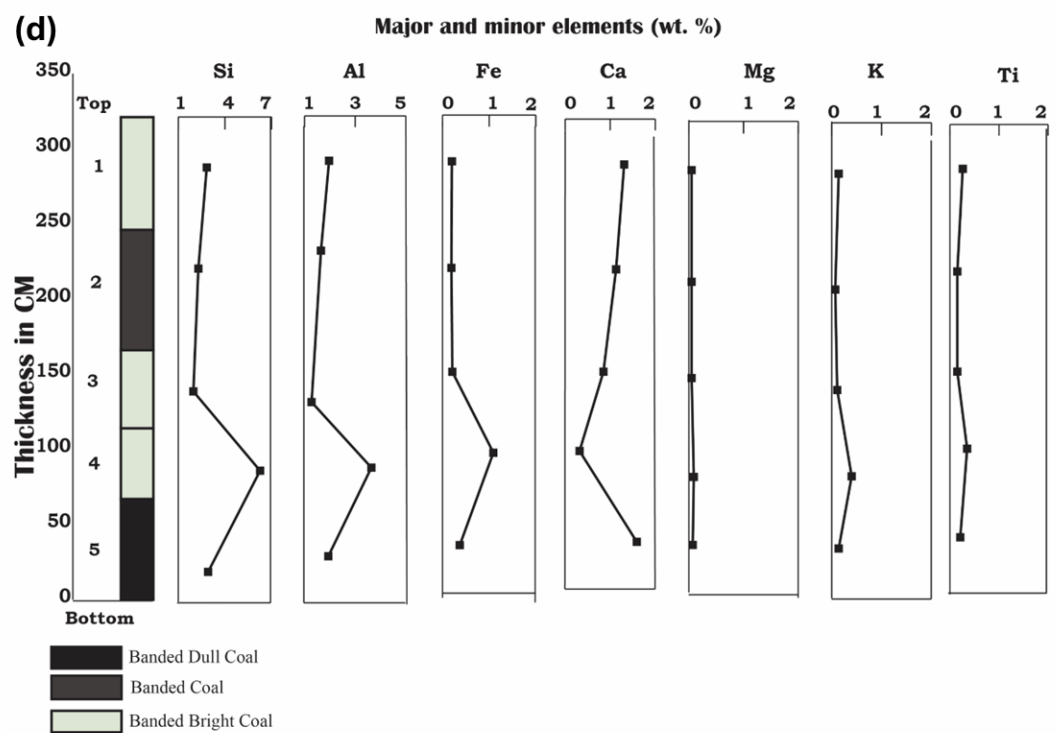
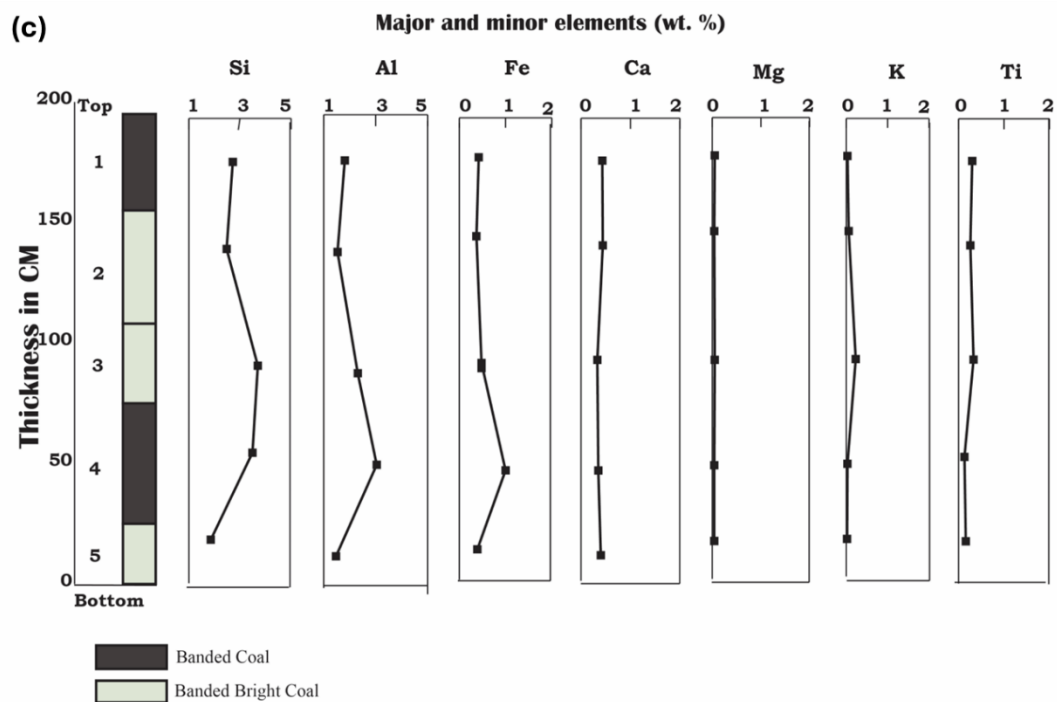
In Damini Seam VI, site-specific variations highlight local controls. At the first site, elevated Si, Al, and Ti in the middle band point to increased clay mineral input, while high Fe in the lower band suggests enhanced pyrite formation under reducing conditions. At the second site, the systematic increase downward in Si and Al reflects progressive detrital enrichment, whereas decreasing Fe indicates changing redox conditions. Higher Ca, Mg, K, and Ti in the lower section suggest mineral concentration due to compaction and diagenesis, as shown in Figure 6.32f.

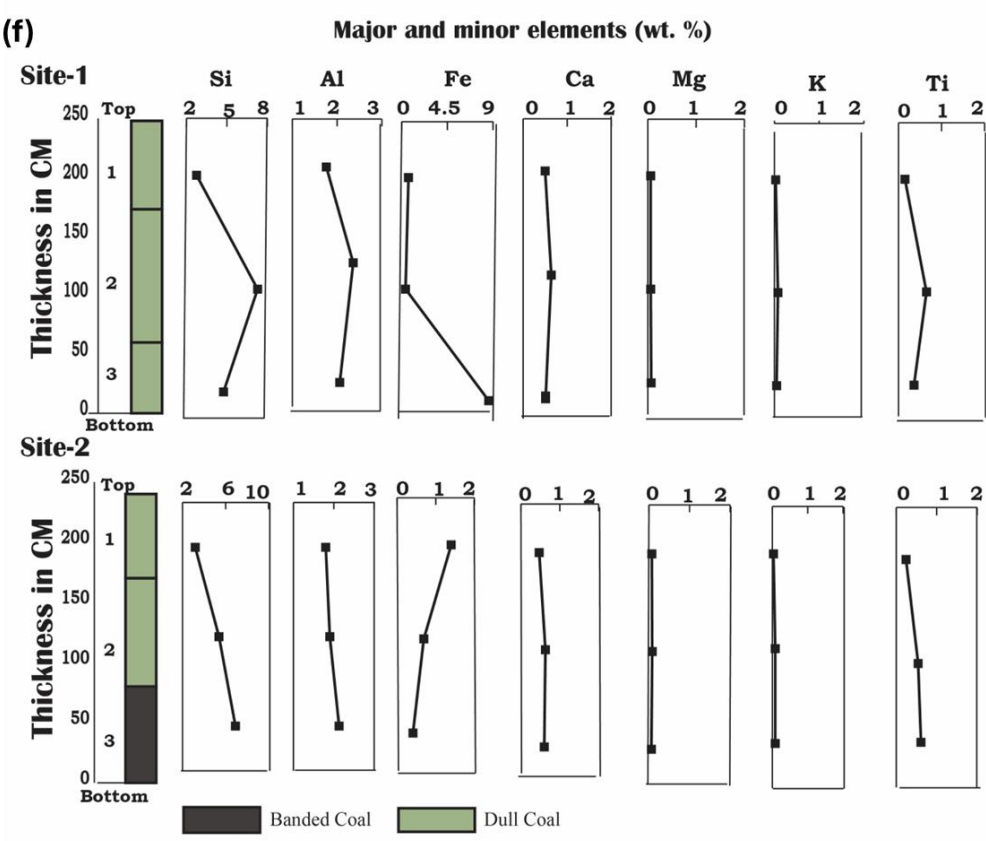
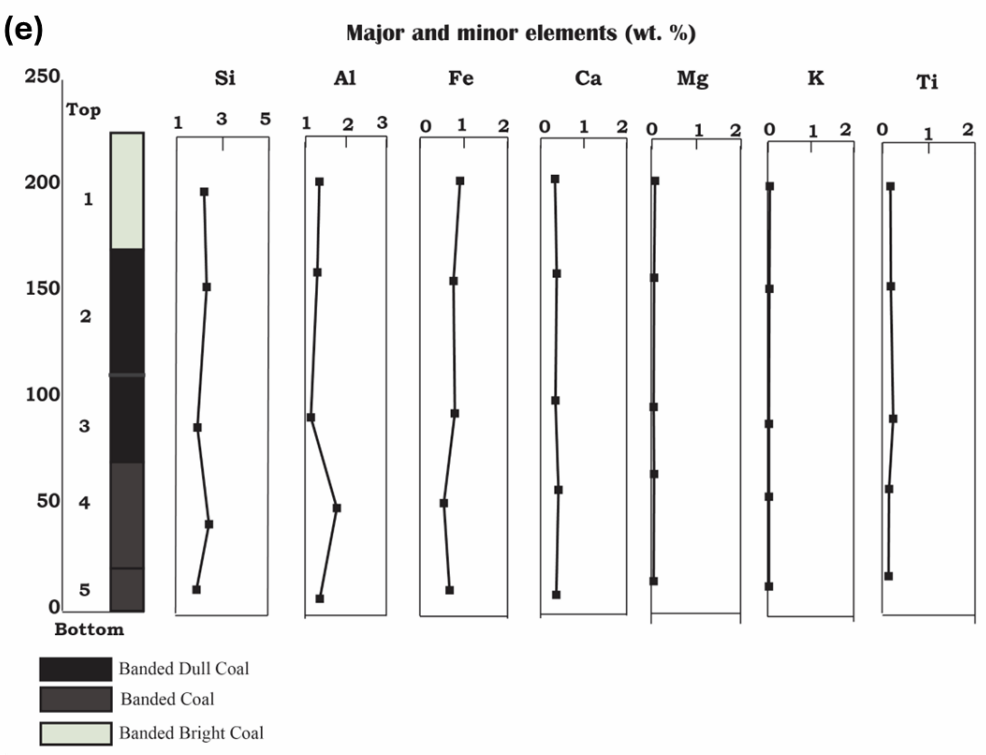
In Damini Seam V, low Si and Al in the banded coal indicate cleaner organic accumulation, while high Fe in the upper dull band suggests iron enrichment during early peat stages. Increasing Ca with depth reflects diagenetic carbonate precipitation. Elevated K and Ti in the upper dull coal are consistent with clay-rich horizons, as shown in Figure 6.32g.

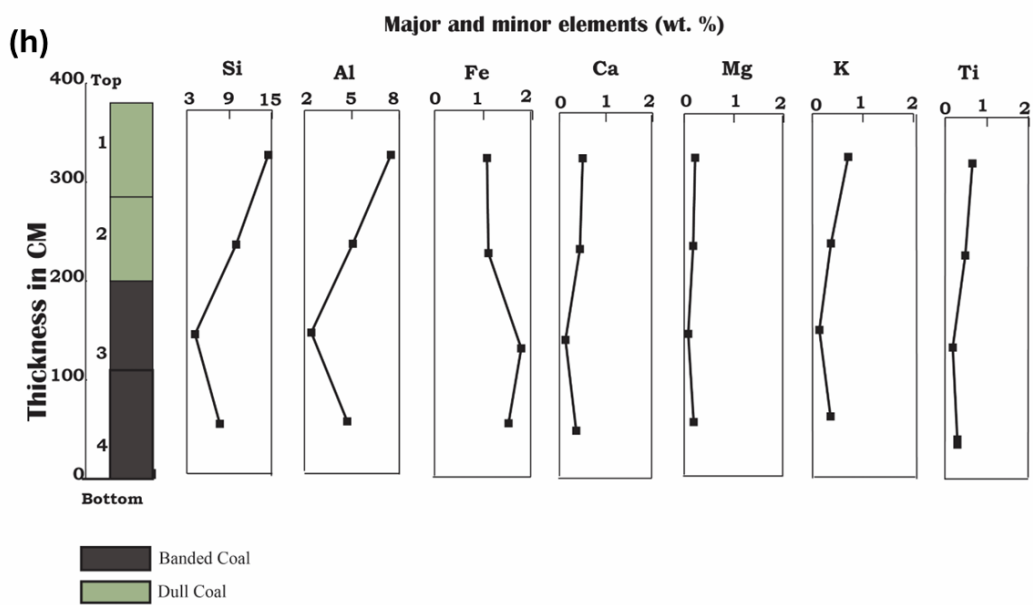
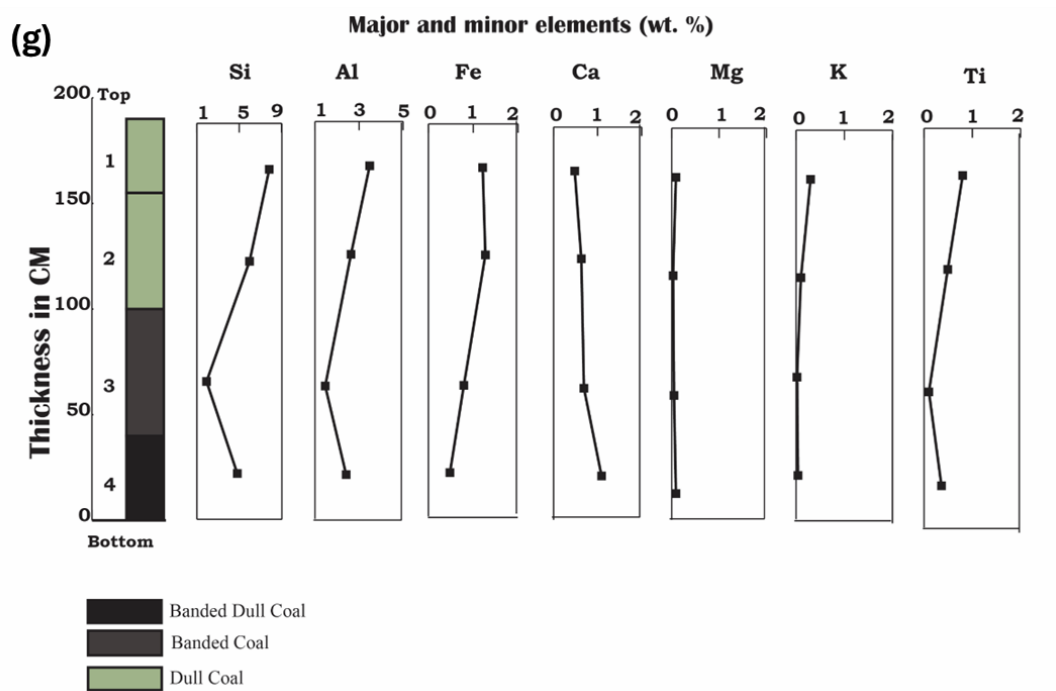
In the Bangwar coal mine, silicon (Si) and aluminium (Al) exhibit similar vertical trends, with comparatively lower concentrations in the second-from-bottom band of banded coal than in the other bands. This depletion suggests reduced input of detrital clay and quartz during the formation of particular horizon. Calcium (Ca) follows the same pattern as Si and Al, indicating limited carbonate mineral contribution within this band. In contrast, iron (Fe) shows elevated concentrations in the same band, implying localized enrichment of iron-bearing minerals, likely controlled by reducing conditions and enhanced pyrite formation. Magnesium (Mg), potassium (K), and titanium (Ti) display higher concentrations in the upper section of the seam, reflecting greater clay mineral and detrital input during the early stages of peat accumulation, as shown in Figure 6.32h.

In the Amalai coal mine, higher Si and Al in the dull coal of the middle seam reflect maximum mineral matter input, while decreasing values downward suggest improved peat preservation. Elevated Fe in the lower bands points to post-depositional pyrite enrichment. The parallel behaviour of K and Ti with Si and Al confirms their association with clay minerals, as shown in Figure 6.32i.









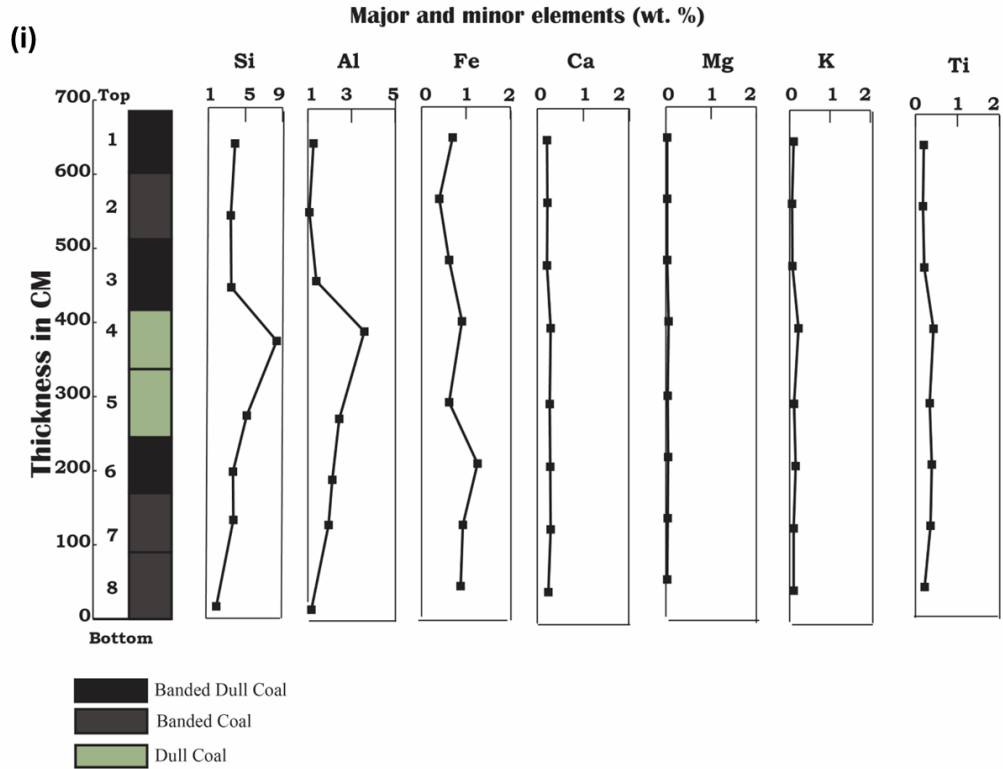


Figure 6.32 Vertical profile of coal seams with variation in major and minor elements (a) Sharda, (b) Dhanpuri, (c) Rajendra, (d) Khairaha Seam VI, (e) Khairaha Seam VII, (f) Damini Seam VI, (g) Damini Seam V, (h) Bangwar, and (i) Amalai coal mine.

6.6.4 Mineral matter origin: detrital input vs diagenetic precipitation

Mineral matter in coal is derived from multiple sources and plays a crucial role in determining coal's geochemistry, reactivity, and environmental behaviour. Broadly, mineral matter in coal can be classified into detrital (terrigenous) minerals and diagenetic (authigenic) minerals depending on their mode of origin. Understanding the relative contribution of these two sources is essential for interpreting coal genesis, depositional environment, and their utilization properties (Taylor et al., 1998; Ward, 2002).

Detrital Input: Detrital minerals are those incorporated into the peat or coal precursor during sedimentation, primarily sourced from the surrounding hinterland and transported into the depositional basin via water, wind, or gravity. Common detrital minerals include quartz, feldspars, muscovite, illite, kaolinite, and heavy minerals such as rutile and zircon.

These minerals are physically mixed with plant debris and often retain their original morphology, indicating limited chemical alteration during coalification.

The distribution of detrital minerals is often controlled by factors such as proximity to the sediment source, sediment influx rate, hydrodynamic conditions, and basin architecture. For example, elevated concentrations of quartz and muscovite, as observed in several coal seams, suggest a significant contribution from terrigenous clastic input, while clay minerals such as kaolinite and illite may indicate weathering of feldspar-rich source rocks in the catchment area (Suárez-Ruiz and Crelling, 2008). Detrital mineral input generally increases the ash yield and can influence the bulk geochemistry of coal, including the major and trace element composition.

Diagenetic Precipitation: Diagenetic minerals form in situ during peatification and coalification through chemical reactions within the depositional environment. These minerals typically precipitate from pore waters enriched in dissolved ions, influenced by microbial activity, pH, redox conditions, and organic acid generation (Taylor et al., 1998). Common diagenetic minerals include pyrite (FeS_2), siderite (FeCO_3), calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$), and occasionally phosphate minerals.

Pyrite formation is often associated with microbial sulphate reduction in waterlogged anoxic peat, where iron reacts with sulphide ions to precipitate as framboidal or euhedral pyrite (Singh et al., 2021; Kishor et al., 2025c). Similarly, carbonates such as calcite and siderite precipitate from alkaline pore waters during diagenesis and are commonly found filling voids or as nodules within coal. Diagenetic minerals can significantly affect coal's behaviour during combustion, gasification, and chemical utilization due to their reactivity and sulfur content.

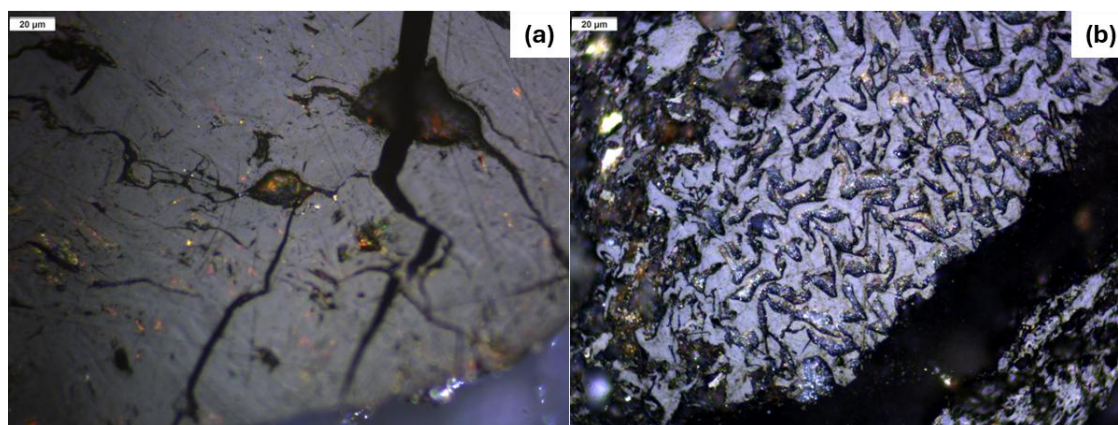
6.6.5 Mineral control on pore blocking and pore generation

The mineral matter in coal plays a critical role in controlling its pore structure, which directly influences permeability, gas storage, and adsorption capacity. Coal porosity is generated primarily through two mechanisms:

- (1) primary pore development during peatification and coalification
- (2) secondary pore formation due to diagenetic and tectonic processes.

The distribution, type, and abundance of minerals within coal have a substantial effect on both processes, particularly on pore blocking and pore generation.

Minerals, especially detrital clays and sulphides, can occlude or fill existing pore spaces, reducing the effective porosity of coal. Clays such as kaolinite, illite, and montmorillonite tend to occur in the form of discrete particles, sheets, or coatings along the walls of cleats and micropores. These minerals can block the access of fluids and gases, thereby limiting gas migration and the availability of adsorption sites, as shown in Figure 6.33.



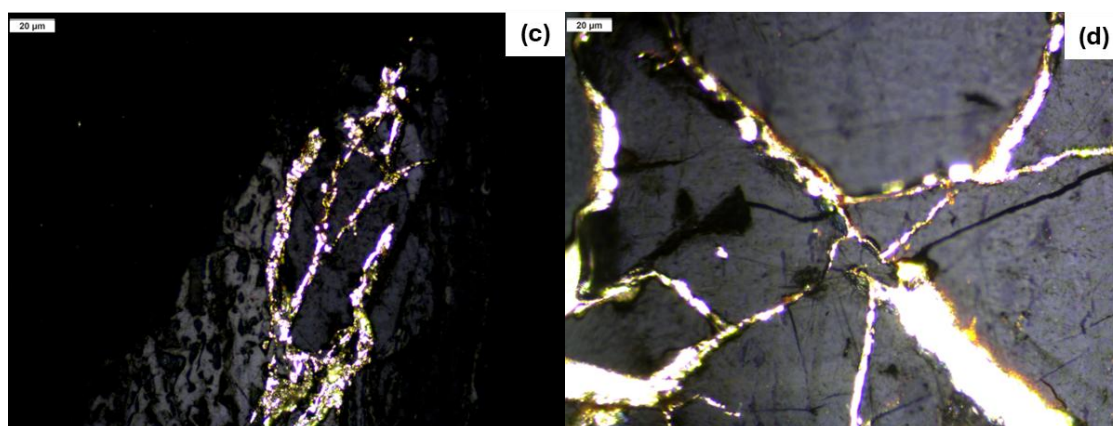


Figure 6.33 Mineral matter filled in pores (a, b) and microfractures (c, d) identified during petrography.

Pyrite and other sulphides, often precipitated during diagenesis, can also fill inter- and intraparticle voids as framboidal clusters, leading to localized pore blockage (Rickard, 2006). Carbonate minerals such as calcite and siderite, when formed as nodules or cements, can similarly reduce pore connectivity. The effect of pore-blocking minerals is particularly pronounced in coals with high mineral matter content, as observed in several coal seams of the Sohagpur coalfield, where inertinite and mineral-rich macerals coincide with reduced porosity.

While some minerals block pores, others contribute to secondary pore formation. During coal maturation, reactive minerals such as carbonates can undergo dissolution under acidic conditions generated by organic matter decay or microbial activity, leaving behind secondary voids that enhance microporosity (Clarkson and Qanbari 2015; Loucks et al., 2017).

6.6.6 Mineral control on brittleness and fracture tendency

The mechanical behaviour of coal, particularly its brittleness and tendency to fracture, is strongly influenced by the type, distribution, and concentration of mineral matter. Brittle fractures in coal are critical in determining cleat development, permeability, and gas flow, which are essential factors for coalbed methane (CBM) extraction and CO₂ sequestration.

Coal brittleness generally increases with high content of rigid, non-plastic minerals such as quartz, feldspar, and carbonates. Quartz, in particular, is mechanically strong and brittle, providing resistance to deformation under stress but promoting fracture propagation along mineral boundaries. Feldspars and carbonates act similarly, forming rigid frameworks within the coal matrix. In contrast, clay minerals, such as kaolinite, illite, and montmorillonite, are relatively soft and deformable, which tends to reduce brittleness and allows them to absorb stress without significant fracturing (Suárez-Ruiz and Crelling, 2008).

The spatial arrangement of minerals controls the initiation and propagation of fractures. Detrital quartz and pyrite nodules often act as stress concentrators, causing cleavage planes or fractures to propagate around these particles (Clarkson and Qanbari 2015; Loucks et al., 2017). Conversely, clay coatings along cleats or fractures may dampen fracture propagation by allowing minor deformation along the clay layer. Carbonate cements, such as calcite and siderite, can either reinforce the coal matrix or, if fractured themselves, provide weak zones where cracks preferentially propagate.

6.6.7 Impact of mineral matter or major, minor and trace elements on gas adsorption

Mineral matter in coal plays a pivotal role in controlling its gas adsorption capacity by influencing pore structure, surface area, and chemical reactivity. Rigid minerals such as quartz, feldspar, and carbonates tend to occupy space within the coal matrix, reducing the effective micropore volume available for gas storage, particularly for methane (CH₄). Conversely, clay minerals such as kaolinite, illite, and montmorillonite can enhance adsorption through their cation exchange capacity (CEC), polar surfaces, and ability to alter the micropore network during moisture swelling or thermal maturation (Suárez-Ruiz and Crelling, 2008; Loucks et al., 2017). Carbonates may act as pore blockers but also

provide sites for CO₂ chemisorption, which is relevant for enhanced coalbed methane recovery and CO₂ sequestration.

The major, minor, and trace elements present in coal further modulate gas adsorption by reflecting the types and abundances of minerals. Elements such as Si and Al are indicative of silicates and clays, with Al-rich clays enhancing CO₂ adsorption through polar interactions. Fe-bearing minerals, mainly pyrite, can contribute redox-active sites and promote localized micropore formation. Ca and Mg, primarily from carbonates, influence both pore space and potential chemical adsorption of CO₂. Trace elements such as Ni, Co, V, and Zn, though present at low concentrations, introduce additional polar or reactive sites, selectively enhancing gas adsorption.

6.6.8 Ash chemistry implications for CBM operations and CO₂ sequestration

The ash chemistry of coal, which reflects the concentration and composition of inorganic constituents, has significant implications for coalbed methane (CBM) production and CO₂ sequestration. Ash is composed of silicates, carbonates, oxides, and minor trace elements, which influence the mechanical, adsorption, and permeability properties of coal seams. High ash content, particularly rich in quartz, feldspar, and carbonates, reduces the effective micropore volume, thereby limiting methane storage and adsorption sites. Conversely, clay-rich ash components such as kaolinite, illite, and montmorillonite can enhance CO₂ adsorption due to their polar surfaces, cation exchange capacity, and ability to expand upon moisture uptake, thereby creating additional micropores (Loucks et al., 2017).

The mineralogical composition of ash also affects the hydraulic and mechanical behaviour of coal seams during CBM operations. Carbonate-rich ash may dissolve under injection fluids, potentially creating secondary porosity that enhances gas permeability,

whereas silicate-dominated ash tends to increase brittleness, facilitating fracture propagation but possibly blocking adsorption sites with fine particles. Trace elements and oxides within the ash can act as reactive sites for CO₂ chemisorption, improving sequestration efficiency, while high concentrations of inert or non-expanding minerals may hinder adsorption and reduce coal swelling, which affects methane desorption.

6.6.9 Mineralogical effects on mechanical strength, porosity and permeability

Minerals in coal significantly influence its mechanical behaviour, porosity, and permeability, which are critical for coalbed methane (CBM) production and CO₂ sequestration. Clay minerals such as kaolinite, illite, and montmorillonite can swell in the presence of water, causing pore blockage and reducing effective permeability. However, they may slightly enhance adsorption through polar surfaces (Clarkson and Qanbari 2015). Carbonate minerals (e.g., calcite, aragonite) can contribute to rigidity and brittleness, increasing mechanical strength but also potentially creating fracture pathways when stressed and dissolved, which may locally enhance permeability.

Pyrite and other sulphide minerals may act as hard, non-swelling inclusions, increase the coal's brittleness but limiting ductility and micropore expansion. Silicate minerals like quartz further enhance brittleness, but their presence can reduce gas storage by occupying micropore space. Overall, the type, abundance, and distribution of minerals control the coal's ability to store and transmit gases: swelling clays and high carbonate content reduce effective porosity, while rigid silicates and pyrite influence fracture development and mechanical integrity (Clarkson and Qanbari 2015; Liu et al., 2024). Understanding these mineralogical effects is essential for predicting gas production efficiency, CO₂ injection behaviour, and reservoir stability.

6.7 Coal Genesis

Coal genesis is the whole process by which plant material is converted into coal over millions of years. It includes the biological, chemical and geological processes that convert remains of dead plants into various types of coal.

The genesis of coal is significant because it elucidates the origin, evolution, and current attributes of coal, which directly affect its distribution, quality, utilization and environmental importance. The process of coal genesis is very important for figuring out the quality and rank of coal. Vegetation type, water chemistry, burial rate, and degree of preservation affect the composition of macerals, moisture, volatile matter and ash. Subsequently, coalification, which is controlled by temperature, pressure and time, determines the rank of coal, which can be peat, lignite, bituminous or anthracite. This information enables accurate estimation of the calorific value, coking behaviours and suitability for industrial applications such as the power industry, steel industry, gasification and liquefaction.

The examination of coal genesis contributes to the reconstruction of depositional environments and paleoclimate. Coal seams are the remains of old plant-forming swamps that grew in a wet, high-productivity environment. Changes in the water table, sediment supply and tectonic stability cause variation in seam thickness, ash yield and maceral assemblages. This makes coal-bearing strata valuable records of climate history and basin evolution.

Understanding how coal forms is important for finding and evaluating coal resources. Knowing how geology affects coal formation can strengthen the field's potential basis, estimate how thick the continuous coal seam will be, and make reserve estimation more

accurate while lowering the risk of exploration, especially in basins with sedimentology makes that change from side to side.

Additionally, studies of coal bed methane (CBM) depend on coal genesis to determine gas origin, storage and movement, depending on coal rank, maceral composition and cleat development. It is also important for mining safety and geotechnical planning because it affects seam strength, gas content and the risk of hazards and dangers. Lastly, coal genesis is important for the environment because it helps us understand long-term carbon storage and the geological perspective on climate change. Knowing how coal forms helps make mines safer and better manage risk.

Understanding coal genesis is crucial for determining how these coals form, including their provenance, climatic conditions, weathering processes, paleomire facies, paleo redox potential, and the paleodepositional environment during coal formation.

6.7.1 Provenances

In coal geology, provenance refers to the origin and source of sediments and the mineral matter associated with coal seam as well as the source of the coal-forming organic material. It explains the origin of inorganic components of coal and surrounding strata and how they were transported and deposited during peat accumulation.

The ratios of Al_2O_3 to TiO_2 and Al_2O_3 to Zr are commonly used as key indicators to characterize sediment provenance. These ratios provide valuable insights into the mineralogical composition of sedimentary materials, helping geologists and researchers in understanding sediment source areas and the processes that govern sediment transport and deposition.

In the case of the Sohagpur coals, the analytical data indicate that the samples fall within an intermediate provenance source, a classification that is effectively illustrated by the

cross plots outlined by Hayashi et al. (1997), as depicted in Figure 6.34. This positioning suggests a complex interplay between various source materials contributing to the coal formation in this region.

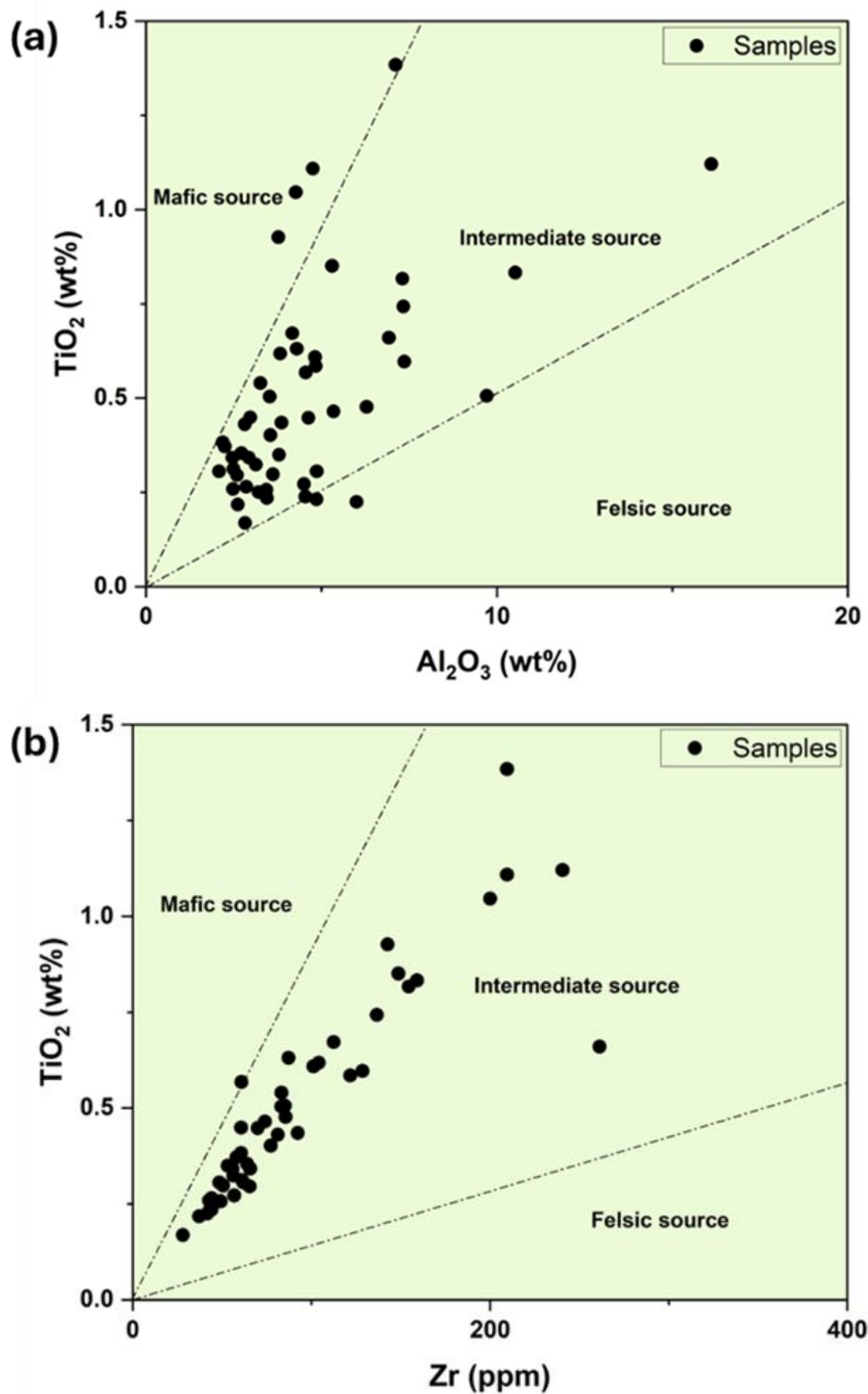


Figure 6.34 Cross plots describing the provenance of these coals (a) TiO₂ vs Al₂O₃, (b) TiO₂ vs Zr (after Hayashi et al., 1997).

6.7.2 Detrital to authigenic affinity

The assessment of detrital versus authigenic affinity in the Sohagpur coals was conducted through the calculation of the detrital influx and the Detrital to Authigenic Index (DAI). The detrital influx was determined using the formula $Al/(Al+Fe)$. This ratio indicates the source of the sedimentary material; values greater than 0.4 typically imply a terrestrial source for the detrital influx. For a more comprehensive evaluation, the DAI was calculated using the equation proposed by Vassilev et al. (1997):

$$DAI = (SiO_2 + Al_2O_3 + K_2O + TiO_2 + Na_2O) / (Fe_2O_3 + CaO + SO_3 + MgO)$$

Upon carrying out these calculations, the average DAI values for the Sohagpur coals have approximately 4.42. This notably high value suggests that the coal samples are characterized by a higher concentration of detrital mineral matter. Such findings point to an allochthonous origin of the coals, indicating that the sedimentary material was transported over a considerable distance before deposition. The strong correlation of these calculated values supports the hypothesis that the Sohagpur coals have a significant influx of detrital material, potentially originating from various geological settings. The detrital signature indicated by the DAI values aligns with findings from previous studies (Sharma et al., 2014; Khan et al., 2023), which assert the importance of understanding sediment sources in evaluating coal provenance.

6.7.3 Climate based on Geochemical data

Climatic conditions play a crucial role in influencing the chemical composition of coal samples, particularly the presence of various oxides and elemental concentrations. A well-established method for analyzing these effects involves creating binary cross plots, notably between SiO_2 and $Al_2O_3+K_2O+Na_2O$. This approach has been widely adopted to interpret climatic conditions that may have prevailed during the formation of these

sediments. Similarly, the examination of trace elemental ratios, such as Rb/Sr, Ga/Rb, and Sr/Cu, as well as major oxide ratios, such as K_2O/Al_2O_3 , can also provide meaningful insights into historical climatic conditions, as illustrated in the accompanying Figure 6.35.

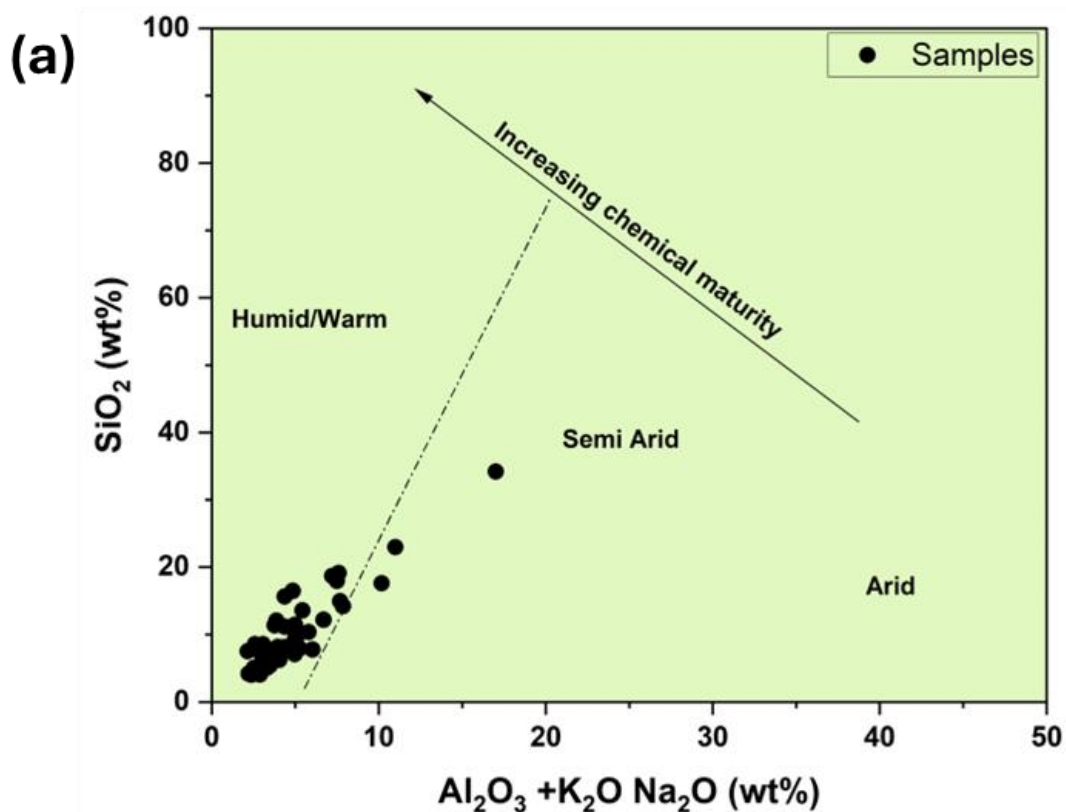
In detail, the binary plots comparing SiO_2 with $Al_2O_3+K_2O+Na_2O$ indicate that the coal deposits are characteristic of warm and humid climatic conditions (Suttner and Dutta 1986). This observation aligns with the results from the Ga/Rb versus K_2O/Al_2O_3 cross plots, which further suggest that these conditions were conducive to the kaolinite development. Kaolinite often forms under warm, wet climates due to its association with intense chemical weathering. In contrast, sediments rich in illite are typically indicative of drier conditions as they tend to form in environments with lower levels of weathering.

According to research by Roy and Roser (2013), illite-rich sediments exhibit low Ga/Rb ratios alongside high K_2O/Al_2O_3 ratios. This is due to the stability and prevalence of potassium and rubidium (Rb) in such settings, reflecting a landscape characterized by weaker chemical weathering. In contrast, sediments enriched with kaolinite will typically present low K_2O/Al_2O_3 ratios, indicating the dominance of kaolinite-related processes, alongside higher Ga/Rb ratios. This is primarily because aluminium and gallium are often associated with the fine-grained aluminosilicate fraction, which is rich in kaolinite, making these indicators reliable markers of warm and humid climates (Hieronymus et al., 2001; Roy and Roser, 2013; Kishor et al., 2025c).

Further nuances arise when analyzing the Rb/Sr versus Sr/Cu cross plots, which also indicate warm and humid climatic conditions for the coal samples under investigation. This behaviour is attributed to the differing mobility of these elements during weathering. Rb is considered relatively immobile when subjected to weathering influences, in stark contrast to strontium (Sr), which is more soluble and easily leached in humid

environments. As a result, intense weathering conditions typically lead to a reduced Sr content, thereby lowering the Rb/Sr ratio.

On the other hand, a high Sr/Cu ratio may indicate arid climatic conditions with limited vegetation cover. In arid settings, strontium tends to accumulate due to reduced leaching potential, while copper, which is often found associated with organic matter and biotic processes, generally flourishes in more humid, vegetated environments. Consequently, the interplay between these elements provides a deeper understanding of the climatic contexts in which these coal deposits were formed. This integrated approach underscores the significance of sediment geochemistry in reconstructing past environmental conditions and enhances our understanding of coal formation in relation to climatic variations.



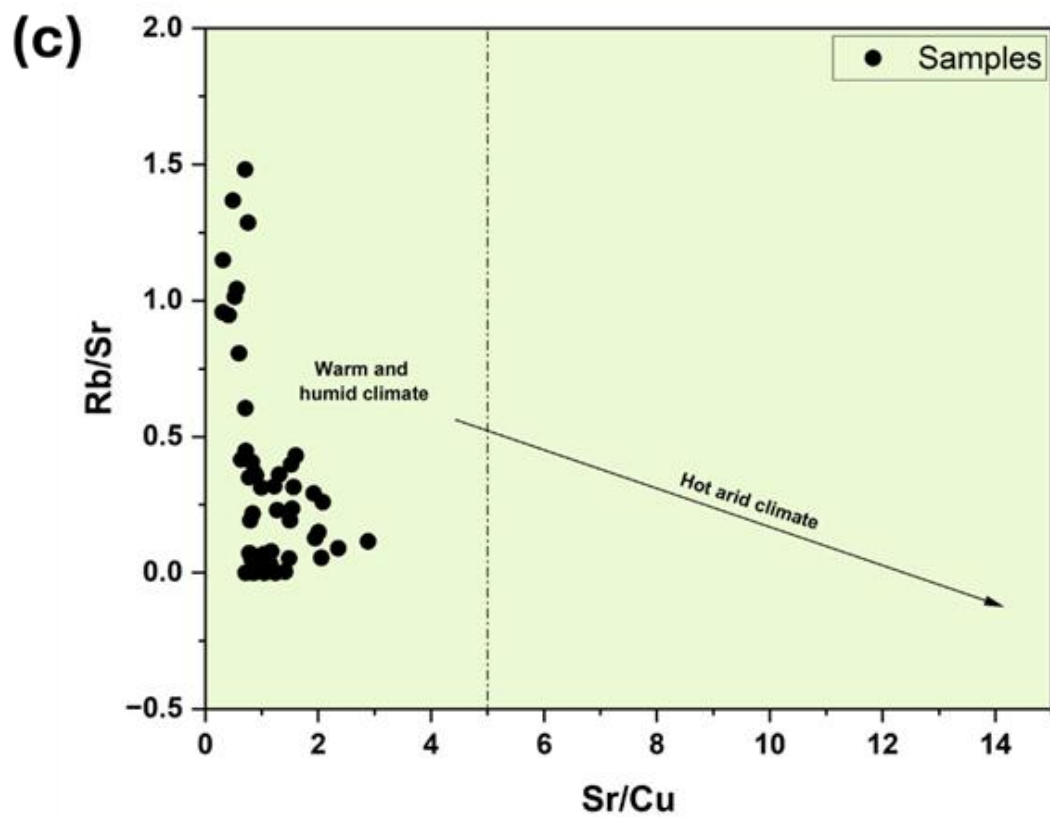
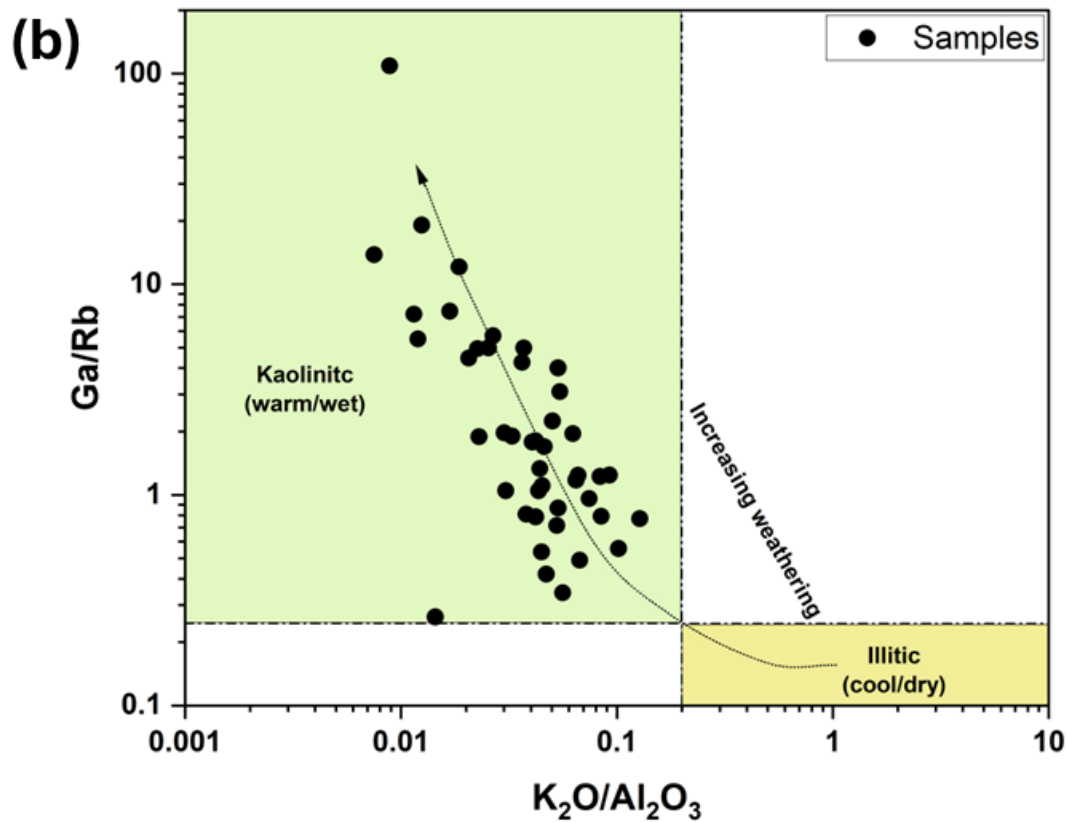


Figure 6.35 Cross plots using XRF data show Warm/Humid climatic conditions during peat formation (a) SiO_2 vs $Al_2O_3+K_2O+Na_2O$ (after Suttner and Dutta 1986), (b) Ga/Rb vs K_2O/Al_2O_3 , (c) Rb/Sr vs Sr/Cu (after Roy and Roser 2013).

6.7.4 Weathering

The intensity and nature of weathering during the sedimentation can be effectively assessed by analysing major oxides obtained by X-ray fluorescence (XRF). Since coal contains both organic and inorganic fractions, the inorganic matter plays a critical role in recording the chemical weathering history of the source area. The extent of alteration of primary minerals, especially feldspars and micas, provides significant information about the prevailing climatic and depositional conditions. To quantify these processes, several geochemical indices have been developed and applied using XRF data. The most widely employed include the Chemical Index of Alteration (CIA), which reflects the degree of feldspar alteration to clay minerals; the Chemical Index of Weathering (CIW), specifically designed to evaluate feldspar weathering independent of K-bearing phases; and the Plagioclase Index of Alteration (PIA), which measures the extent of plagioclase breakdown. Additional indices, such as the Chemical Proxy of Alteration (CPA), the Weathering Index of Parker (WIP), and the Index of Compositional Variability (ICV), further refine the assessment by accounting for the mobility of alkali and alkaline earth elements and the sediment maturity. Together, these proxies provide robust insights into the intensity of chemical weathering, climatic conditions, and sediment recycling processes (Buggle et al., 2011; Cox et al., 1995; Fedo et al., 1995; Harnois, 1988; Nesbitt and Young, 1982).

Table 6.5 Geochemical weathering proxies and respective formula.

Proxies	Formula	Reference(s)
CIA	$(Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)) \times 100$	Nesbitt and Young (1982)
CIW	$(Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O)) \times 100$	Harnois (1988)
PIA	$(Al_2O_3 - K_2O) / (Al_2O_3 + CaO^* + Na_2O - K_2O) \times 100$	Fedo et al. (1995)
CPA	$Al_2O_3 / (Al_2O_3 + Na_2O) \times 100$	Buggle et al. (2011)
WIP	$[(2Na_2O/0.35) + (MgO/0.9) + (2K_2O/0.25) + (CaO^*/0.7)] \times 100$	Parker (1970)
ICV	$(Fe_2O_3 + K_2O + Na_2O + CaO + MgO + TiO_2) / Al_2O_3$	Cox et al. (1995)

Table 6.5 above presents the formulas for the geochemical weathering proxies applied to evaluate the intensity of chemical alteration in the studied coal samples. These proxies are calculated using the molar proportions of major oxides, and careful attention is required to correct for CaO derived from non-silicate phases such as carbonates and phosphates. In this regard, the correction proposed by McLennan et al. (1993) is widely adopted, in which CaO* represents the CaO content derived solely from silicate minerals. The correction procedure ensures that if the molar proportion of CaO is less than Na₂O, CaO* is considered equal to CaO, whereas if CaO exceeds Na₂O, then CaO* is adjusted to equal the molar proportion of Na₂O.

Table 6.6 Calculated weathering indices of Sohagpur coals.

Mine/Seam name	Band No.	CIA	CIW	PIA	CPA	WIP	ICV
Sharda	1	90.08	100	100	100	4.15	0.7
Sharda	2	92.54	100	100	100	3.32	0.43
Sharda	3	93.45	100	100	100	4.04	0.43
Sharda	4	91.61	100	100	100	4.24	0.45
Sharda	5	91.7	100	100	100	3.78	0.36
Sharda	6	95.65	100	100	100	1.58	0.36
Sharda	7	90.9	100	100	100	3.85	0.32
Sharda	8	87.85	100	100	100	3.79	0.57
Dhanpuri	1	95.46	100	100	100	1.32	0.68
Dhanpuri	2	95.79	100	100	100	1.26	1.11
Dhanpuri	3	93.33	100	100	100	1.81	1.11
Dhanpuri	4	95.65	100	100	100	2.67	0.58
Dhanpuri	5	94.61	100	100	100	3.42	0.35
Rajendra	1	98.74	100	100	100	0.57	0.53
Rajendra	2	97.21	100	100	100	0.86	0.6
Rajendra	3	93.65	100	100	100	2.65	0.47
Rajendra	4	99.43	100	100	100	0.46	0.38
Rajendra	5	99.18	100	100	100	0.35	0.52
Khairaha VI	1	95.25	100	100	100	1.75	0.75
Khairaha VI	2	97.19	100	100	100	0.96	0.72
Khairaha VI	3	94.44	100	100	100	1.39	0.81

Mine/Seam name	Band No.	CIA	CIW	PIA	CPA	WIP	ICV
Khairaha VI	4	93.2	100	100	100	4.7	0.46
Khairaha VI	5	95.17	99.81	99.8	99.91	1.83	0.92
Khairaha VII	1	97.29	99.23	99.22	99.61	0.79	0.88
Khairaha VII	2	98.21	100	100	100	0.61	0.85
Khairaha VII	3	98.67	100	100	100	0.4	0.98
Khairaha VII	4	99.19	100	100	100	0.46	0.51
Khairaha VII	5	99.05	100	100	100	0.39	0.7
Damini VI 1st site	1	98.7	100	100	100	0.6	0.6
Damini VI 1st site	2	97.82	100	100	100	1.14	0.6
Damini VI 1st site	3	98.46	100	100	100	0.87	3.33
Damini VI 2nd site	1	98.77	100	100	100	0.67	0.93
Damini VI 2nd site	2	97.32	100	100	100	1.18	0.82
Damini VI 2nd site	3	97.61	100	100	100	1.09	0.64
Damini V	1	94.53	100	100	100	3.65	0.62
Damini V	2	97.28	99.69	99.68	99.85	1.24	0.72
Damini V	3	98.49	99.48	99.47	99.74	0.5	0.88
Damini V	4	98.79	100	100	100	0.91	0.65
Bangwar	1	94.28	100	100	100	8.8	0.29
Bangwar	2	95.37	100	100	100	4.9	0.37
Bangwar	3	96.15	100	100	100	1.88	0.7
Bangwar	4	95.14	100	100	100	4.84	0.42
Amalai	1	94.84	100	100	100	1.18	0.75
Amalai	2	96.21	100	100	100	0.77	0.64
Amalai	3	96.85	100	100	100	0.84	0.63
Amalai	4	96.05	100	100	100	2.64	0.39
Amalai	5	96.33	99.5	99.49	99.75	1.54	0.44
Amalai	6	95.51	100	100	100	1.78	0.77
Amalai	7	96.58	100	100	100	1.26	0.68
Amalai	8	94.53	100	100	100	1.18	0.97
Avg		95.8	99.95	99.95	99.98	2.02	0.69
Min		87.85	99.23	99.22	99.61	0.35	0.29
Max		99.43	100	100	100	8.8	3.33

The results of the present study reveal that the CIA (Chemical Index of Alteration) values for these coals are consistently above 85, as shown in Table 6.6 and Figure 6.36. Such

high values are generally considered to be diagnostic of intense chemical weathering in the source region and suggest extensive leaching of mobile cations such as Ca^{2+} , Na^+ , and K^+ relative to Al^{3+} , which remains relatively immobile during alteration. Similarly, the CIW (Chemical Index of Weathering), PIA (Plagioclase Index of Alteration), and CPA (Chemical Proxy of Alteration) values are all greater than 99 (Table 6.6). These extreme values indicate almost complete weathering of feldspars into clay minerals, suggesting strong hydrolytic alteration under warm humid climatic conditions. Since higher values of these indices correspond to more intense weathering, the results provide robust evidence for advanced alteration of the detrital mineral assemblage prior to coal deposition.

In contrast, the WIP (Weathering Index of Parker) values for the samples are markedly low (<10). A decrease in WIP reflects the preferential removal of mobile alkali and alkaline earth elements during intense leaching, and the low values reported here are therefore consistent with the conclusions drawn from CIA, CIW, PIA, and CPA. The convergence of these independent geochemical indices strongly supports the inference of prolonged and strong chemical weathering in the provenance area of the studied coal deposits (Trentin et al., 2025).

The ICV (Index of Compositional Variability) provides an additional measure of sediment maturity, reflecting the relative proportions of stable and unstable minerals. The average ICV values for these coals are below 1, suggesting a compositionally mature inorganic fraction. Such low values typically indicate sediment recycling and extensive chemical alteration, where the mineralogical composition becomes dominated by stable phases such as kaolinite, quartz, and heavy minerals. This observation is significant because it implies that the detrital input into these coal-bearing successions was already highly weathered before burial. Comparable ICV values have been reported by Panda et

al. (2025) for the Talcher Coalfield and by Pillai et al. (2023) for the Damodar Valley Basin, both part of the Gondwana Supergroup. The consistency of these findings across different basins suggests that strong chemical weathering was a widespread phenomenon influencing Gondwana coal formation in India.

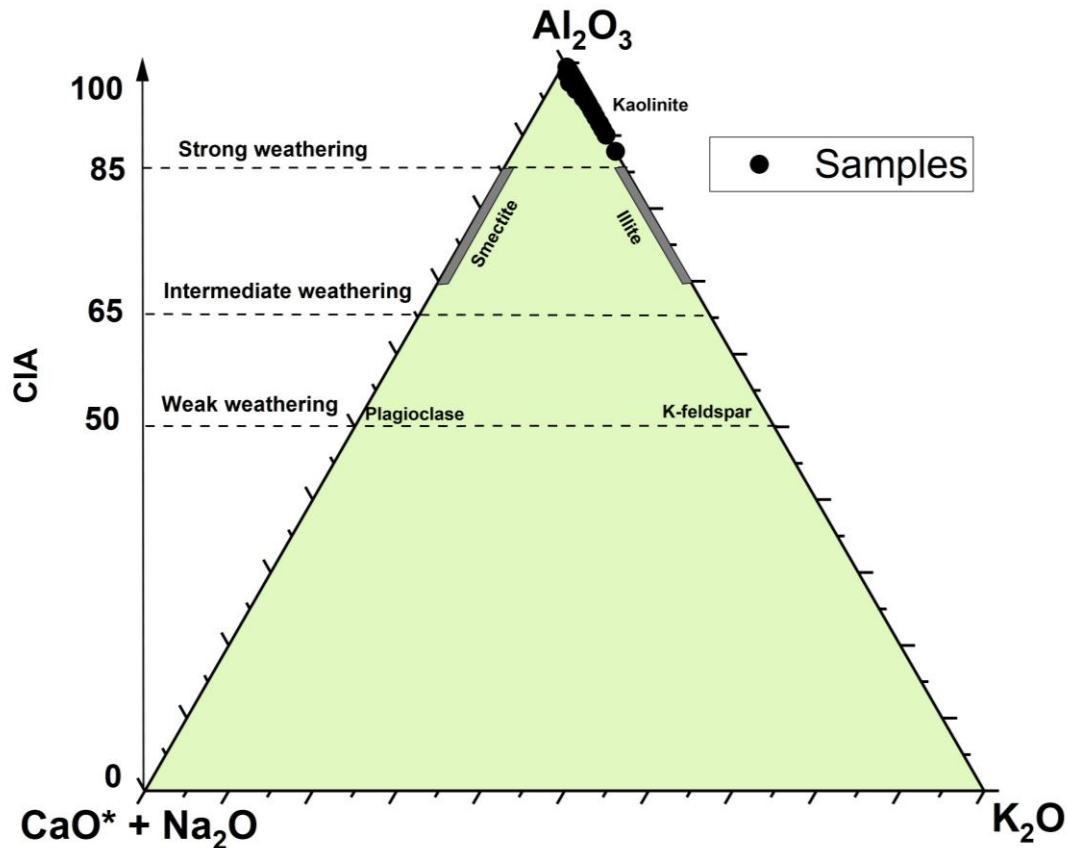


Figure 6.36 Al_2O_3 - $\text{CaO}^*+\text{Na}_2\text{O}$ - K_2O ternary plot and its corresponding chemical index of alteration values of coal samples for weathering intensity (after Nesbitt and Young 1982).

6.7.5 Evolution of coals of Sohagpur coalfield

Paleo-depositional conditions play a fundamental role in controlling coal behaviour throughout its various stages of utilization. The development of coal-forming peat swamps was influenced by several interrelated factors, including floral evolution, paleoclimate, paleogeographic setting, and regional tectonics. Coal facies, which represent the primary genetic types of coal, are governed by parameters such as depositional style, peat-forming plant communities, hydrological conditions, pH,

microbial activity, sulphur availability, peat temperature, and redox potential (Stach et al., 1982). Petrographic constituents, particularly coal macerals, provide valuable paleoenvironmental information both through their presence or absence and their relative abundance. For instance, the occurrence of telalginite reflects aquatic depositional conditions as it originates from planktonic algae (Diessel, 1982). However, a high concentration of a specific maceral type strengthens such interpretations.

Rapid subsidence promotes the preservation of woody tissues, resulting in elevated telovitrinite content, whereas periodic influx of brackish water may raise pH levels and increase the proportion of detrovitrinite (Diessel, 1992). To enhance paleoenvironmental resolution, several researchers have employed maceral ratios and facies indices, either through cross-plots or triangular diagrams. Cohen (1973) utilized particle-to-matrix ratios to characterize peat types, while Diessel (1986) introduced the gelification index (GI) and tissue preservation index (TPI) based on maceral gelification and fragmentation. Microlithotype analysis has also been widely applied for paleoenvironmental reconstruction (Smyth, 1979; Singh et al., 2013c).

Advancements in organic petrology and the development of petrography-based depositional models have significantly improved interpretations of peat-forming environments (Hacquebard and Donaldson, 1969; Diessel, 1986; Calder et al., 1991; Singh et al., 2013c). Nevertheless, robust interpretations require integration with geochemical, palynological, and sedimentological data (Bechtel et al., 2003; Radhwani et al., 2018).

In this study, petrographic data were evaluated using established depositional models. A combined petrographic and geochemical approach was applied to provide insights into

source vegetation, depositional conditions, and overall coal characteristics, thereby supporting improved utilization and sustainable management of these resources.

6.7.6 Development of flora

The Gondwana coals are generally interpreted to have originated in forested peat swamps. Their dominance of vitrinite, accompanied by appreciable proportions of liptinite and inertinite macerals, suggests derivation from forest-type vegetation that flourished under warm, humid to tropical climatic conditions. Periodic fire events and flooding in peat swamps enhanced detrital influx, accounting for the presence of inertinite and mineral-rich horizons within the coal seams, respectively (Jasper et al., 2017). Such maceral assemblages are consistent with peat accumulation in low-lying forest swamps subjected to fluctuating water tables.

The *Glossopteris* flora is widely reported from most major Gondwana basins of India; however, plant fossil records from the Sohagpur Coalfield of the South Rewa Basin remain comparatively sparse. Available palaeobotanical evidence from the Barakar Formation in the Sohagpur Coalfield indicates a diverse floral assemblage comprising pteridophytes and gymnosperms. Pteridophytes are represented by equisetalean axes belonging to the order Equisetales, while gymnosperms include members of the orders *Glossopteridales* and *Cordaitales*. *Cordaitales* is represented by *Noeggerathiopsis hislopii*, whereas *Glossopteridales* dominates the assemblage with one species of *Gangamopteris* (*G. intermedia*) and several species of *Glossopteris*, including *G. communis*, *G. gigas*, *G. giridihensis*, *G. indica*, *G. longicaulis*, *G. spatulata*, and *Glossopteris* sp. The abundance of large *Glossopteris* leaves, particularly *G. communis*, *G. gigas*, *G. indica*, and *G. spatulata*, points to favourable warm, temperate, and humid climatic conditions during peat accumulation and coal formation (Agnihotri et al., 2016)

The occurrence of megaspores in the Barakar Formation of the Dhanpuri Opencast Mine provides additional palaeoecological insights. These megaspores indicate the presence of lycopsids, which are otherwise absent in the megafloral record. The diversity of exosporial ornamentation, including laevigate, granulate, verrucate, baculate, and spinate forms, suggests a wide range of lycopsid source plants. The widespread distribution of megaspores such as *Bokarosporites rotundus*, *Banksisporites utkalensis*, and *Talchirella trivedii* across different Lower Gondwana basins of India further indicates the presence of common ancestral lycopsid. Additionally, the rare occurrence of spinate megaspores such as *Biharisporites* indicates intermittent aquatic or waterlogged conditions during peat deposition (Agnihotri et al., 2018).

Overall, the presence of diverse megafossils, including pteridophytes and gymnosperms, supported by macro-charcoal evidence (Jasper et al., 2017) and palynological data, reflects the development of a luxuriant and heterogeneous vegetation cover during deposition of the Barakar Formation in the Sohagpur Coalfield. This dense vegetation, combined with favourable climatic and hydrological conditions, facilitated high organic productivity and preservation, ultimately leading to the formation of thick and laterally persistent coal seams in the region.

6.7.7 Coal facies and paleo mire characteristics

Organic entities preserved in coal, referred to as macerals, are among the most reliable tools for deciphering peat-forming environments and reconstructing paleo-mire characteristics. Since macerals retain textural and chemical signatures of the parent plant material, their distribution and relative abundance provide insights into vegetation types, hydrological regimes, and prevailing climatic conditions during peat accumulation.

Among the three maceral groups, vitrinite is typically dominant in most Gondwana coals and is considered to represent peat formed under wet forest swamp conditions. This is particularly evident from the presence of telovitrinite, which is derived from woody tissues of higher plants that flourished in forested swamps. In contrast, detrovitrinite originates from finely comminuted plant tissues deposited under reed-marsh or herbaceous swamp settings (Taylor et al., 1998). The predominance of vitrinite thus reflects environments with abundant vegetation, high groundwater levels, and sustained peat accumulation.

The liptinite group of macerals provides additional paleoenvironmental clues. For example, sporinite, derived from spores and pollen, often indicates subaqueous or periodically flooded conditions, reflecting proximity to standing water bodies. Conversely, cutinite and resinite, which originate from cuticles and plant exudates, are commonly associated with swamp forests rich in resinous and wax-bearing vegetation (Taylor et al., 1998; Teichmüller, 1989). The presence of these liptinite macerals therefore implies significant botanical diversity in peat-forming environments, coupled with fluctuating hydrological regimes.

In contrast, the inertinite macerals form predominantly through the oxidation, charring, or incomplete combustion of organic matter during peat accumulation. The dominance of fusinite and semifusinite within coal has long been interpreted as evidence of dry or fire-prone paleo-mires (Teichmüller, 1989). Such assemblages reflect seasonal fluctuation in the water table, periodic exposure of peat surfaces, and enhanced oxidation of plant material. In many Gondwana coals, inertinite-rich facies are associated with climatic variability, including the alternation of wet and dry phases.

To systematically quantify these paleoenvironmental signatures, Diessel (1986) introduced two important petrographic parameters: the Tissue Preservation Index (TPI) and the Gelification Index (GI). Both indices are derived from maceral ratios obtained through petrographic analysis and serve as robust indicators of mire conditions. The TPI is designed to measure the degree of tissue preservation in coals, thereby distinguishing between woody, structured peat (forest swamps) and herbaceous, degraded peat (marshes and reeds). High TPI values indicate well-preserved woody tissues and forest swamp conditions, while low TPI values suggest greater degradation and deposition in reed or herbaceous swamps.

The GI, on the other hand, reflects the balance between gelified macerals (vitrinite group) and inert macerals (inertinite group). High GI values indicate peat accumulation under permanently waterlogged, reducing conditions with limited oxidation, favouring the formation of vitrinite-rich coal. Conversely, low GI values imply peat accumulation under oxidizing conditions with greater inertinite enrichment, suggesting drier mire environments or frequent wildfire activity. The formulas of these indices are presented below and are applied in the present study to characterize the paleomire conditions of Permian Gondwana coals:

$$\text{TPI} = (\text{Telinite} + \text{Collotelinite} + \text{Semifusinite} + \text{Fusinite}) / (\text{Collodetrinite} + \text{Macrinite} + \text{Inertodetrinite})$$

$$\text{GI} = (\text{Vitrinite} + \text{Macrinite}) / (\text{Semifusinite} + \text{Fusinite} + \text{Inertodetrinite})$$

The combined interpretation of TPI and GI values provides a robust framework for reconstructing paleo mire conditions. According to Lamberson et al. (1991), the occurrence of high TPI and GI values together suggests poor aerobic breakdown and effective tissue preservation, indicating deposition under permanently water-saturated conditions. Well-preserved plant tissues are generally characterized by TPI values

between 1 and 7, whereas lower TPI values typically imply significant input from oxidized vegetative matter or extensive tissue degradation (Dai et al., 2020). Therefore, variation in these indices can be directly linked to the relative dominance of forest swamp versus herbaceous swamp settings, as well as to climatic fluctuations that controlled peat hydrology.

For the Sohagpur coals, the calculated TPI and GI values indicate a spectrum of depositional settings ranging from dry forest to wet forest swamps. The lower TPI values in some intervals reflect either herbaceous plant input or enhanced humification under drier conditions. In comparison, the higher TPI values correspond to better tissue preservation and stronger woody contributions. Similarly, variation in GI values indicated alternating phases of oxidation and gelification, reflecting fluctuations in water table stability and mire hydrology. Taken together, the combined use of TPI and GI demonstrates that the Sohagpur coals formed under dynamic paleoenvironmental conditions, influenced by both vegetation type and climatic regime, and record a transition between relatively dry forest swamp settings to more persistently wet forest swamp environments.

In addition to the Tissue Preservation Index (TPI) and Gelification Index (GI), another widely applied facies model for interpreting paleo mire conditions is that proposed by Calder et al. (1991). This model employs two petrographic parameters, the Groundwater Index (GWI) and the Vegetation Index (VI), which together provide insights into groundwater influence, relative rainfall, groundwater level fluctuations within the mire, vegetation type, mineral matter incorporation, and the preservation state of maceral precursors (Calder et al., 1991; Kalkreuth et al., 1991; Ligouis and Doubinger, 1991). The following formula is used to determine the GWI and VI:

$$\text{GWI} = (\text{Gelinite} + \text{Corpogelinite} + \text{Vitrodetrinite} + \text{Mineral matter}) / (\text{Telinite} + \text{Collotelinite} + \text{Collodetrinite})$$

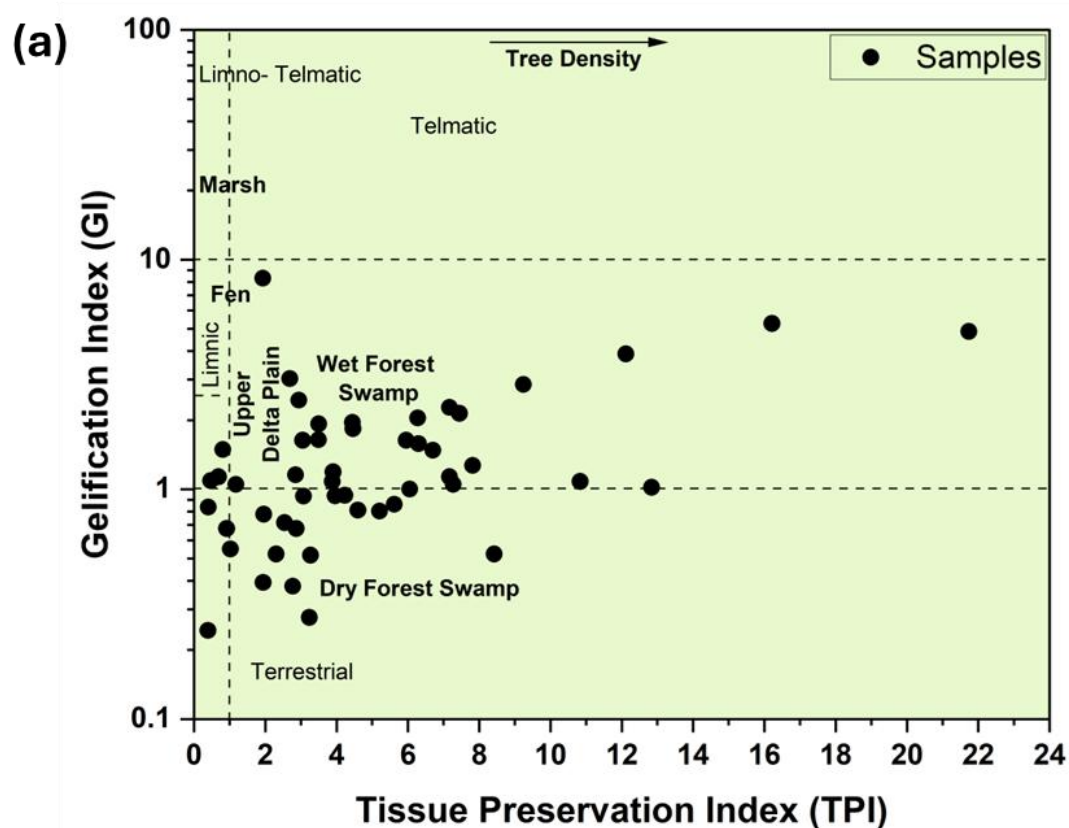
$$\text{VI} = (\text{Telinite} + \text{Collotelinite} + \text{Semifusinite} + \text{Fusinite} + \text{Resinite}) / (\text{Collotelinite} + \text{Sporinite} + \text{Cutinite} + \text{Liptodetrinite} + \text{Intertodetrinite})$$

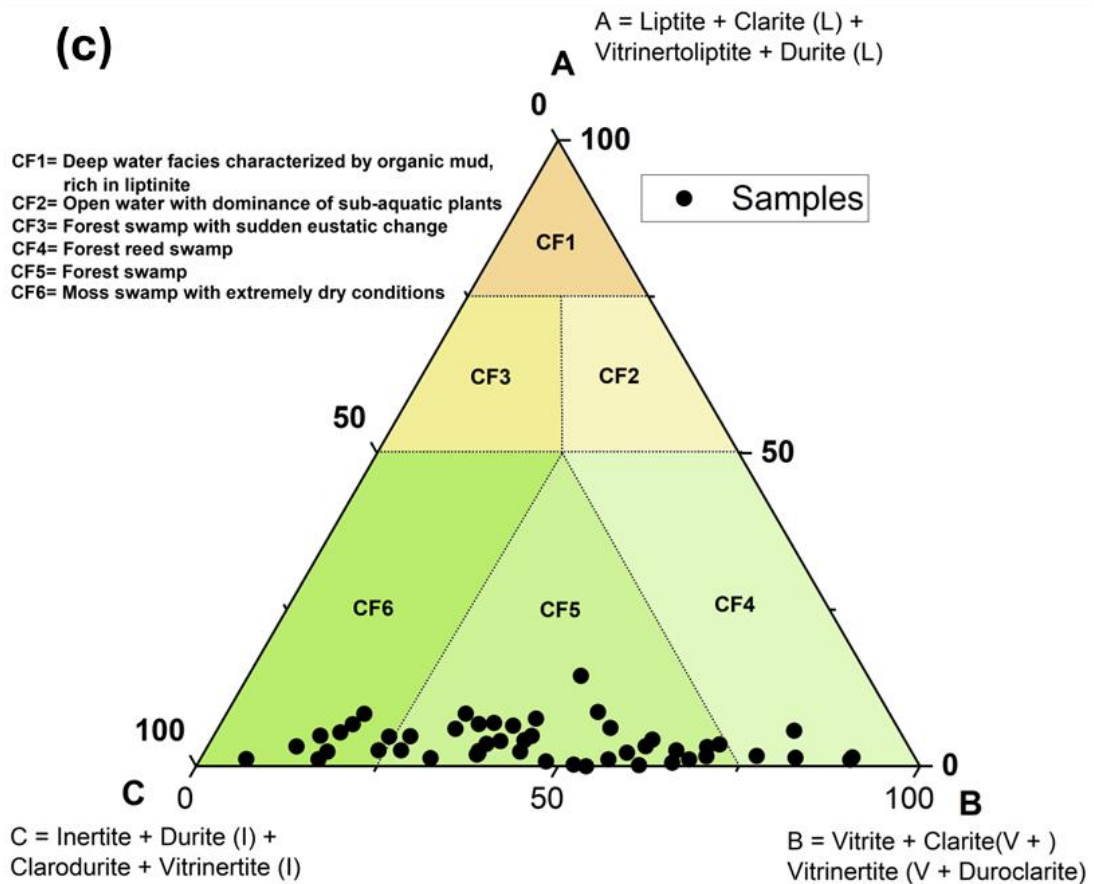
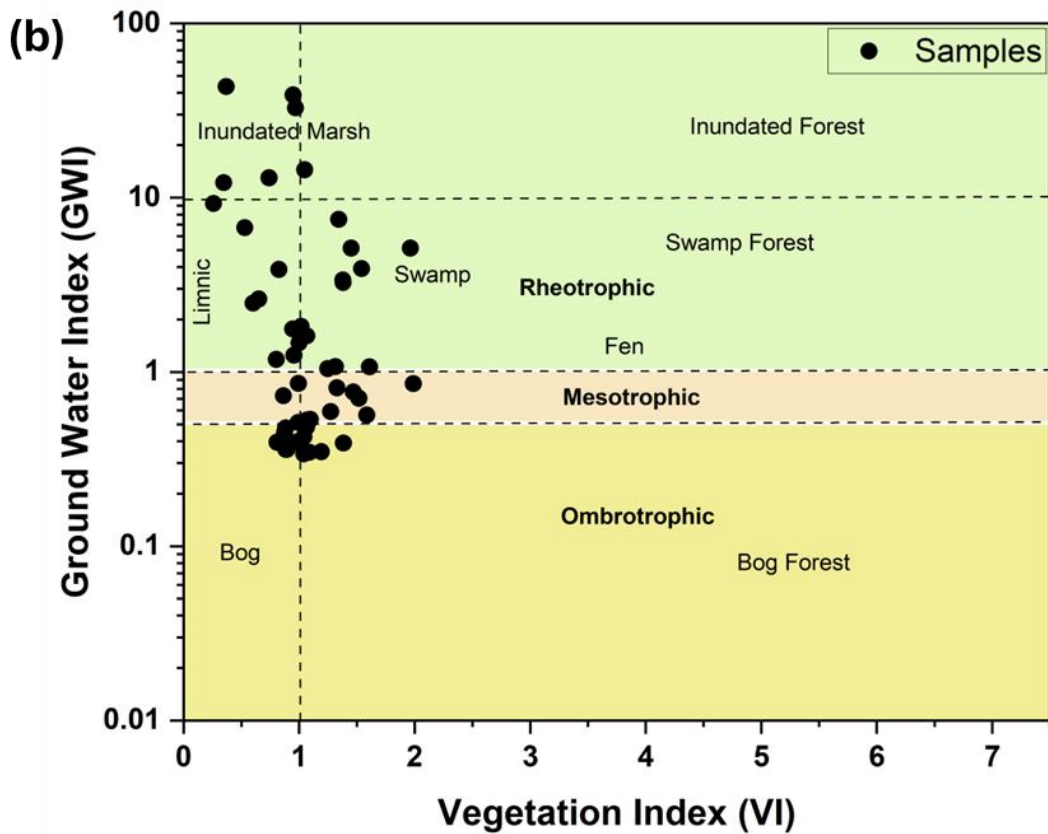
The Vegetation Index (VI) is primarily a measure of the botanical composition of the peat-forming vegetation. VI values less than 1 signify a greater contribution from herbaceous and/or aquatic plants, indicating reed-marsh or herbaceous swamp settings. In contrast, VI values greater than 1 reflect peat accumulation dominated by woody vegetation such as forest swamps. This distinction is significant because it directly links the maceral composition to vegetation type, enabling the reconstruction of mire floras and their environmental preferences.

The Groundwater Index (GWI) reflects the hydrological regime and the degree of groundwater influence on peat accumulation. A GWI value below 0.5 is characteristic of ombrotrophic mires, which are rain-fed, nutrient-poor, and acidic, with minimal groundwater input. These settings are dominated by precipitation as the primary water and nutrient source, leading to relatively low mineral input and the accumulation of acidic peat. A GWI value greater than 1 represents rheotrophic conditions, in which peat is fed by surface or groundwater that is comparatively rich in dissolved minerals. Such environments favour greater nutrient availability, incorporation of mineral matter, and greater preservation of gelified macerals. Intermediate values, between 0.5 and 1, indicate mesotrophic conditions, representing transitional environments with moderate nutrient levels, influenced by precipitation and limited groundwater input. These mesotrophic mires reflect fluctuating water tables and alternating phases of ombrotrophic and rheotrophic conditions.

Application of these indices to the Sohagpur coals provides important paleoenvironmental insights. The calculated VI values suggest a significant input from

woody vegetation, consistent with the dominance of forest swamp conditions in the paleomire. At the same time, fluctuations in GWI values indicate periodic variations in the water table, alternating between wetter phases with stronger groundwater influence and drier intervals characterized by more ombrotrophic conditions. The results imply that the Sohagpur mire was neither permanently waterlogged nor consistently rain-fed but rather experienced dynamic hydrological fluctuations, with alternating contributions from rainfall and groundwater recharge.





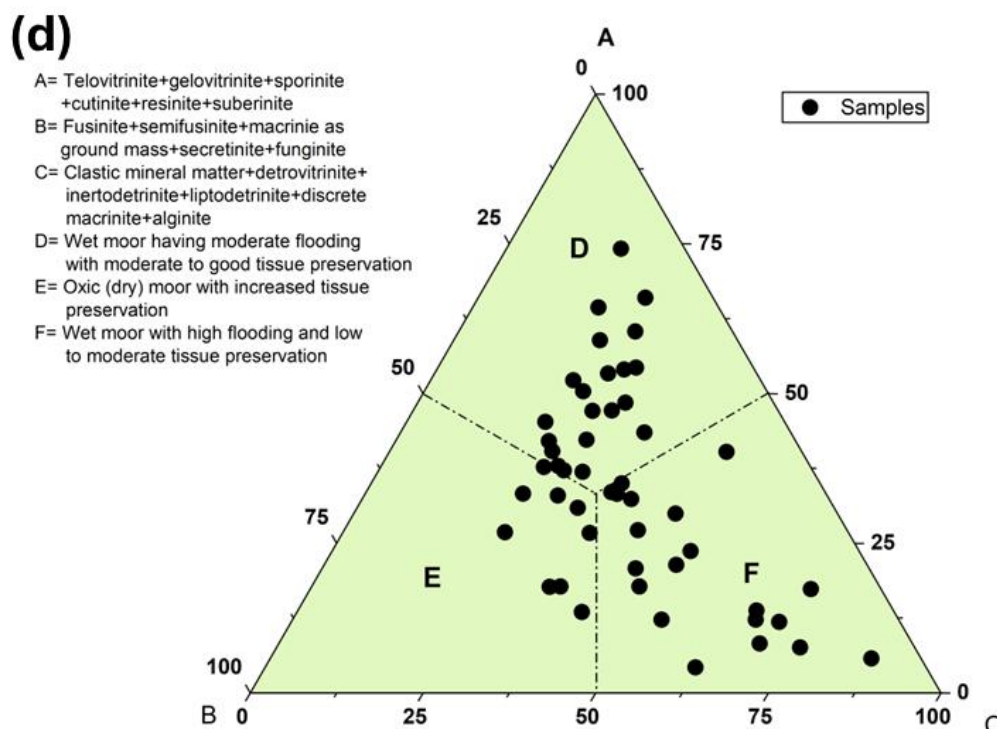


Figure 6.37 Paleo mire conditions (a, b) (after Deissel, 1986, and modified by Kalkreuth et al., 1991) and (modified after Calder et al., 1991) on maceral basis and (c) on microlithotype basis (after Singh et al., 2013c) and d (after Singh et al., 2012).

Another important facies model applied to characterize the paleomire conditions of the studied coals is that proposed by Singh et al. (2013c). Unlike indices such as TPI, GI, GWI, and VI, which are derived from maceral group proportions, this model is based on the microlithotype composition of coal. Microlithotypes, being intimate petrographic associations of different macerals, provide a more integrated picture of peat-forming processes by capturing not only the botanical input but also the sedimentological and geochemical conditions under which peat accumulated.

In this model, three parameters, A, B, and C, are calculated from specific microlithotypes present in coal:

A = Liptite + Clarite (L) + Vitrinertoliptite + Durite (L)

B = Vitrite + Clarite (V) + Vitrinertite (V) + Duroclarite

C = Inertite + Durite (I) + Clarodurite + Vitrinertite (I)

Here, parameter A essentially reflects the contribution of liptinite-rich microlithotypes, which are associated with hydrogen-rich components such as spores, resins, and waxy tissues and are typically linked to herbaceous and resinous vegetation as well as its periodically waterlogged settings. Parameter B represents the vitrinite-dominated microlithotypes, which signify woody input from forest vegetation, preservation under humid conditions, and peat accumulation in relatively wet forest swamps. Parameter C captures the contribution of inertinite-rich microlithotypes, indicative of oxidized organic matter, wildfire activity, or intermittent drying of the peat surface. By plotting these three parameters on a ternary diagram, Singh et al. (2013c) demonstrated that coal facies can be effectively classified into distinct paleo-mire settings ranging from moss swamps and forest reed swamps to forest swamps. The ternary system thus integrates maceral associations into a broader framework that directly reflects mire hydrology, vegetation type, and oxidation-reduction conditions. Table 6.7 presents the values of VI, GWI, TPI, GI, and ABC for the ternary plot.

Table 6.7 VI, GWI, TPI, GI, and A, B, C (normalised to 100%) values for paleo mire characteristics.

Mine/Seam name	Band No.	VI	GWI	TPI	GI	A	B	C
Sharda	1	1.10	0.53	6.30	1.58	2.17	58.42	39.40
Sharda	2	1.38	3.25	2.87	0.68	1.30	31.74	66.96
Sharda	3	1.09	0.35	6.70	1.48	2.53	65.06	32.41
Sharda	4	0.99	0.86	6.28	2.05	6.13	54.17	39.71
Sharda	5	0.90	0.39	4.46	1.84	3.18	60.51	36.31
Sharda	6	0.81	0.40	3.05	1.63	4.27	60.88	34.85
Sharda	7	0.88	0.36	9.24	2.86	5.67	79.77	14.56
Sharda	8	1.47	0.77	5.62	0.86	2.33	43.60	54.07
Dhanpuri	1	1.45	5.13	3.24	0.28	4.90	14.70	80.40
Dhanpuri	2	1.38	0.39	7.82	1.27	0.17	61.09	38.74
Dhanpuri	3	1.61	1.07	7.27	1.05	0.00	53.88	46.12
Dhanpuri	4	0.80	1.18	2.69	3.03	1.60	69.68	28.72
Dhanpuri	5	0.26	9.25	0.41	0.84	7.61	43.15	49.24
Rajendra	1	1.02	1.82	3.88	1.08	8.41	33.04	58.55
Rajendra	2	0.83	3.88	3.49	1.65	14.44	45.93	39.63

Mine/Seam name	Band No.	VI	GWl	TPI	GI	A	B	C
Rajendra	3	0.88	0.48	16.21	5.28	1.43	89.96	8.61
Rajendra	4	1.25	1.04	6.05	1.00	4.19	43.26	52.56
Rajendra	5	1.52	0.71	10.83	1.08	0.27	52.01	47.72
Khairaha VI	1	1.04	0.42	12.12	3.88	1.67	76.59	21.74
Khairaha VI	2	1.04	0.34	7.45	2.14	3.08	69.06	27.86
Khairaha VI	3	0.88	0.45	21.74	4.86	1.04	89.83	9.13
Khairaha VI	4	1.27	0.59	4.60	0.81	3.57	38.33	58.10
Khairaha VI	5	1.99	0.86	8.42	0.52	2.44	37.80	59.76
Khairaha VII	1	1.19	0.35	4.23	0.94	0.76	47.95	51.29
Khairaha VII	2	0.96	1.25	1.94	0.39	4.73	24.30	70.97
Khairaha VII	3	1.00	1.47	2.85	1.16	1.88	37.90	60.22
Khairaha VII	4	1.33	0.81	7.17	1.14	8.69	51.17	40.14
Khairaha VII	5	1.06	0.48	3.90	1.19	1.10	56.41	42.49
Damini VI 1st site	1	1.38	3.36	3.96	0.94	2.54	23.94	73.52
Damini VI 1st site	2	0.97	32.76	1.93	8.30	5.97	32.84	61.19
Damini VI 1st site	3	0.53	6.74	0.69	1.13	2.55	27.04	70.41
Damini VI 2nd Site	1	0.60	2.48	0.92	0.68	8.38	19.04	72.59
Damini VI 2nd Site	2	1.05	14.44	2.94	2.45	6.92	37.69	55.38
Damini VI 2nd Site	3	0.37	43.43	0.47	1.09	6.71	18.29	75.00
Damini V	1	0.35	12.19	0.40	0.24	4.80	27.20	68.00
Damini V	2	0.94	1.76	3.07	0.93	6.48	40.56	52.96
Damini V	3	0.99	0.51	4.45	1.96	0.55	65.50	33.95
Damini V	4	0.65	2.62	1.17	1.05	1.87	37.83	60.30
Bangwar	1	1.31	1.07	12.84	1.02	6.74	35.67	57.58
Bangwar	2	1.07	1.61	2.54	0.72	4.85	43.93	51.21
Bangwar	3	0.89	0.36	3.50	1.93	1.38	82.11	16.51
Bangwar	4	1.59	0.57	5.21	0.80	2.11	37.94	59.95
Amalai	1	1.07	0.53	7.17	2.27	1.08	67.57	31.35
Amalai	2	0.95	38.86	1.02	0.55	1.15	6.34	92.51
Amalai	3	0.86	0.73	1.96	0.78	4.04	40.00	55.96
Amalai	4	0.74	13.00	0.81	1.49	1.13	16.34	82.54
Amalai	5	1.96	5.13	3.27	0.52	5.41	17.23	77.36
Amalai	6	1.54	3.92	2.77	0.38	3.18	12.27	84.55
Amalai	7	1.34	7.52	2.31	0.52	2.34	16.96	80.70
Amalai	8	0.98	0.40	5.95	1.63	3.50	70.55	25.95

An additional model proposed by Singh et al. (2012), which considers maceral composition parameters, primarily focuses on flooding spells that occurred during peat formation, and conditions for tissue preservation are presented in Figure 6.37 (d).

Application of these models to the Sohagpur coal samples shows that the data points are not clustered within a single paleoenvironmental field but instead fall across a range of facies types. Most of the sample plots fall within the zone corresponding to moss swamps with extremely dry conditions to forest swamp environments, suggesting that peat accumulation alternated between phases of dry, oxidized mire conditions and wetter, forest-dominated swamp settings. This interpretation is consistent with inertinite-rich intervals reflecting periodic drying, oxidation, and wildfire influence, as well as vitrinite-dominated intervals representing wetter conditions with enhanced woody input. A smaller subset of samples plots within the forest reed swamp field, indicating localized contributions from herbaceous vegetation and suggesting that certain intervals of the mire were dominated by reed-marsh or herbaceous swamp environments. These variations highlight the spatial and temporal heterogeneity of mire conditions in the Sohagpur Basin, controlled by fluctuations in climate, groundwater levels, and vegetation patterns.

The ternary distribution of microlithotype-derived parameters (A, B, and C) confirms that the paleo mire was highly dynamic, recording alternating phases of extremely dry moss swamp, forest swamp, and forest reed swamp conditions. When integrated with maceral-based indices such as TPI, GI, GWI, and VI, this model strengthens the reconstruction of a complex mire system influenced by both hydrological variability and vegetation diversity (Figure 6.37).

The correlation between the Tissue Preservation Index (TPI) and the Gelification Index (GI) provides critical insights into peat-forming conditions, depositional environments, coal quality, and the overall evolutionary history of a coal basin. TPI primarily reflects the degree of preservation of original plant tissues and is strongly influenced by vegetation type, rate of burial, and extent of oxidation, whereas GI represents the degree

of gelification of organic matter, largely controlled by water saturation, redox conditions, and microbial activity during peat accumulation (Diessel, 1986; Calder et al., 1991).

Seam-wise correlation of GI and TPI helps to differentiate stable forest swamps from more dynamic or stressed depositional settings. A positive correlation between GI and TPI indicates peat accumulation under persistently waterlogged conditions in forested swamps, where limited oxygen availability suppresses oxidation and enhances gelification, while rapid burial favours preservation of structured plant tissues. Such conditions are typical of groundwater-fed, low-energy peat swamps and are conducive to the formation of thick, laterally continuous coal seams with relatively high-quality coal. In the present dataset, most seams across the coalfield exhibit this positive GI–TPI relationship (Figure 6.38), suggesting stable hydrological conditions, minimal sediment influx, and efficient preservation of organic matter during peat formation.

In contrast, low or weak correlations between GI and TPI, as observed in the Dhanpuri, Damini VI, and Bangwar coal mines, reflect peat accumulation in more unstable and oxidizing swamp environments. These settings are commonly characterized by fluctuating water tables, periodic exposure of peat to oxygen, enhanced microbial degradation, and episodic clastic sediment input. Such conditions promote higher degrees of tissue breakdown, reduced gelification, and dilution of organic matter by mineral matter, ultimately resulting in thinner, less continuous seams and comparatively inferior coal quality. These peat swamps are more consistent with rain-fed systems or marginal swamp environments influenced by external sediment supply and hydrological instability.

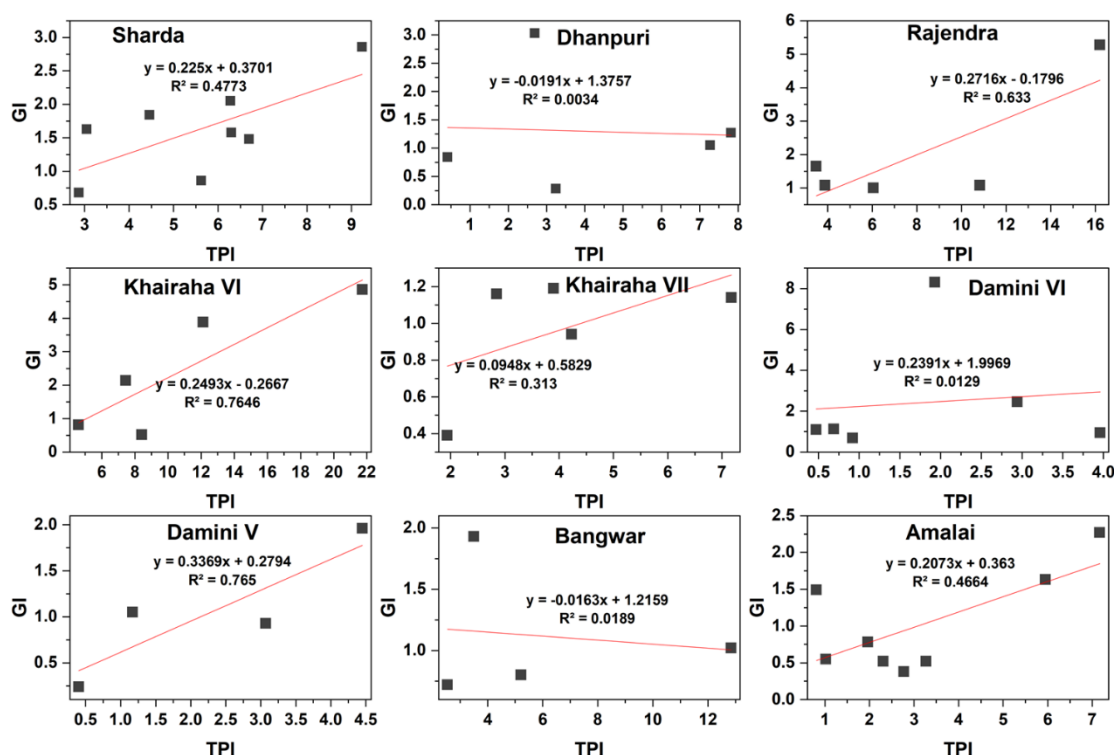


Figure 6.38 Correlation between tissue preservation index (TPI) and gelification index (GI) for different mines and seams of the Sohagpur coalfield.

The relationship between the Groundwater Index (GWI) and the Vegetation Index (VI) for different coal seams of the Sohagpur Coalfield provides a quantitative framework for interpreting peat-forming hydrological conditions, dominant vegetation types, and their combined influence on coal characteristics and seam development. GWI reflects the degree of groundwater influence and stability of the water table during peat accumulation, whereas VI represents the relative contribution of woody versus herbaceous vegetation to the peat (Calder et al., 1991; Diessel, 1992). When evaluated together, these indices effectively integrate two fundamental controls on coal genesis, which are hydrology and botanical input.

A positive correlation between GWI and VI indicates peat accumulation in forested swamps under persistently high and stable water-table conditions. Such environments favour enhanced preservation of woody plant tissues, reduced oxidation, and extensive gelification, resulting in higher vitrinite contents and comparatively better coal quality.

In the present study, this positive GWI–VI relationship is clearly observed in the Sharda and Khairaha Seam VI, as shown in Figure 6.39, suggesting that groundwater-fed forest swamps promoted the development of thicker, laterally more continuous coal seams with favourable petrographic characteristics. Conversely, a weak or low correlation between GWI and VI, as observed in the Dhanpuri, Rajendra, Khairaha Seam VII, Damini Seam VI, Damini Seam V, Bangwar, and Amalai seams, reflects peat formation under relatively drier or fluctuating water-table conditions. These environments are typically characterized by a greater herbaceous vegetation, enhanced exposure of peat to oxygen, increased oxidation, and higher degrees of organic matter degradation. Such conditions result in reduced vitrinite preservation, poorer coal quality, and increased heterogeneity within the seams.

The GWI–VI relationship has important implications for coal utilization and resource evaluation. Seams formed under stable, groundwater-dominated forest swamps are generally characterized by better washability, higher organic purity, and improved coalbed methane (CBM) potential due to favourable maceral composition and pore development. In contrast, seams developed under fluctuating or water-stressed conditions tend to exhibit inferior coal quality, higher mineral matter content, and comparatively lower CBM potential. Thus, the combined interpretation of GWI and VI serves as a valuable tool for understanding peat-forming environments and predicting variations in coal quality and gas potential across the Sohagpur Coalfield.

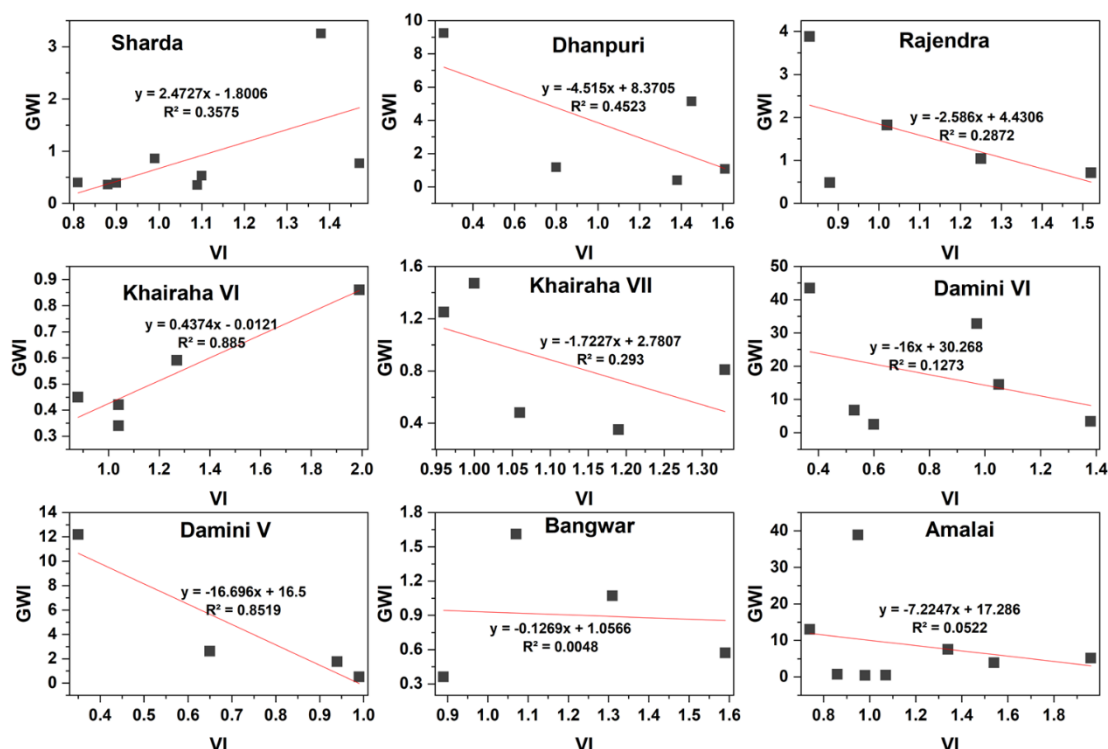


Figure 6.39 Correlation between the Groundwater Index (GWI) and the Vegetation Index (VI) for different mines and seams of the Sohagpur coalfield.

6.7.8 Paleo redox conditions

The reconstruction of paleo-redox conditions is fundamental to understanding the oxygen availability in coal-forming depositional environments. Redox conditions not only influence the preservation of organic matter but also control the type of vegetation contributing to peat accumulation, the extent of microbial degradation, and the incorporation of trace elements into coal. Both inorganic geochemical proxies and organic petrographic parameters are widely used to evaluate redox conditions, and together they provide complementary insights into the depositional environment of coal seams.

One of the most widely applied inorganic approaches is the V versus Ni cross-plot, which effectively discriminates between oxic, dysoxic, and anoxic depositional regimes. Vanadium is preferentially enriched under reducing conditions due to its ability to substitute into porphyrin structures in organic matter, whereas nickel concentrations are

also influenced by organic matter source and depositional redox state. According to Galarraga et al. (2008), anoxic environments are indicated when Ni concentrations are below 90 ppm, and the V/Ni ratio is greater than 3. In contrast, V/Ni ratios between 1.9 and 3 suggest deposition under dysoxic to oxic conditions, typically reflecting organic matter input from diverse sources, including both continental and marine precursors. V/Ni ratios less than 1.9 are diagnostic of strongly oxic environments, generally linked to terrestrial organic matter dominance. V/Ni ratios exceeding 3 with Ni concentrations greater than 90 ppm indicate deposition in euxinic, strongly reducing marine carbonate environments. The Sohagpur coal samples, when plotted on the V–Ni cross-plot, fall within the oxic to oxic-dysoxic field, suggesting that coal deposition took place under fluctuating but predominantly oxygenated conditions. These results imply that redox conditions during peat accumulation were not permanently reducing but instead alternated between moderately oxygenated and weakly reducing environments, likely reflecting seasonal or longer-term fluctuations in water table and peat hydrology. Another cross plot has been plotted based on the values of total sulphur vs $V/(V+Ni)$ and this indicates that coals of most of the seams formed in weak anaerobic environment and relatively moderate $V/(V+Ni)$ ratio of these seams in combination with the total sulphur contents below 1% also suggests reducing (suboxic) conditions during deposition (Hakimi et al. 2017).

Complementary evidence on redox conditions is provided by maceral-based ternary plots, which provide organic petrographic insights into the depositional environments. Mukhopadhyay (1986) proposed a ternary plot based on maceral composition calculated on a mineral matter-free basis. When the Sohagpur coal data are plotted on this diagram, the samples cluster within the mildly oxic to anoxic field, suggesting that peat was deposited in forest swamp settings with variable but generally reducing conditions

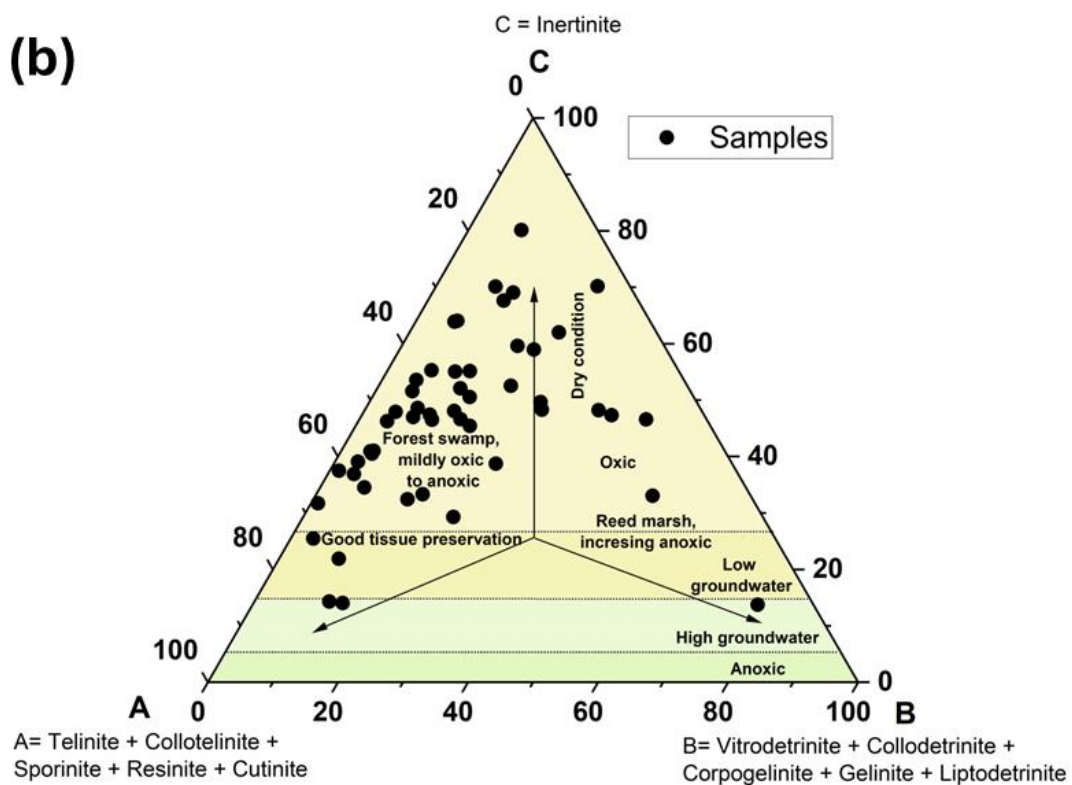
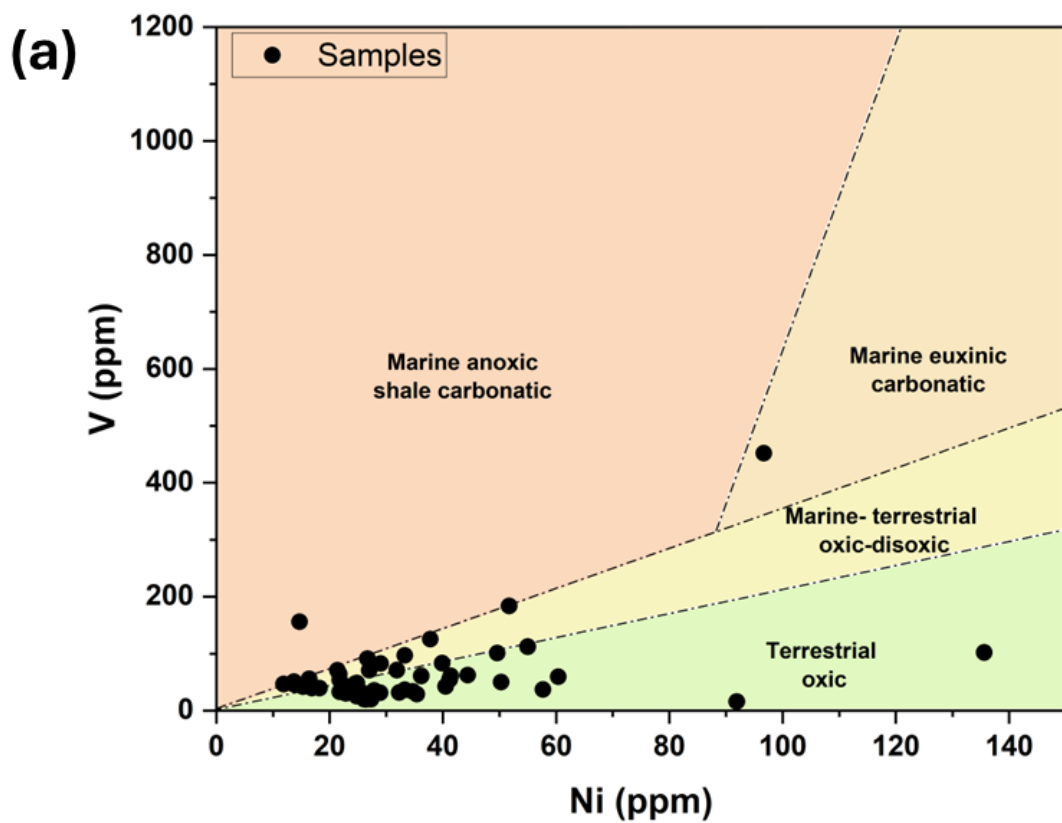
conducive to the preservation of vitrinite macerals. In addition, the ternary diagram of Singh and Singh (1996), originally developed for the Permian Rajmahal coals, has been applied to the Sohagpur dataset. This model incorporates maceral composition along with mineral matter data, providing a more nuanced picture of depositional redox states. The results indicate that the Sohagpur coals experienced alternating oxic to anoxic conditions, reflecting a fluctuating paleoenvironment in which mire hydrology, vegetation input, and oxidation processes varied over time. Importantly, inertinite-rich coal facies tend to plot within the oxic domain, indicating enhanced oxidation and fire activity, whereas vitrinite-rich samples cluster within the anoxic/wet field, reflecting waterlogged, reducing mire conditions (Singh and Singh, 1996). The paleo redox values derived from petrographic data are shown in Table 6.8.

Table 6.8 Cross plot values for paleo redox conditions based on petrography data.

Mine/Seam name	Band no.	A	B	C	Mineral matter	Vitrinite + Liptinite	Inertinite
Sharda	1	53.99	4.97	41.05	17.35	48.81	33.84
Sharda	2	20.38	20.64	58.98	20.94	32.98	46.07
Sharda	3	57.35	3.52	39.13	11.66	54.52	33.82
Sharda	4	50.30	16.37	33.33	15.30	57.50	27.20
Sharda	5	54.49	4.98	40.53	10.12	55.73	34.15
Sharda	6	59.08	4.00	36.91	12.08	57.26	30.66
Sharda	7	71.06	3.46	25.49	13.67	65.11	21.22
Sharda	8	35.13	12.77	52.10	9.22	44.05	46.73
Dhanpuri	1	20.70	9.17	70.13	16.77	25.08	58.15
Dhanpuri	2	49.29	4.44	46.27	13.21	46.92	39.88
Dhanpuri	3	34.47	14.97	50.57	16.46	42.93	40.61
Dhanpuri	4	47.60	23.09	29.31	23.21	55.22	21.57
Dhanpuri	5	24.48	27.20	48.32	27.47	37.82	34.71
Rajendra	1	36.98	17.57	45.45	13.53	49.65	36.82
Rajendra	2	36.34	24.91	38.75	9.46	60.39	30.15
Rajendra	3	72.25	13.68	14.07	13.06	75.16	11.78
Rajendra	4	44.93	8.05	47.02	17.95	45.16	36.89
Rajendra	5	43.43	7.96	48.61	16.60	43.81	39.59
Khairaha VI	1	68.93	9.17	21.90	14.94	66.73	18.33
Khairaha VI	2	67.21	1.05	31.74	15.67	57.92	26.41
Khairaha VI	3	74.16	11.51	14.34	12.48	75.27	12.25
Khairaha VI	4	41.14	5.26	53.60	11.41	43.07	45.53

Mine/Seam name	Band no.	A	B	C	Mineral matter	Vitrinite + Liptinite	Inertinite
Khairaha VI	5	30.12	5.94	63.94	14.35	31.81	53.84
Khairaha VII	1	42.76	5.64	51.59	6.73	47.11	46.16
Khairaha VII	2	29.61	6.31	64.08	11.07	33.21	55.72
Khairaha VII	3	37.83	15.54	46.63	20.13	44.34	35.53
Khairaha VII	4	42.26	11.18	46.55	15.49	45.72	38.79
Khairaha VII	5	47.15	4.90	47.95	12.23	47.14	40.63
Damini VI 1st site	1	24.02	26.30	49.68	16.74	42.62	40.64
Damini VI 1st site	2	8.57	77.65	13.78	34.54	56.56	8.90
Damini VI 1st site	3	15.79	35.96	48.25	19.14	42.23	38.63
Damini VI 2nd Site	1	22.57	17.81	59.62	9.15	38.54	52.31
Damini VI 2nd Site	2	15.09	51.85	33.07	22.13	52.96	24.91
Damini VI 2nd Site	3	14.24	38.41	47.35	18.75	42.78	38.47
Damini V	1	11.71	8.13	80.16	39.17	12.07	48.76
Damini V	2	38.07	13.83	48.10	17.96	44.36	37.67
Damini V	3	54.52	4.52	40.95	16.72	49.95	33.33
Damini V	4	27.14	20.30	52.57	14.50	44.74	40.76
Bangwar	1	42.17	10.41	47.42	15.92	45.41	38.67
Bangwar	2	32.15	12.70	55.15	20.63	37.47	41.90
Bangwar	3	61.08	1.40	37.51	14.69	54.27	31.04
Bangwar	4	34.43	10.49	55.08	8.82	42.53	48.65
Amalai	1	53.07	14.47	32.46	9.36	62.67	27.98
Amalai	2	4.97	24.83	70.20	21.64	26.53	51.83
Amalai	2	37.97	6.72	55.31	12.92	39.39	47.69
Amalai	4	9.32	44.07	46.61	15.33	46.77	37.90
Amalai	5	18.52	12.40	69.08	28.06	23.79	48.15
Amalai	6	20.68	11.66	67.65	15.41	28.24	56.35
Amalai	7	15.01	22.95	62.04	22.16	30.49	47.35
Amalai	8	58.67	6.78	34.55	11.43	58.60	29.98

Taken together, the integration of inorganic trace elements with organic petrographic models (Mukhopadhyay, 1986; Singh & Singh, 1996) demonstrates that the Sohagpur coals were deposited under dynamic redox conditions, fluctuating between oxic, dysoxic, and anoxic states (Figure 6.40).



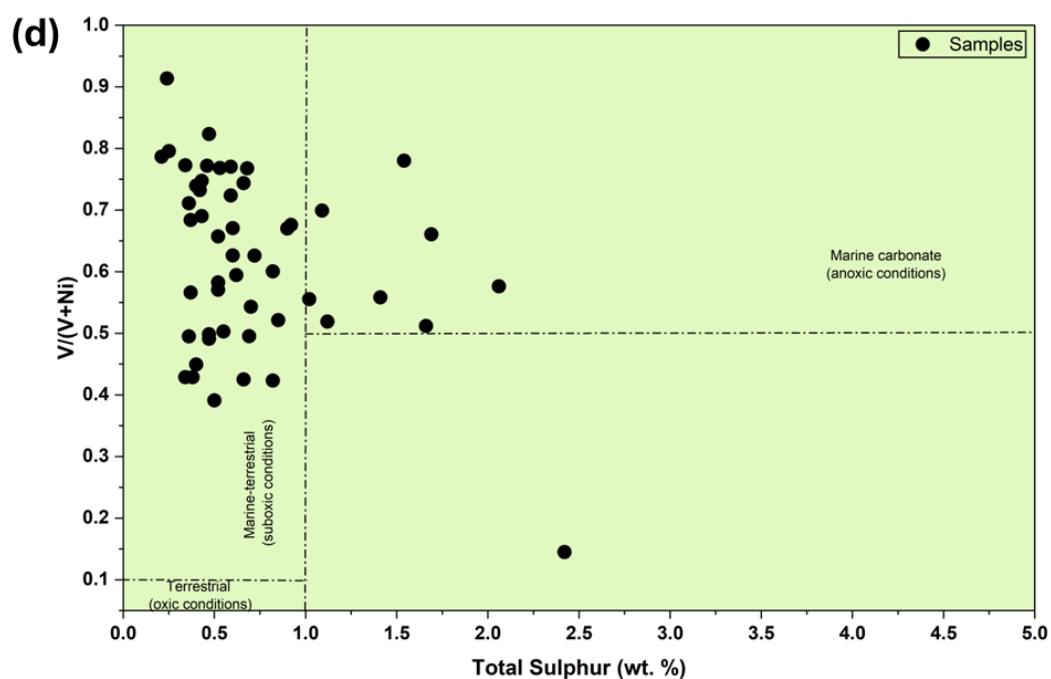
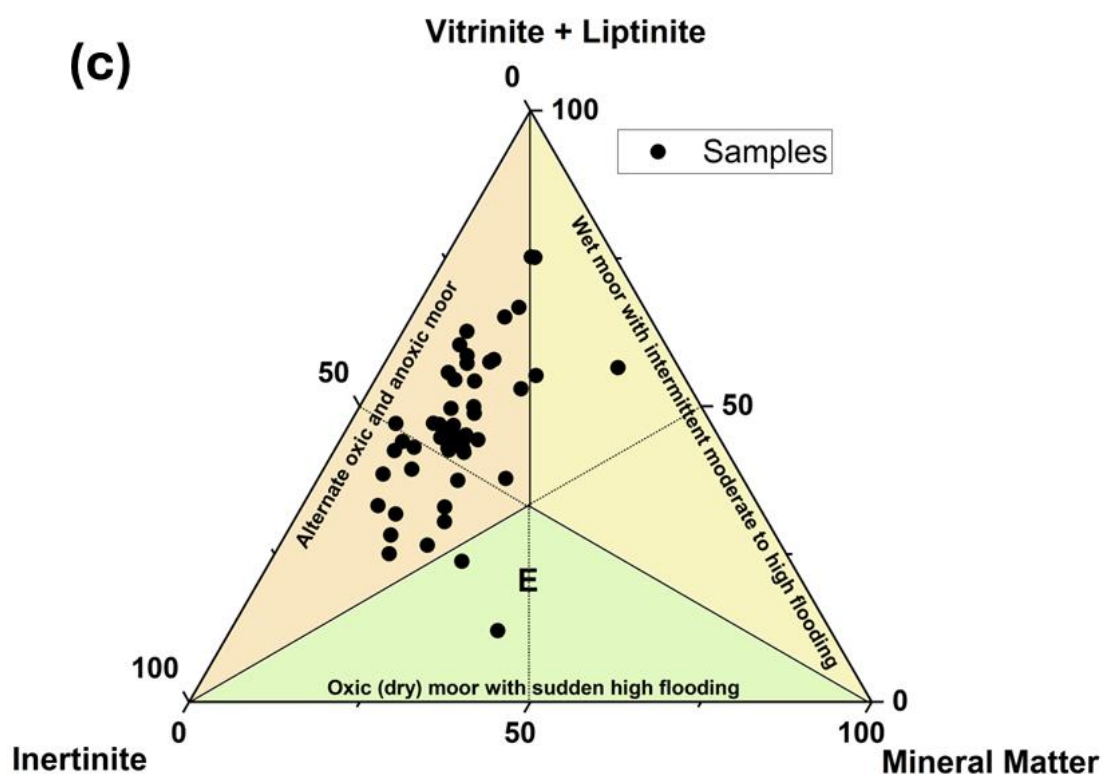


Figure 6.40 Paleo redox conditions of Sohagpur coals based on (a) trace elemental data (after Galrangaa et al., 2008), (b, c) on petrological data (after Mukhopadhyay, 1986 and Singh & Singh, 1996) and (d) Total sulphur vs V/V+Ni (after Hakimi et al., 2017)

6.7.9 Paleodepositional environment

The depositional environment of the Sohagpur coals has been assessed by integrating both organic petrographic proxies and inorganic geochemical indices, providing a robust reconstruction of the paleoenvironmental setting.

Inorganic geochemical ratios and cross-plots serve as powerful tools for discriminating between fluvial, deltaic, and marine depositional settings. For the Sohagpur coals, two significant cross-plots have been employed: V vs. Al_2O_3 and MgO vs. Al_2O_3 , along with a ternary diagram of $\text{MgO}\text{--}\text{Fe}_2\text{O}_3\text{--}\text{SiO}_2/\text{Al}_2\text{O}_3$. The geochemical trends observed in these diagrams consistently indicate a fluvio-deltaic depositional environment, reflecting alternating terrestrial and marginal marine influences during peat accumulation and subsequent sedimentation.

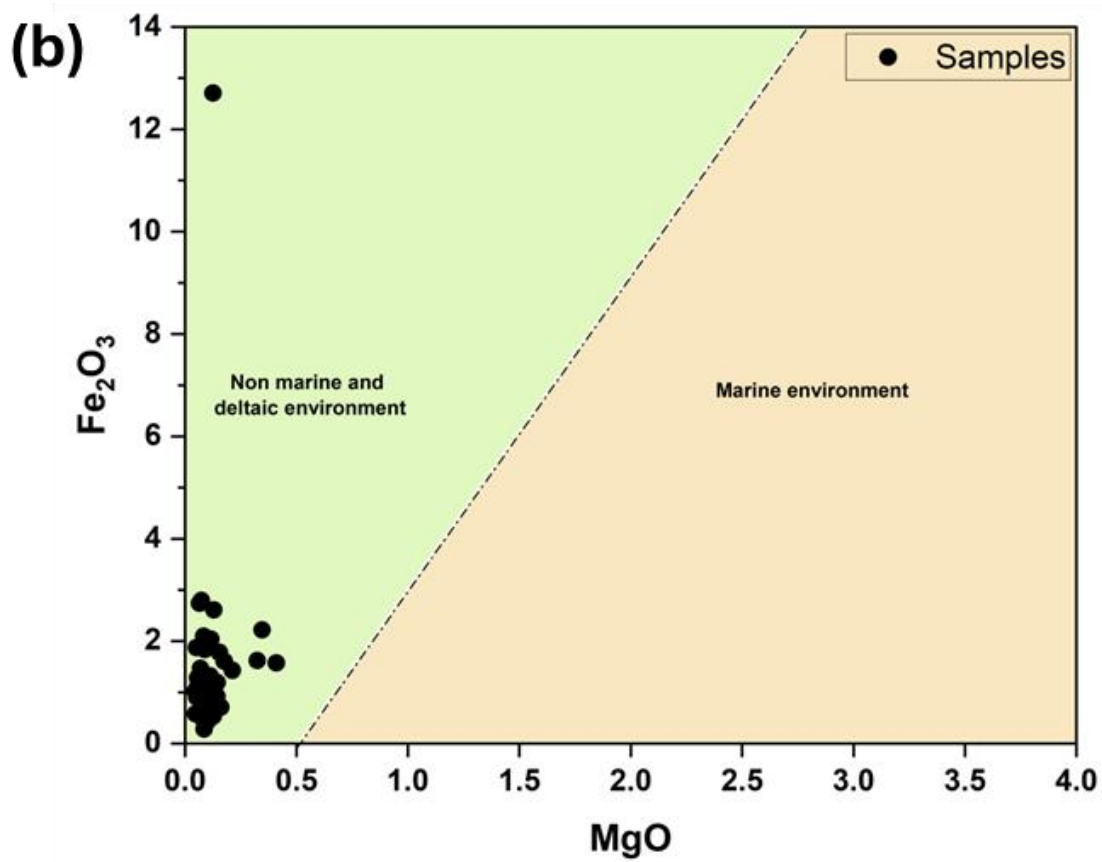
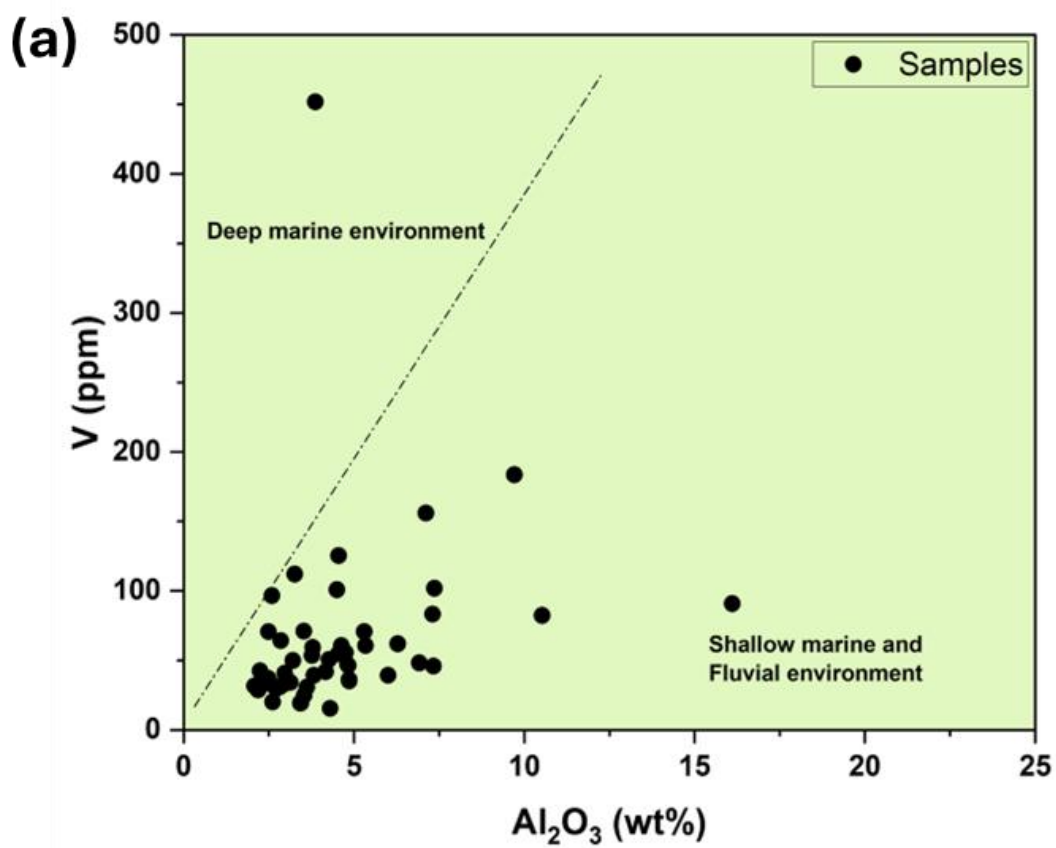
The geochemical behaviour of Vanadium (V) provides critical insights into depositional settings. Vanadium is typically enriched in sediments deposited under marine or reducing conditions, as it substitutes into clay minerals and organic complexes. In the V vs. Al_2O_3 cross-plot, samples with relatively high V concentrations correspond to marine-influenced facies, reflecting the vanadium incorporation under reducing, oxygen-poor conditions. Conversely, Al_2O_3 serves as a proxy for clay mineral abundance, often associated with fluvial or shallow-marine deposition where terrigenous input is dominant (Mortazavi et al., 2014). The distribution of data points between these two endmembers suggests that the Sohagpur coals formed in an environment with fluctuating marine and fluvial influences, consistent with a deltaic setting at the terrestrial–marine interface.

Magnesium also serves as a critical discriminator of depositional regimes. High MgO contents in sediments typically indicate marine depositional conditions, as magnesium is abundant in seawater and commonly incorporated into marine carbonates and dolomitic sediments during diagenesis. The MgO vs. Fe_2O_3 relationship observed in the Sohagpur

samples reveals that although some intervals reflect marine influence (elevated MgO), it supports the interpretation of a mixed fluvio-deltaic system.

The ternary diagram of $\text{MgO}-\text{Fe}_2\text{O}_3-\text{SiO}_2/\text{Al}_2\text{O}_3$ further refines this interpretation. Fe_2O_3 enrichment is often associated with non-marine to deltaic depositional environments, where terrestrial input, accelerated weathering, and oxidative conditions dominate. Such environments promote the influx of detrital iron oxides from the hinterland, in contrast to the magnesium-rich signature of marine sediments. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio also provides a valuable provenance and environmental signal. High ratios are typical of non-marine to deltaic settings, indicating a substantial influx of quartz grains from continental sources, most likely transported via fluvial processes (Ratcliffe et al., 2007). In contrast, lower ratios often suggest marine influence, where clay mineral input is dominant relative to quartz.

Taken together, the cross-plot and ternary diagram evidence highlights the dynamic depositional conditions of the Sohagpur coals. The coals accumulated in a transitional setting influenced by both marine incursions (as reflected in V and MgO enrichment) and continental input (as evidenced by elevated Fe_2O_3 and high $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios). Such geochemical signatures are consistent with fluvio-deltaic depositional environments (Figure 6.41).



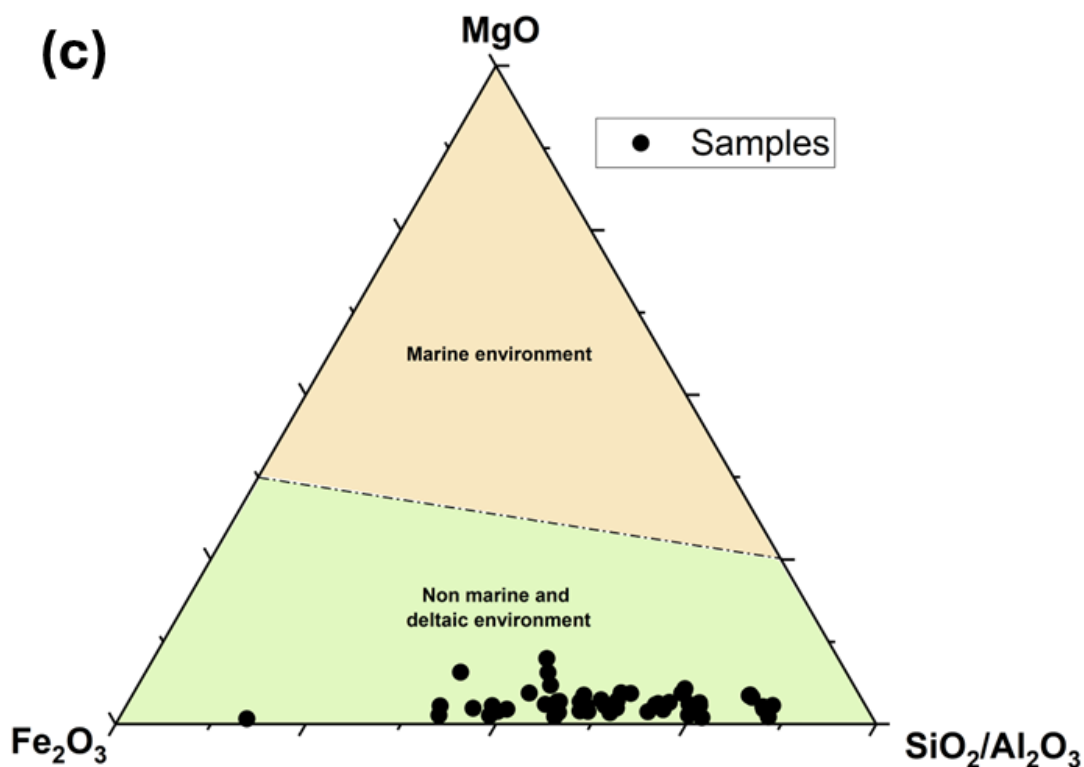


Figure 6.41 Depositional environment of Sohagpur coal based on XRF data (after Mortazavi et al., 2014).

Based on the organic petrographic constituents, particularly the microlithotype data, two ternary diagrams have been employed to reconstruct the depositional conditions of the Sohagpur coal samples. Microlithotypes, which represent aggregates of macerals grouped according to their optical and genetic affinities, are widely used to infer depositional settings because they integrate information about the vegetation source, oxidation processes, and sedimentary energy regime.

The first ternary model, proposed by Smyth (1979), is constructed using microlithotype values on carbominerite free basis. This model defines five distinct depositional fields, namely lake, river, brackish, upper deltaic, and lower deltaic environments, and has been effectively used in coal facies analysis worldwide. The underlying rationale of this model is that the relative proportions of vitrinite-rich, inertinite-rich, and intermediate microlithotypes capture the influence of hydrological regime, oxidation, and sediment influx during peat accumulation. According to Smyth's model, the Durite + Inertite

association indicates a low water table and extensive oxidation of organic matter in the peat swamp, reflecting the accumulation of dry peat (Diessel, 1992). In contrast, the dominance of Vitrite + Clarite indicate good tissue preservation, a high-water table, and limited oxidation, consistent with deposition under relatively reducing conditions. Intermediate microlithotypes, such as clarodurite or vitrinertite, suggest higher-energy depositional regimes that may include frequent flooding, wildfire activity, or significant reworking and transport of organic matter (Guatame and Rincón, 2021). The plotting of Sohagpur coal data on Smyth's ternary diagram reveals that the samples predominantly occupy the fields corresponding to fluvio-deltaic to lacustrine depositional environments. This implies that peat accumulation occurred under transitional settings where both fluvial influx and lacustrine influences were significant. Such environments are consistent with delta-plain peat mires, which receive alternating inputs of terrigenous clastic and organic debris.

Table 6.9 Cross plot values for paleodepositional model based on petrography data.

Mine/Seam name	Band no.	Durite+ Inertite	Vitrite + Clarite	Intermedia tes	V+C	VI+ DC+ CD	I+D
Sharda	1	33.97	47.01	19.02	47.66	17.91	34.44
Sharda	2	53.91	24.35	21.74	24.67	20.70	54.63
Sharda	3	26.58	47.09	26.33	48.31	24.42	27.27
Sharda	4	31.62	44.61	23.77	47.15	19.43	33.42
Sharda	5	30.25	52.39	17.36	54.02	14.78	31.20
Sharda	6	28.10	48.21	23.69	50.14	20.63	29.23
Sharda	7	5.10	65.03	29.87	66.80	27.96	5.24
Sharda	8	45.35	30.23	24.42	30.50	23.75	45.75
Dhanpuri	1	78.62	7.80	13.59	7.88	12.61	79.50
Dhanpuri	2	32.78	49.17	18.05	49.25	17.91	32.84
Dhanpuri	3	41.75	45.15	13.11	45.15	13.11	41.75
Dhanpuri	4	23.40	57.45	19.15	58.38	17.84	23.78
Dhanpuri	5	30.96	18.27	50.76	19.25	48.13	32.62
Rajendra	1	56.65	26.59	16.76	27.63	13.51	58.86
Rajendra	2	36.56	23.66	39.78	25.48	35.14	39.38
Rajendra	3	7.58	86.27	6.15	87.16	5.18	7.66
Rajendra	4	42.09	28.14	29.77	28.47	28.94	42.59
Rajendra	5	41.29	42.63	16.09	42.63	16.09	41.29

Mine/Seam name	Band no.	Durite+ Inertite	Vitrite + Clarite	Intermedia tes	V+C	VI+ DC+ CD	I+D
Khairaha VI	1	18.39	73.91	7.69	74.92	6.44	18.64
Khairaha VI	2	19.97	64.26	15.77	66.03	13.45	20.52
Khairaha VI	3	6.43	85.48	8.09	85.65	7.90	6.44
Khairaha VI	4	55.24	31.90	12.86	32.84	10.29	56.86
Khairaha VI	5	54.88	29.27	15.85	29.72	14.55	55.73
Khairaha VII	1	40.18	35.62	24.20	35.78	23.85	40.37
Khairaha VII	2	69.68	18.71	11.61	19.12	9.67	71.21
Khairaha VII	3	52.96	27.69	19.35	27.99	18.48	53.53
Khairaha VII	4	32.16	45.77	22.07	46.43	20.95	32.62
Khairaha VII	5	35.90	45.97	18.13	46.48	17.22	36.30
Damini VI 1st site	1	67.04	13.52	19.44	13.71	18.29	68.00
Damini VI 1st site	2	61.19	35.82	2.99	36.92	0.00	63.08
Damini VI 1st site	3	58.59	10.10	31.31	10.20	30.61	59.18
Damini VI 2nd Site	1	66.24	10.15	23.60	11.08	16.62	72.30
Damini VI 2nd Site	2	45.38	26.15	28.46	26.77	26.77	46.46
Damini VI 2nd Site	3	58.54	15.24	26.22	15.82	23.42	60.76
Damini V	1	66.40	22.40	11.20	23.53	6.72	69.75
Damini V	2	38.87	23.66	37.46	25.30	33.13	41.57
Damini V	3	28.60	55.54	15.87	55.84	15.40	28.76
Damini V	4	55.06	33.33	11.61	33.84	10.27	55.89
Bangwar	1	44.66	26.12	29.21	27.68	25.00	47.32
Bangwar	2	49.03	34.71	16.26	35.66	13.97	50.37
Bangwar	3	13.53	74.08	12.39	75.12	11.16	13.72
Bangwar	4	53.54	25.84	20.62	26.13	19.72	54.15
Amalai	1	16.58	43.85	39.57	44.20	39.08	16.71
Amalai	2	91.64	4.03	4.32	4.07	3.49	92.44
Amalai	2	49.91	28.62	21.47	29.83	18.16	52.01
Amalai	4	81.97	10.14	7.89	10.26	6.84	82.91
Amalai	5	74.32	12.50	13.18	12.80	11.07	76.12
Amalai	6	80.91	9.55	9.55	9.63	8.72	81.65
Amalai	7	76.90	8.19	14.91	8.28	13.91	77.81
Amalai	8	20.41	60.35	19.24	61.42	17.80	20.77

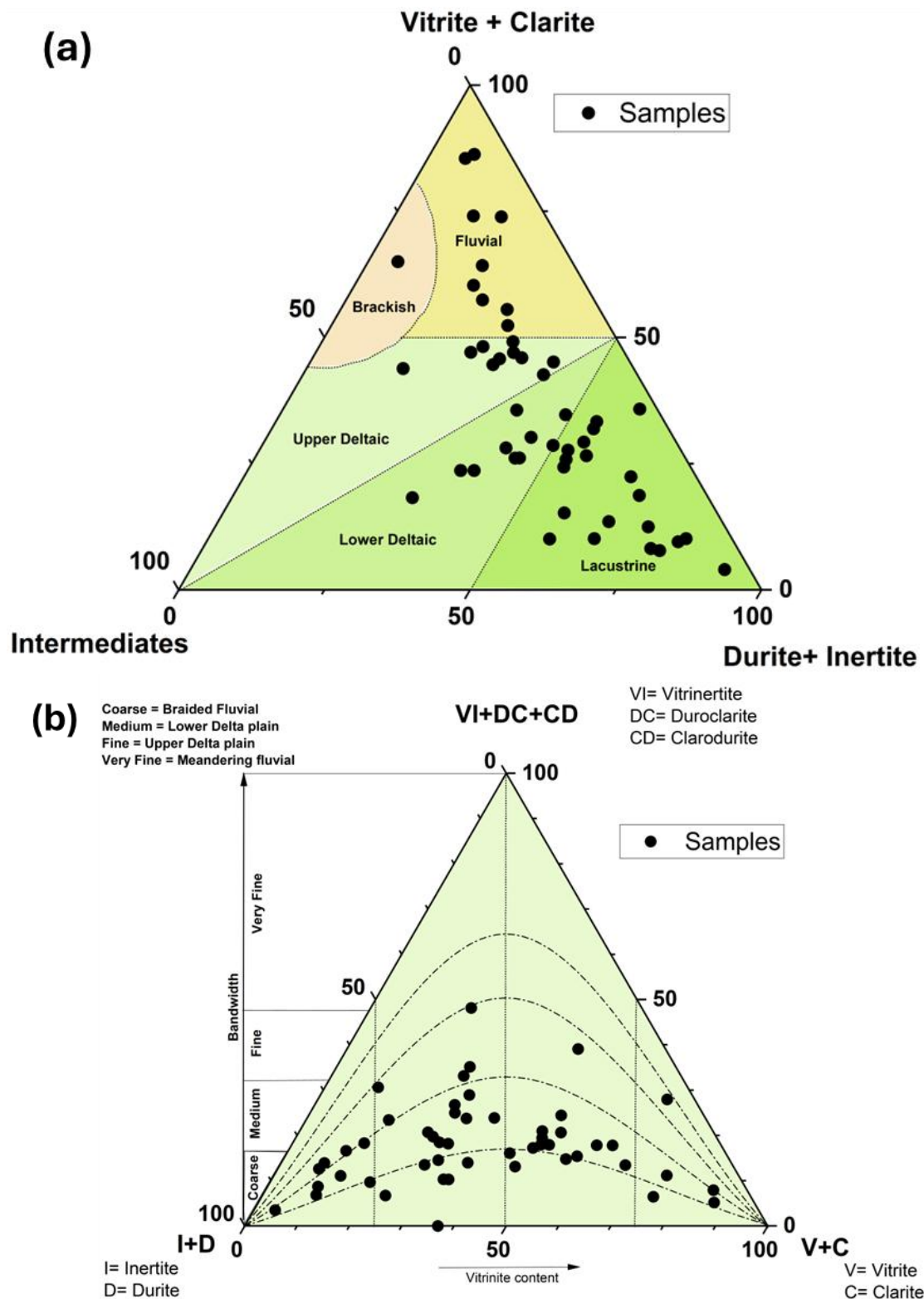


Figure 6.42 Depositional model based on microlithotype data proposed by (a) Smyth (1979) and (b) Hunt (1982).

To further refine this interpretation, a second ternary model, developed by Hunt (1982), has been applied. Unlike Smyth's environmental classification, Hunt's model is based on the microscopic "bandwidth" of coal layers, which reflects the degree of layering between

vitritite-rich and inertinite-rich microlithotypes. The model delineates four bandwidth categories: coarse, medium, fine, and very fine, which correspond to specific depositional regimes-namely, braided fluvial, lower delta plain, upper delta plain, and meandering fluvial systems. Importantly, in Hunt's ternary diagram, the curve begins at vitrite = 0 and inertite = 0. Maximum bandwidth is achieved when vitrite and inertite occur in approximately equal proportions, producing alternating bright and dull coal bands (Hunt, 1989).

The Sohagpur microlithotype data shown in Table 6.9, when plotted on Hunt's ternary diagram, fall predominantly within the coarse to fine bandwidth, suggesting deposition in braided fluvial to deltaic plain environments. This interpretation aligns well with the Smyth model, further strengthening the conclusion that the depositional setting of these coals was controlled by fluvio-deltaic systems with intermittent lacustrine phases (Figure 6.42).

6.8 Pore characterization and the influence of petrographic constituents on pore characterization and gas adsorption

6.8.1 Multiscale pore characterization

The multiscale pore characterization of the Sohagpur coal samples has been carried out by integrating results from scanning electron microscopy, low-pressure gas adsorption (LPGA), small-angle X-ray scattering (SAXS), and mercury intrusion porosimetry analyses, which together provide a comprehensive understanding of the pore size distribution and surface characteristics of the coal. The characterization of pores at different scales is essential for evaluating the storage capacity and transport properties of gases in coal seams, thereby contributing to a better understanding of the coalbed methane potential and CO₂ sequestration capacity.

SEM investigations of the Sohagpur coal samples reveal a well-developed, highly heterogeneous pore system, with pore sizes ranging from a few micrometres to several hundred micrometres. These pores occur predominantly as voids within the coal matrix and are mainly classified as intraparticle pores. The morphology of these intraparticle pores is highly variable, encompassing nearly spherical and sub-rounded forms as well as irregular, elongated, and locally interconnected geometries, reflecting differences in maceral composition, degree of coalification, and post-depositional modification.

The spatial distribution of pores within the coal matrix is distinctly non-uniform. Certain zones exhibit a high pore density with strong interconnectivity, forming effective pathways for gas storage and migration. In contrast, other areas are relatively compact, characterized by isolated or poorly connected pores that restrict fluid flow. Such heterogeneity in pore architecture plays a crucial role in governing gas adsorption capacity, diffusion behaviour, and the overall permeability of the coal seams. Regions dominated by interconnected pore networks are particularly favourable for enhanced gas transport, whereas compact zones may act as barriers, limiting permeability.

In addition to matrix pores, SEM observations also document the presence of well-developed microfracture networks within the coal samples. These microfractures often cut across maceral boundaries and locally link isolated pores, thereby enhancing pore connectivity and permeability. Collectively, the coexistence of intraparticle pores, heterogeneous pore distribution, and microfracture systems underscores the complex nature of the coal pore structure and highlights its significance in controlling gas storage, migration, and production behaviour in the Sohagpur coal seams.

In the present study, CO₂ adsorption at 273 K using LPGA was employed to examine the micropore structure (pore size < 2 nm), which plays a critical role in controlling the coal sorption behaviour. Unlike N₂ adsorption, which is limited in detecting narrow

micropores due to kinetic restrictions at 77 K, CO₂ adsorption provides a more reliable measure of micropores owing to its smaller molecular size and higher diffusivity. The adsorption isotherms obtained for the studied coal samples were modelled using Density Functional Theory (DFT) and the Dubinin–Astakhov (DA) model, both of which allow quantitative estimation of pore size distribution and micropore volume.

Among the studied samples, sample K-7 showed a significantly higher abundance of micropores than the other samples (Figure 6.43). This is evident from the pore size distribution curves obtained with both the DFT and DA models, where K-7 shows a pronounced peak indicating micropore dominance. The peak profile clearly indicates that K-7 contains a larger population of micropore, which directly contributes to its greater adsorption capacity. This observation is further corroborated by the CO₂ adsorption isotherm, which shows that K7 has the highest adsorbed volume among all samples. The micropore surface area, estimated using the Dubinin–Radushkevich (DR) model, also supports these findings, with K-7 exhibiting a distinctly higher surface area than the other coal samples.

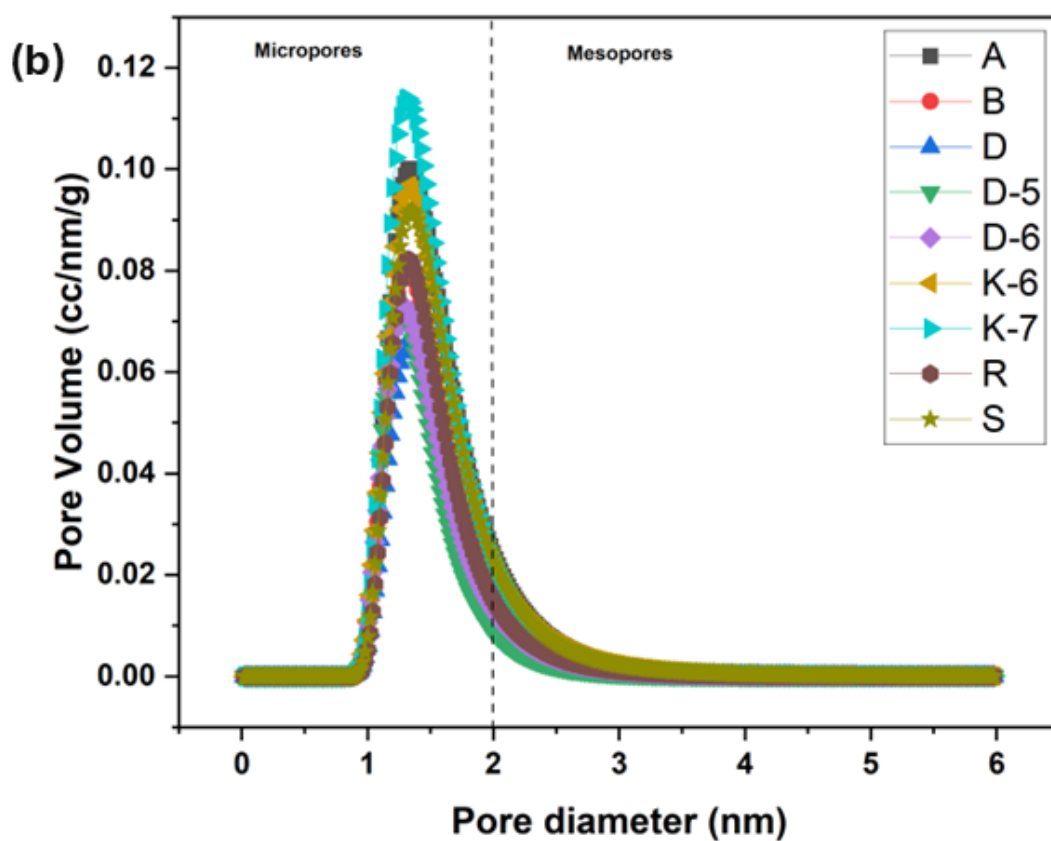
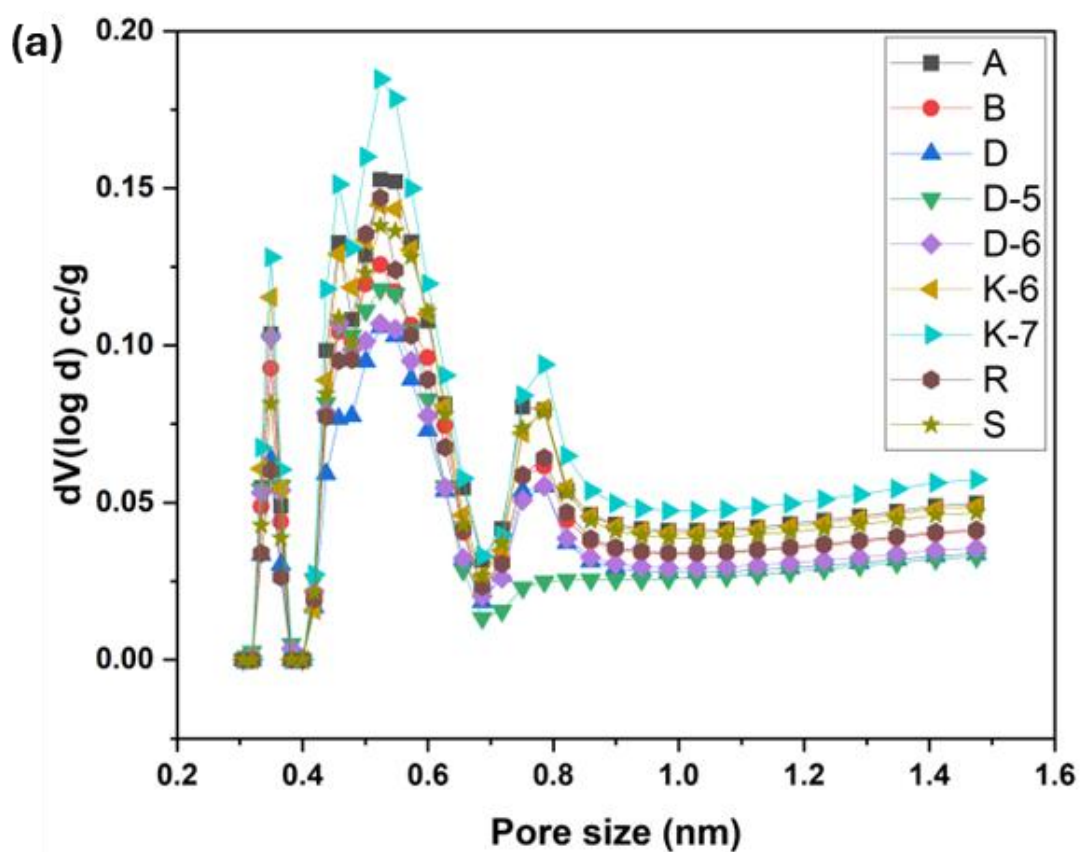


Figure 6.43 Pore size distribution of coal samples through CO_2 adsorption with DFT model (a) and DA model (b).

The nitrogen (N_2) adsorption–desorption technique in low-pressure gas adsorption (LPGA) analysis is a widely employed method for characterizing mesopores (2–50 nm) and macropores (>50 nm) in coal. Unlike CO_2 adsorption, which is more effective in quantifying micropores due to its smaller molecular diameter and higher diffusivity, N_2 adsorption at 77 K provides valuable insights into the larger pore domains that control gas diffusion and permeability within the coal matrix. Therefore, the combination of N_2 and CO_2 adsorption experiments enables a multiscale understanding of pore structures, ranging from micropores to macropores.

The pore size distribution (PSD) curves derived from the density functional theory (DFT) and the Barrett–Joyner–Halenda (BJH) models highlight the distribution of micropores to mesopores and mesopores to macropores, respectively. The DFT model provides a more rigorous representation of the micropore-to-mesopore range, while the BJH model is particularly effective in resolving mesopores and smaller macropores, which are significant for controlling diffusion and transport of adsorbed gases. The PSD curves reveal that, in general, the studied coal samples contain a relatively limited abundance of micropores, while mesopores and macropores dominate the pore architecture.

Among the samples, sample code S exhibits a noticeably higher abundance of smaller mesopores, as reflected in the DFT and BJH pore size distribution profiles (Figure 6.44). This interpretation is strongly supported by the N_2 adsorption–desorption isotherm, where sample S shows a prominent hysteresis loop, indicative of capillary condensation within mesopores. The broader hysteresis loop compared to other samples clearly demonstrates that sample S has a larger volume of smaller mesopores. These findings are consistent with those reported by Kishor et al. (2025a), who documented a similar mesopore enrichment in these Gondwana coals. The adsorption isotherms of all samples correspond to the Type IIB category according to the International Union of Pure and

Applied Chemistry (IUPAC) classification. Type IIB isotherms are typically associated with materials that contain both mesopores and macropores, with unrestricted monolayer–multilayer adsorption behaviour at low relative pressures and significant capillary condensation effects at higher pressures. The assignment to this isotherm category is further corroborated by the BJH pore size distribution curves, which consistently indicate the presence of mesopores transitioning into macropores across the studied coal samples.

A distinct steep slope in the N₂ adsorption isotherm is observed at higher relative pressures ($p/p_0 = 0.8\text{--}1.0$), reflecting the filling of macropores. Such features are characteristic of coal samples with macropores, as reported by Hazra et al. (2018). The macropores, although contributing minimally to surface area, serve as conduits that enhance gas migration, thereby improving permeability within the coal matrix.

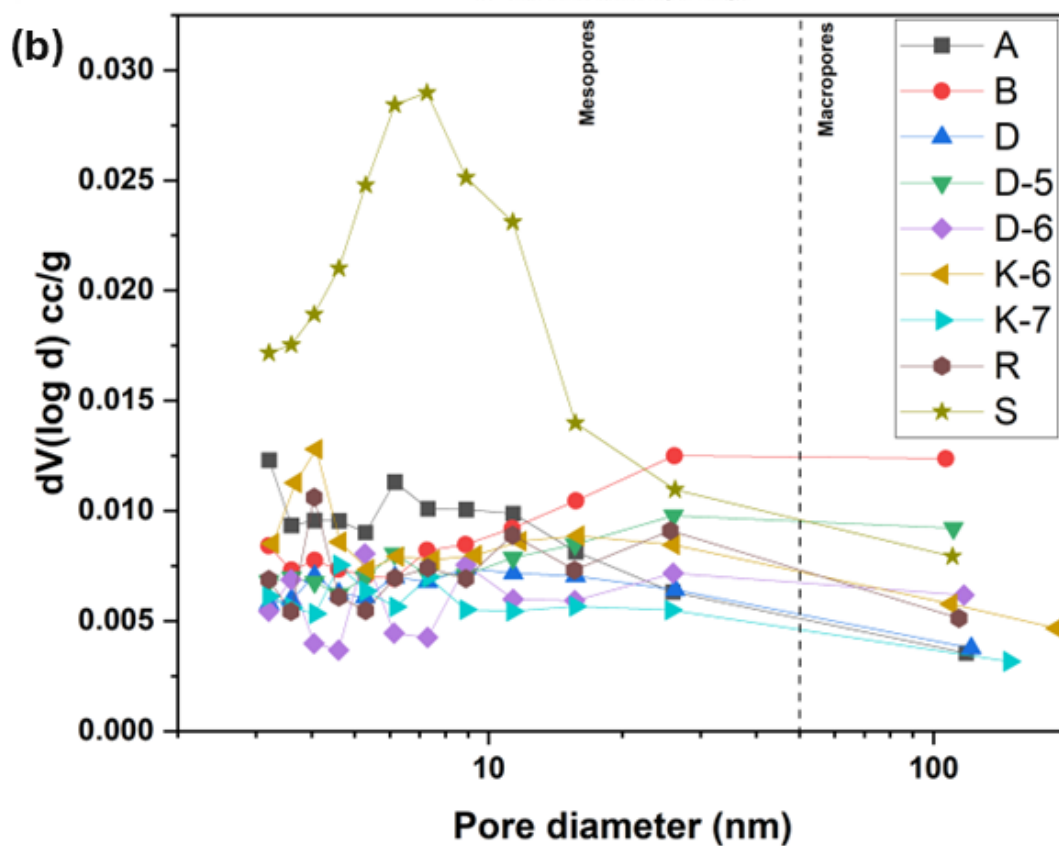
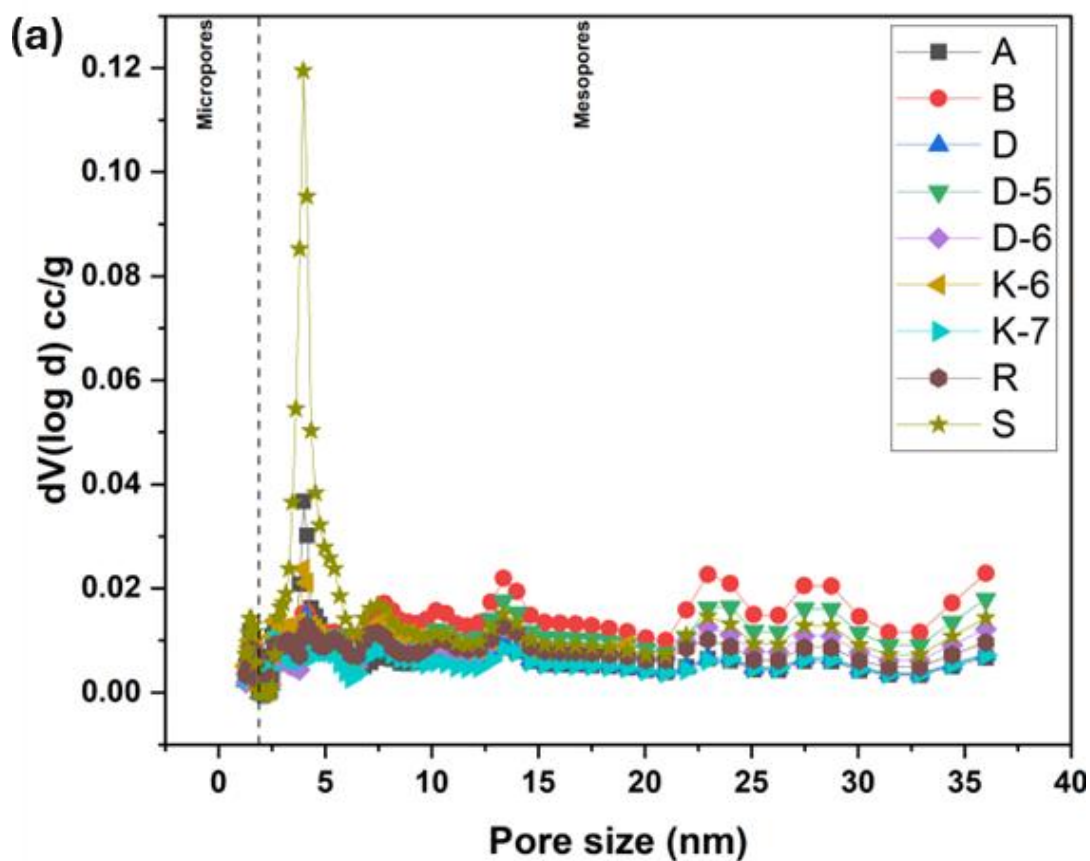


Figure 6.44 Pore size distribution of coal samples through N_2 adsorption with DFT model (a) and BJH model (b).

The small-angle X-ray scattering (SAXS) technique provides additional insights into the pore architecture of coal, complementing the results obtained from low-pressure gas adsorption (LPGA) methods. Unlike gas adsorption, which primarily probes the accessible pore space, SAXS has the advantage of capturing information on both open (accessible) and closed (inaccessible) pores. This makes SAXS particularly useful in coal studies, as it allows for the detection of pores that may not be accessible to gas molecules due to connectivity limitations or constricted pore throats.

The SAXS-derived pore size distribution (PSD) curves of the studied coal samples reveal the coexistence of mesopores (2–50 nm) and macropores (>50 nm), reinforcing interpretations from LPGA analyses. Specifically, SAXS results indicate that all samples exhibit a significant contribution from macropores, with mesopores present in lower proportions. Among the studied samples, sample code S stands out due to its higher abundance of mesopores in the 8–11 nm range, as revealed by the SAXS PSD profile. This observation is in strong agreement with the BJH-derived PSD curves from N₂ adsorption, which also suggested that sample S is enriched in smaller mesopores compared to the other samples. The consistency across SAXS and LPGA datasets enhances the reliability of this interpretation. Moreover, the SAXS PSD curves show that the studied coal samples exhibit a pronounced high-intensity peak near 100 nm in pore size, indicating a dominant contribution from macropores (Figure 6.45). This feature highlights the fact that macropores, although providing relatively minor contributions to surface area, constitute a large fraction of the total pore volume in these coals.

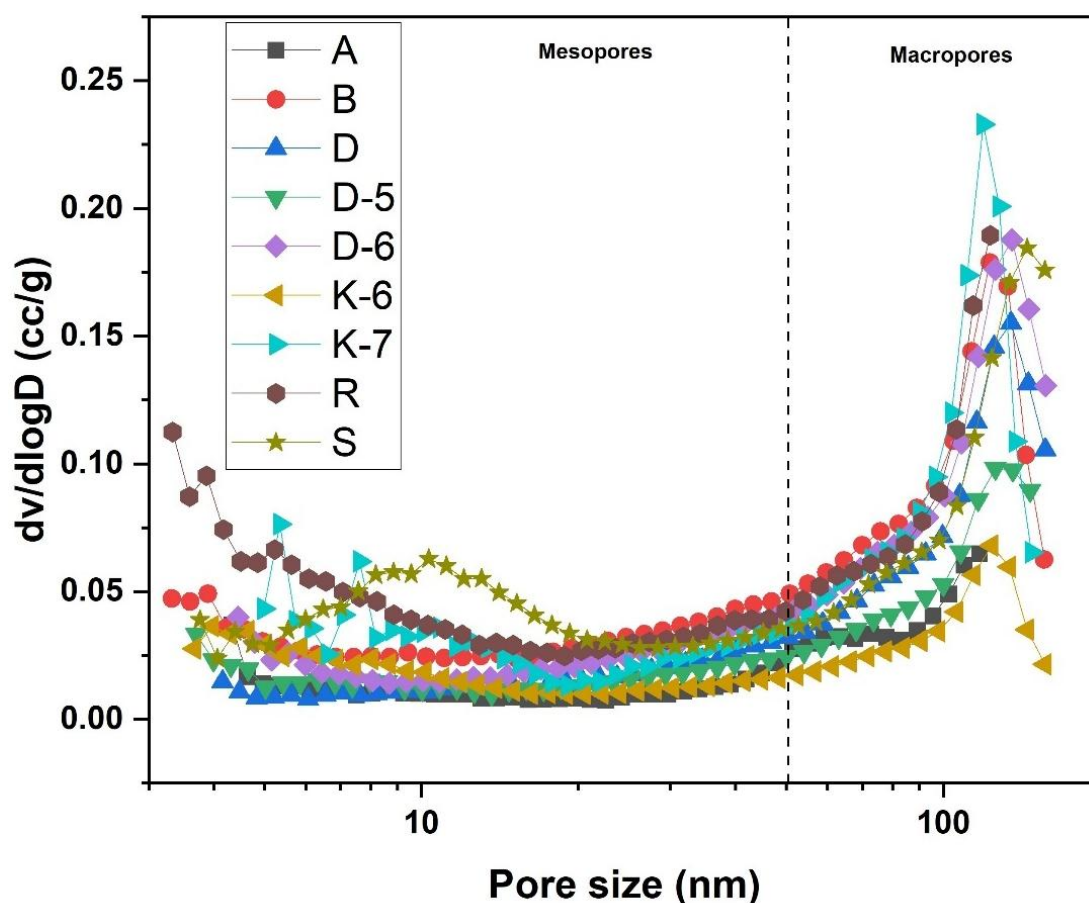


Figure 6.45 Pore size distribution of coal samples through SAXS analysis.

The MIP technique is a widely accepted method for determining pore size distribution (PSD) in porous materials due to its ability to cover a broad pore diameter range, typically from approximately 3 nanometers (nm) to 1,000,000 nm (1 mm). This technique relies on the intrusion of mercury under controlled pressure into the porous network of the sample, from which the distribution and volume of pores can be inferred. The results of this analysis are presented in the form of PSD curves for each coal sample, as illustrated in Figure 6.46.

The generated PSD curves reveal notable differences in pore structures among the analyzed coal samples. Samples labelled R, K7, K6, D6, and D5 demonstrate a pronounced increase in cumulative pore volume at pore diameters exceeding approximately 100,000 nm. This sharp upsurge in pore volume at the upper end of the

measurable size range suggests the presence of significant macro-porosity in the form of microfractures, intergranular voids, or cleat systems.

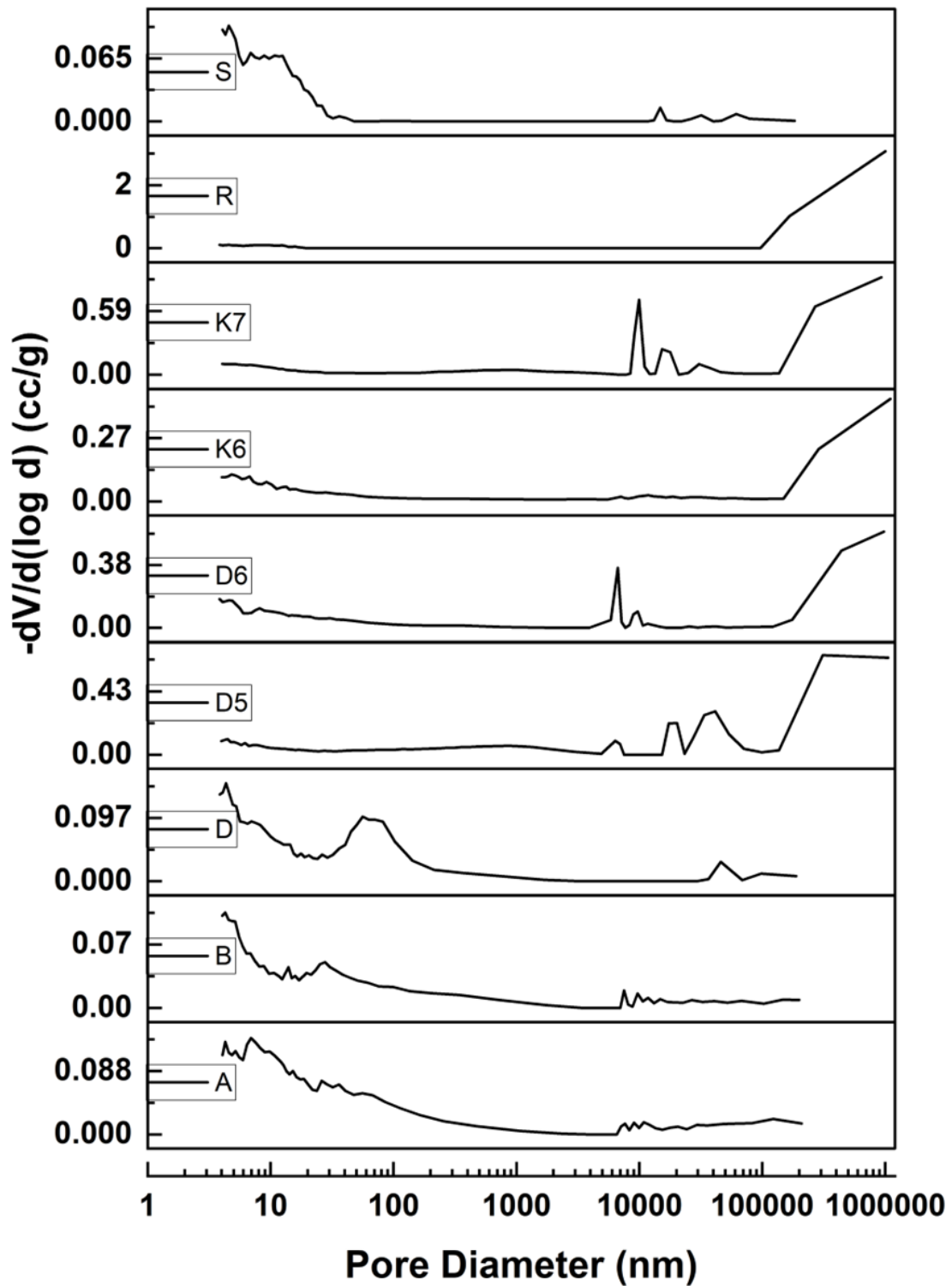


Figure 6.46 Pore size distribution from MIP analysis.

6.8.2 Pore connectivity (accessibility) index

Pore connectivity / pore accessibility is an important parameter that describes the extent of pore access within the coal matrix. It essentially reflects the proportion of pores that can actively participate in gas storage and transport processes relative to the total pore network. The index is expressed as a ratio of the accessible pore volume, derived from low-pressure gas adsorption experiments to the total pore volume (accessible + inaccessible) estimated by SAXS analysis. A higher pore connectivity value indicates that the pores are well connected and easily accessible to gas molecules, whereas lower values suggest a significant fraction of closed or poorly connected pores.

Chandra et al. (2020) defined the pore connectivity index on a scale ranging from 0 to 1, where values approaching 1 imply a highly accessible pore network and values approaching 0 indicate the dominance of inaccessible pores. Following their approach, as well as that of Kumar et al. (2025b), the mesopore connectivity index was calculated using the pore volume data from the DFT model of N₂ adsorption (LPGA) as the accessible pore fraction and the SAXS-derived mesopore volume as the total pore fraction. The formula is expressed as:

$$\text{Pore connectivity index} = \frac{\text{DFT pore volume from LPGA (mesopore range)}}{\text{SAXS pore volume (mesopore range)}}$$

The results of this calculation show that the mesopore connectivity index in the studied coals ranges from 0.203 to 0.929. The variability in values highlights significant differences in the mesopore accessibility among the studied samples. Samples with higher connectivity indices indicate a well-developed mesopore network with strong accessibility, which enhances both gas storage and migration pathways. Conversely, lower connectivity indices suggest that a substantial portion of the mesopores are isolated or inaccessible, which may hinder gas adsorption efficiency and reduce permeability.

It is important to note, however, that the above equation only accounts for mesopores (2–50 nm) and does not fully capture the contribution of macropores, which play a critical role in governing overall pore volume and connectivity in coals. To address this limitation, the present study introduces a modified pore connectivity index that encompasses the full pore size range (mesopores and macropores). This extended index uses the BJH pore volume (from N₂ adsorption), which covers pores up to 200 nm, as the accessible pore fraction, and the total pore volume from SAXS (mesopores + macropores) as the combined accessible and inaccessible fraction. The modified formula is expressed as:

$$\text{Pore connectivity index (for full range)} = \frac{\text{BJH Pore volume}}{\text{SAXS Total pore volume}}$$

Table 6.10 Pore connectivity index values of coal samples.

Code of coal samples	DFT Pore volume	SAXS Mesopore Volume cc/g	Pore connectivity for mesopores	Pore volume % increased through SAXS in the Mesopore range	BJH Pore Volume (cc/g)	Total Pore Volume (cc/g)	Pore connectivity for mesopores + macropores	Pore volume % increased through SAXS in the full range
A	0.013	0.014	0.929	7.69	0.012	0.030	0.406	150.00
B	0.017	0.040	0.425	135.29	0.019	0.088	0.215	363.16
D	0.010	0.017	0.588	70.00	0.010	0.058	0.174	480.00
D-5	0.014	0.019	0.737	35.71	0.015	0.046	0.325	206.67
D-6	0.010	0.026	0.385	160.00	0.011	0.076	0.146	590.91
K-6	0.012	0.022	0.545	83.33	0.013	0.039	0.333	200.00
K-7	0.009	0.031	0.290	244.44	0.009	0.077	0.116	755.56
R	0.012	0.059	0.203	391.67	0.012	0.094	0.127	683.33
S	0.025	0.047	0.532	88.00	0.026	0.093	0.279	257.69

The calculated pore connectivity values presented in Table 6.10 are in full agreement with the pore size distributions (PSD) shown in Figure 6.47, which compares the BJH PSD with the SAXS PSD. For instance, sample code A exhibits a notably high pore

connectivity index within the mesopore range. This observation is strongly supported by the PSD curves in Figure 6.47, where sample A shows a distinct overlapping trend between the BJH-derived and SAXS-derived mesopore distributions. Such an overlap, particularly in the mid-mesopore range, clearly indicates that nearly all the pores detected by SAXS in this size domain correspond to accessible (open) pores rather than isolated or inaccessible pores. This consistency between calculated indices and graphical PSD evidence further validates the reliability of the pore connectivity assessment in the studied coals.

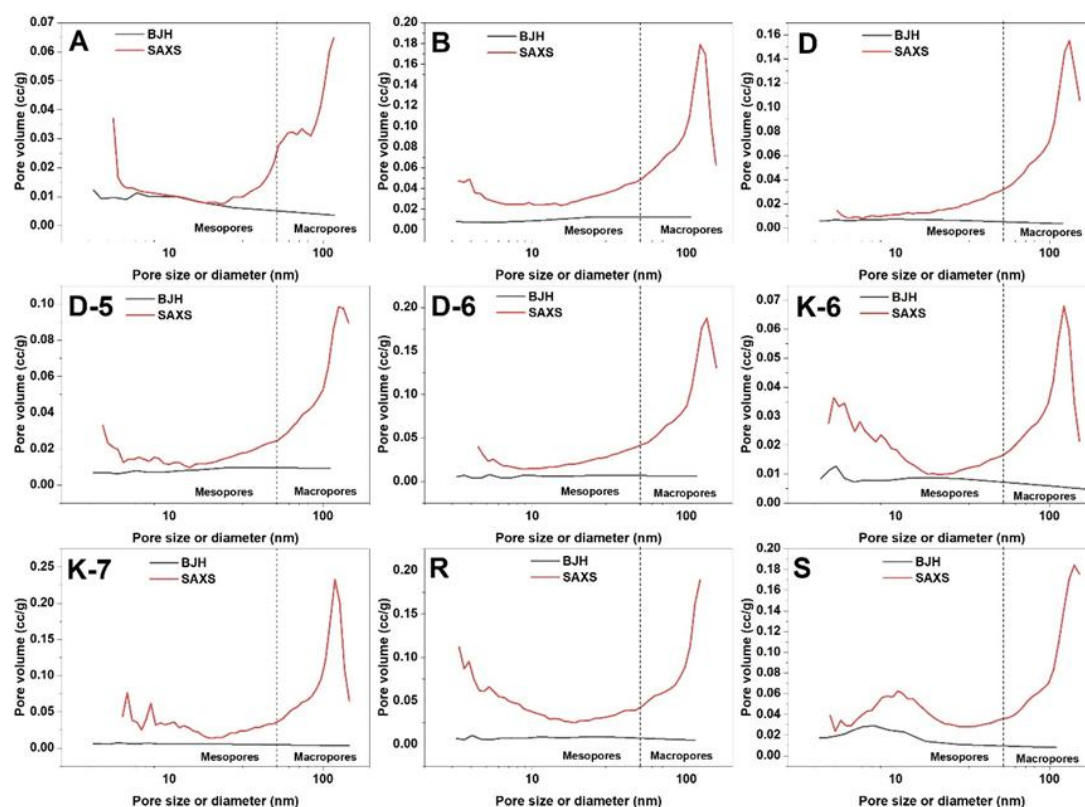


Figure 6.47 Combined PSD curve of BJH and SAXS analysis for the whole range (Mesopores + Macropores).

6.8.3 Influence of Petrographic constituents on gas adsorption and pore characterization

During the petrographic study, both maceral groups and mineral matter constituents were systematically quantified to assess their influence on pore development and accessibility, as characterized through LPGA and SAXS analyses. To assess the relationship between

petrographic composition and pore attributes, a Pearson correlation matrix was constructed (Table 6.11). The results reveal distinct and meaningful correlations between maceral assemblages and pore characteristics at different scales.

The micropore parameters, obtained from CO₂ adsorption in LPGA, exhibit strong positive correlations with the combined vitrinite and inertinite fraction (V+I). Specifically, V+I shows correlation coefficients of 0.71 with DR micropore surface area (MSA) and 0.87 with DA micropore volume (MV). These values clearly suggest that an increase in the relative abundance of vitrinite and inertinite enhances the micropore development in coal. Vitrinite, being a gelified maceral, and inertinite, with its oxidized and porous structure, together promote the formation of micropores that are readily accessible in the coal matrix. In contrast, the combination of liptinite and mineral matter (L+MM) displays a negative correlation with micropore parameters, indicating that higher volumes of these constituents tend to reduce micropore surface area and volume. This is consistent with the tendency of liptinite to preserve organic matter in dense forms, while mineral matter tends to occupy or block pore spaces, thereby limiting micropore development.

For mesopore attributes, derived from N₂ adsorption, no significant correlations with maceral proportions were observed. This lack of correlation suggests that mesopore formation in the studied coals is less directly controlled by maceral composition and may instead be influenced by secondary processes such as devolatilization, structural reorganization, or redistribution of mineral matter during coalification. The SAXS-derived pore attributes present a different scenario. Here, liptinite shows a strong positive correlation with total pore area, mesopore area, and mesopore volume. This observation highlights the role of liptinite macerals in contributing not only to open but also to closed pore systems, since SAXS integrates information from both accessible and inaccessible pores. The regression plots further substantiate these trends: V+I vs. micropore

parameters (Figure 6.48 a, b) confirm the positive influence of vitrinite and inertinite on LPGA-derived micropores, while liptinite vs. SAXS parameters (Figure 6.48 e, f) demonstrate the dominant control of liptinite on overall pore networks, particularly within the mesopore domain.

The positive correlation of vitrinite + inertinite (V+I) with micropore volume and surface area can be explained by the origin and transformation processes of these macerals during coalification. Vitrinite, primarily derived from woody plant material, undergoes significant devolatilization during coalification, leading to the development of a fine and interconnected micropore network. In contrast, inertinite originates from oxidized or charred plant matter, which inherently contains pores due to combustion and oxidative degradation. Thus, both macerals collectively contribute to the formation and preservation of micropores, accounting for their strong correlations with DR micropore surface area and DA micropore volume.

On the other hand, the remaining maceral and mineral constituents: liptinite and mineral matter (L+MM), display a negative correlation with micropore parameters. This outcome is consistent with their inherent properties and modes of occurrence. Liptinite macerals are widely recognized as being more ductile compared to vitrinite and inertinite (Hou et al., 2020). Derived mainly from waxy, resinous, and cuticular plant components, liptinite tends to resist devolatilization and does not undergo the same structural transformation as vitrinite. Consequently, it contributes very little to micropore formation, since its ductile nature prevents the development of a rigid pore framework. Similarly, mineral matter often occupies pore spaces or blocks pore throats, thereby restricting the development and accessibility of micropores.

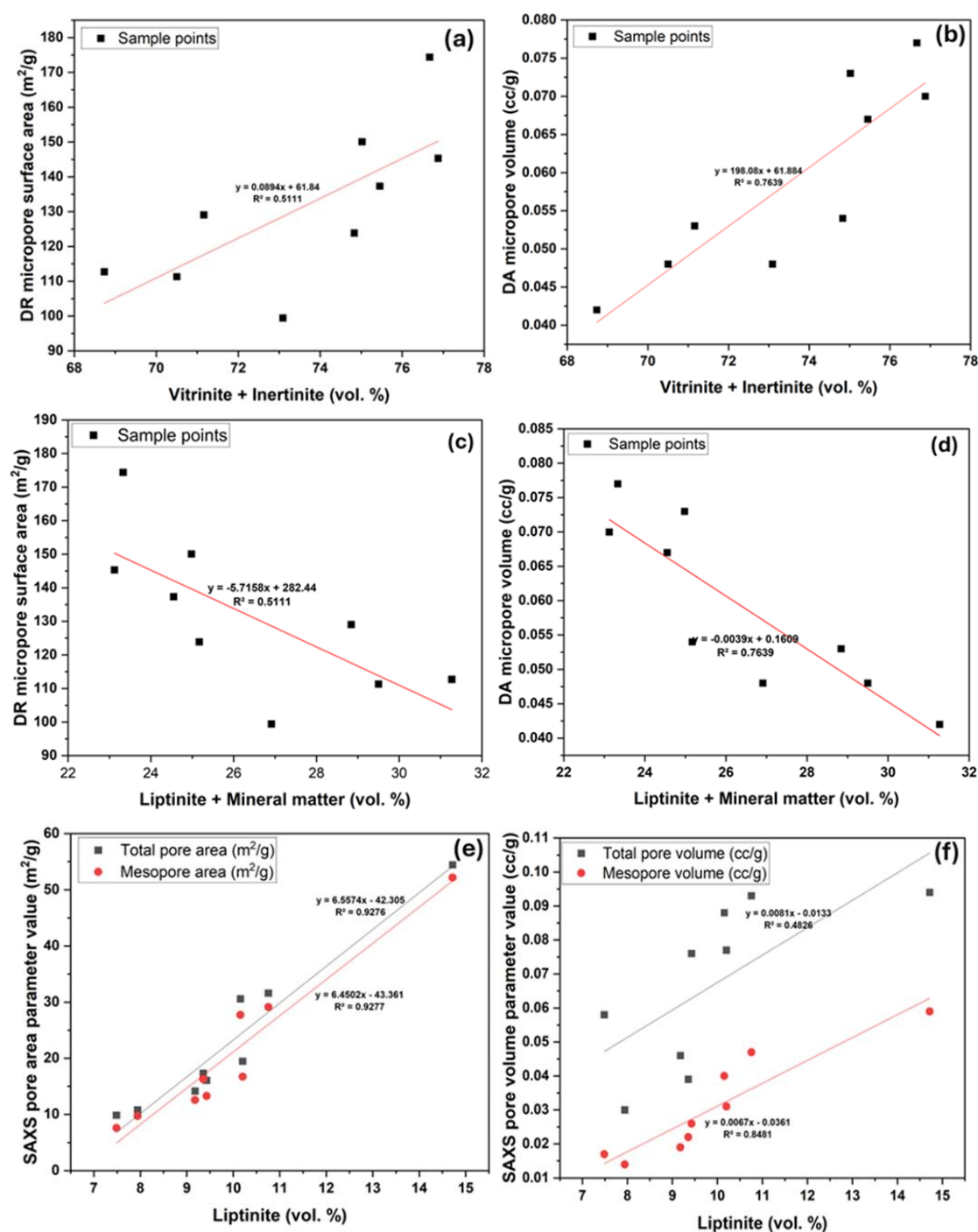


Figure 6.48 Regression chart between the vitrinite + inertinite with LPGA parameters (a, b), between liptinite + mineral matter with LPGA parameters, and between liptinite (c, d) and SAXS pore parameters (e, f).

Similarly, the pore connectivity index is significantly influenced by the coal's maceral composition. The liptinite group of macerals, known for their ductile nature, tends to form close, isolated pores, which in turn reduce overall pore connectivity. As the liptinite content increases, the ability of the pore system to remain interconnected decreases.

Conversely, a lower proportion of liptinite macerals is associated with higher pore connectivity, likely due to the presence of more rigid macerals such as vitrinite and inertinite, which support the development of open and interconnected pore structures.

This trend is clearly shown in Figure 6.49.

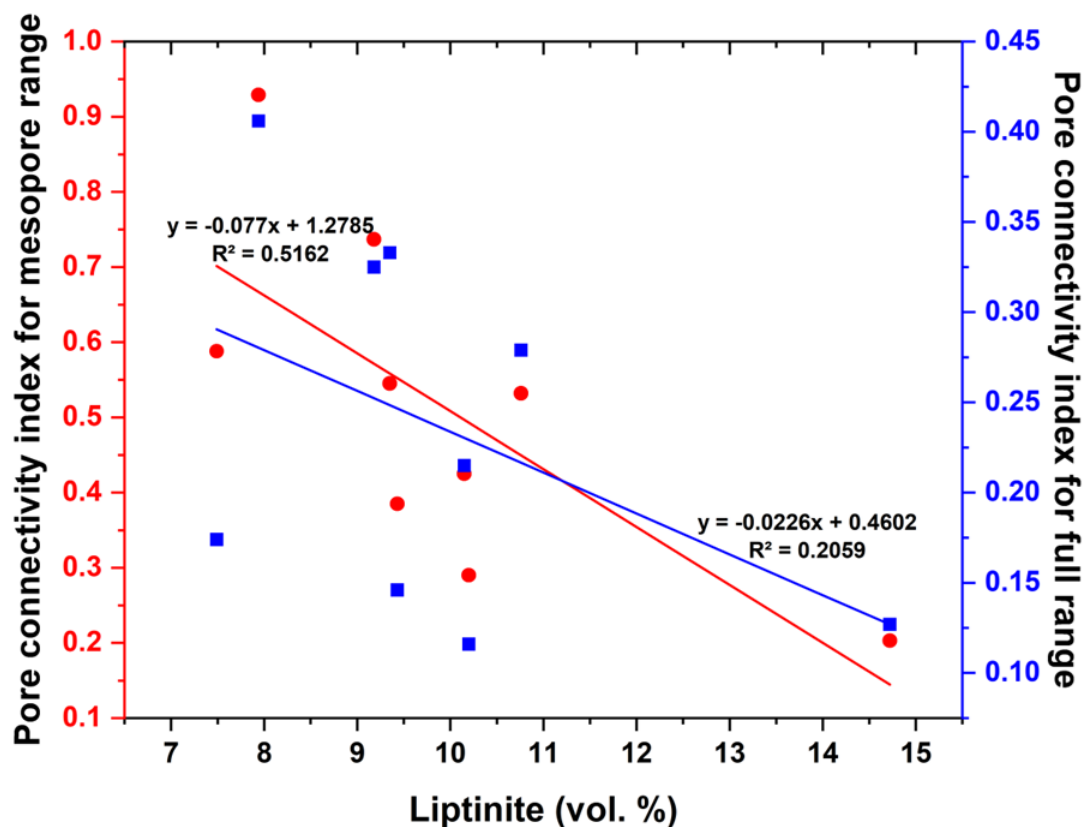


Figure 6.49 Regression plot between the liptinite content and pore connectivity index values for mesopore and full range.

Table 6.11 Pearson's correlation matrix between micro petrographic constituents and pore attributes obtained from LPGA and SAXS analyses.

	V	L	I	MM	V+I	L+MM	DR MSA	DA MV	BET SA	BJH PV	DFT PV	TPA	MaA	MeA	TPV	MaV	MeV
V	1.00																
L	0.41	1.00															
I	-0.84	-0.54	1.00														
MM	-0.62	-0.50	0.21	1.00													
V+I	0.41	-0.15	0.14	-0.78	1.00												
L+MM	-0.41	0.15	-0.14	0.78	-1.00	1.00											
DR MSA	0.16	0.16	0.25	-0.73	0.71	-0.71	1.00										
DA MV	0.30	-0.03	0.20	-0.74	0.87	-0.87	0.93	1.00									
BET SA	0.43	0.10	-0.22	-0.43	0.42	-0.42	0.23	0.39	1.00								
BJH PV	0.26	0.17	-0.20	-0.24	0.15	-0.15	-0.06	0.03	0.88	1.00							
DFT PV	0.24	0.17	-0.16	-0.26	0.18	-0.18	-0.01	0.09	0.92	0.99	1.00						
TPA	0.43	0.96	-0.52	-0.54	-0.08	0.08	0.07	-0.06	0.22	0.31	0.31	1.00					
MaA	-0.06	0.31	0.01	-0.12	-0.09	0.09	-0.15	-0.23	-0.13	0.16	0.10	0.35	1.00				
MeA	0.45	0.96	-0.53	-0.54	-0.08	0.08	0.08	-0.05	0.23	0.31	0.31	1.00	0.30	1.00			
TPV	0.26	0.69	-0.31	-0.40	-0.05	0.05	-0.05	-0.14	0.16	0.39	0.35	0.74	0.86	0.71	1.00		
MaV	-0.02	0.22	-0.02	-0.08	-0.07	0.07	-0.19	-0.24	-0.07	0.20	0.14	0.25	0.99	0.21	0.83	1.00	
MeV	0.45	0.92	-0.49	-0.58	0.00	0.00	0.10	-0.01	0.32	0.44	0.43	0.97	0.52	0.95	0.87	0.45	1.00

(For petrographic constituents V= Vitrinite, L= Liptinite, I= Inertinite, MM= Mineral matter, For LPGA CO₂ MSA = Micropore surface area, MV= Micropore volume, For LPGA N₂ SA= Surface Area, PV= Pore Volume, For SAXS TPA= Total Pore Area, MaA= Macropore Area, MeA= Mesopore Area, TPV= Total Pore Volume, MaV= Macropore Volume and MeV= Mesopore Volume).

6.8.4 Effect of petrography constituents on high-pressure CO₂ adsorption

As highlighted in the previous section, the petrographic composition influences coal pore characteristics, which are crucial for assessing the CO₂ storage potential. High-pressure CO₂ adsorption is commonly used to evaluate the suitability of coal for CO₂ sequestration. Coals and organic-rich shales typically show a Type I isotherm under high-pressure CO₂ conditions, confirmed by previous researchers (Bakshi et al., 2020; Kumar, 2023; Shukla et al., 2025; Tambaria et al., 2023), indicating CO₂ adsorption onto a monolayer surface, which is important for determining CO₂ storage capacity. However, the CO₂ adsorption isotherm for Sohagpur coal deviates from this expected Type I behaviour, suggesting different adsorption dynamics. To further investigate this anomaly, the Langmuir adsorption volume was calculated for the experimental pressure, and the Langmuir isotherm was plotted to compare the theoretical and experimental adsorption volumes (Figure 6.50). The Langmuir volume provides an estimate of the monolayer adsorption capacity, helping to quantify CO₂ retention on coal samples. Table 6.12 presents the adsorbed CO₂ volume from the high-pressure analysis, along with the calculated Langmuir volume for the coal samples at experimental pressure conditions. This comparison reveals the differences between the experimental and calculated CO₂ adsorption, providing insights into the adsorption mechanism in Sohagpur coal.

Table 6.12 Coal samples with the experimental volume and Langmuir volume in the same pressure range.

Sample	Experimental volume (cc/g)	Langmuir volume (cc/g)
A	28.357	20.122
B	36.978	7.62
D	37.552	12.43
D-5	33.744	4.46
D-6	43.26	20.889
K-6	42.653	21.04
K-7	51.507	25.09
R	54.075	30.31
S	17.024	39.47

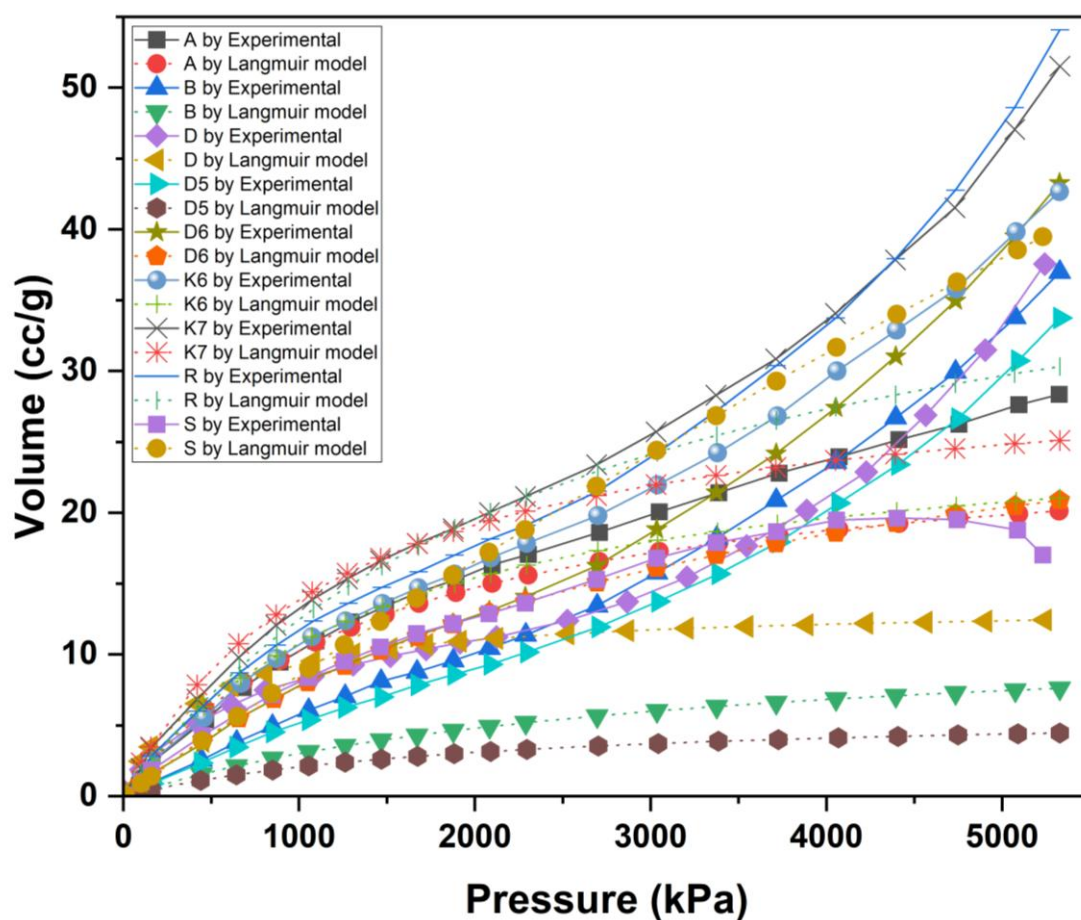


Figure 6.50 Isotherms on experimental and Langmuir model values for coal samples within the same pressure range.

To investigate the impact of petrographic constituents on CO₂ adsorption, regression plots were constructed. As noted in the previous section, a similar relationship between the petrographic components and the Langmuir volume was observed. The Vitrinite + Inertinite volume % shows positive correlation with the Langmuir volume, while Liptinite + Mineral matter shows negative correlation (Fig. 6.51, a). However, no significant correlation was found between the experimental adsorption values and petrographic constituents (Fig. 6.51, b). This discrepancy suggests that during high-pressure CO₂ adsorption, the pore structure may deform or close, disrupting its original configuration. Alternatively, the abundance of meso- and macropores in these coals, as supported by MIP and SAXS analysis, may contribute to the rise in adsorption with

increasing pressure. Previous study done by Shukla et al. (2025) on Permian coal and shale also showed that a sample rich in vitrinite showed a positive correlation between collotelinite sub maceral of vitrinite group and CO₂ adsorption volume, a similar relationship observed by Bakshi et al. (2020), where CO₂ adsorption is positively correlated with the vitrinite content present in the samples.

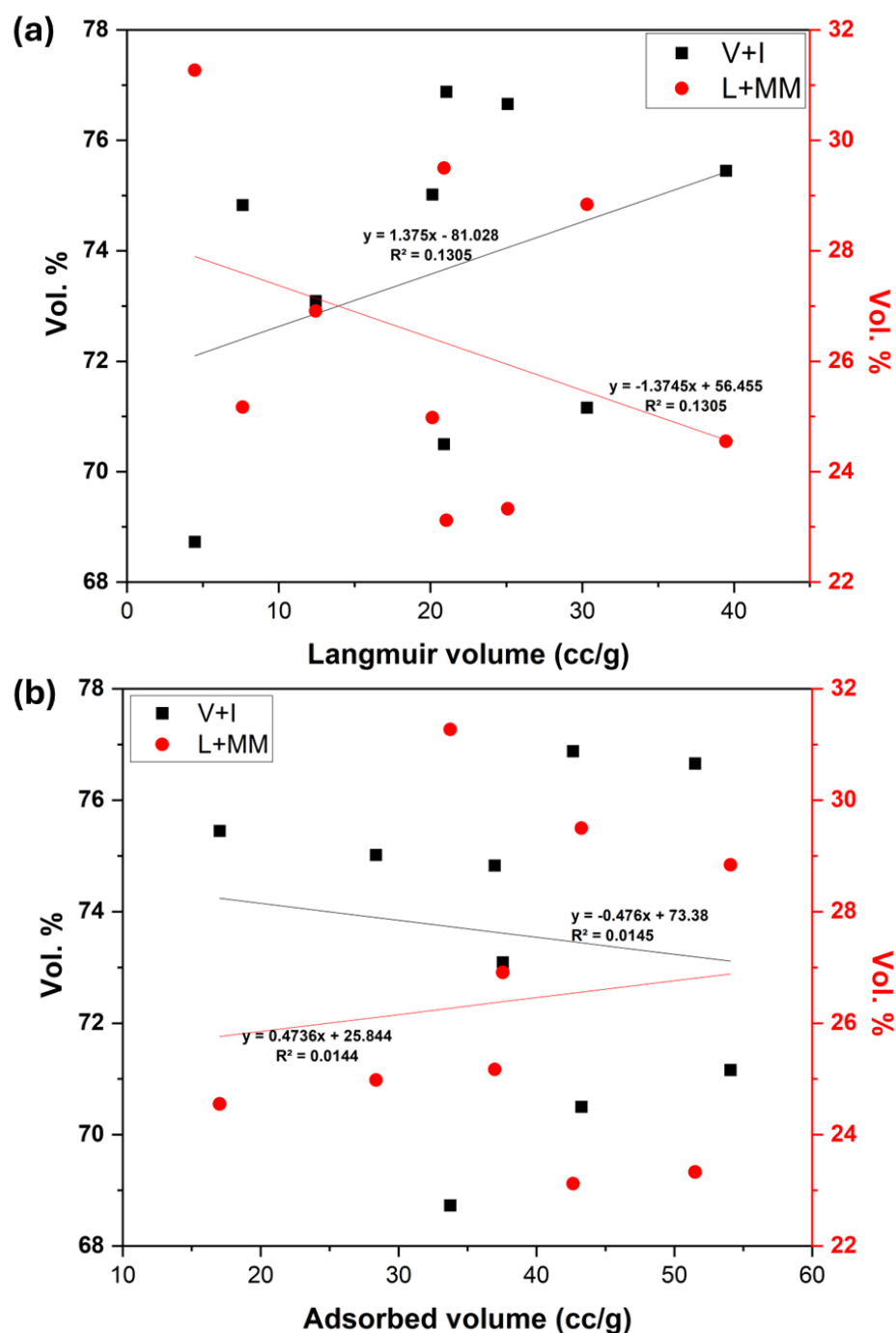


Figure 6.51 Calculated Langmuir volume (cc/g) correlation (a) and experimental adsorbed volume (cc/g) correlation (b) with petrographic constituents.

6.8.5 Role of rank on pore development

Coal rank exerts a fundamental control on the development, distribution, and evolution of pore structures within coal. Rank reflects the degree of coalification, which is governed by burial depth, temperature, pressure, and time. As coal rank increases from lignite through bituminous to anthracite, significant physicochemical transformations occur that directly influence pore type, pore volume, specific surface area, and pore connectivity (Wang et al., 2014).

In low-rank coals, such as lignite and sub-bituminous coal, pore systems are largely inherited from original plant tissues. These coals are characterized by high moisture content, abundant oxygen-containing functional groups, and relatively weak molecular bonding. As a result, pore structures are dominated by macropores and mesopores with relatively high total porosity. However, these pores are often poorly connected and mechanically unstable, making them susceptible to collapse during compaction. Consequently, low-rank coals generally exhibit low specific surface area and limited gas adsorption capacity despite their relatively high porosity. As coal rank increases towards bituminous stage, devolatilization and thermal maturation intensify, leading to the breakdown of aliphatic structures and the progressive development of aromatic carbon networks. These processes promote the generation of secondary pores, particularly micropores, while preserving portions of the existing meso- and macropore framework (Gurdal and Yalcin 2001; Busch and Gensterblum, 2011; Gensterblum et al., 2013).

This rank interval typically represents the most favourable conditions for pore development, as it balances pore generation with compaction effects, resulting in enhanced gas storage and transport properties. At high ranks, including anthracite, continued coalification leads to strong aromatization, molecular ordering, and structural shrinkage. These changes favour the dominance of micropores while simultaneously

reducing the volume of mesopores and macropores (Laxminarayana and Crosdale 2002; Safaei-Farouji et al., 2023). Although high-rank coals often possess a large specific surface area and strong gas adsorption capacity, pore connectivity is significantly reduced due to pore collapse and tightening of the coal matrix. As a result, permeability tends to be low, and gas migration becomes increasingly dependent on fractures rather than matrix pores. As the Sohagpur coals belong to the bituminous coal rank, these coals possess enough surface area and pore size to adsorb the gas, as well as better connectivity to higher rank coals.

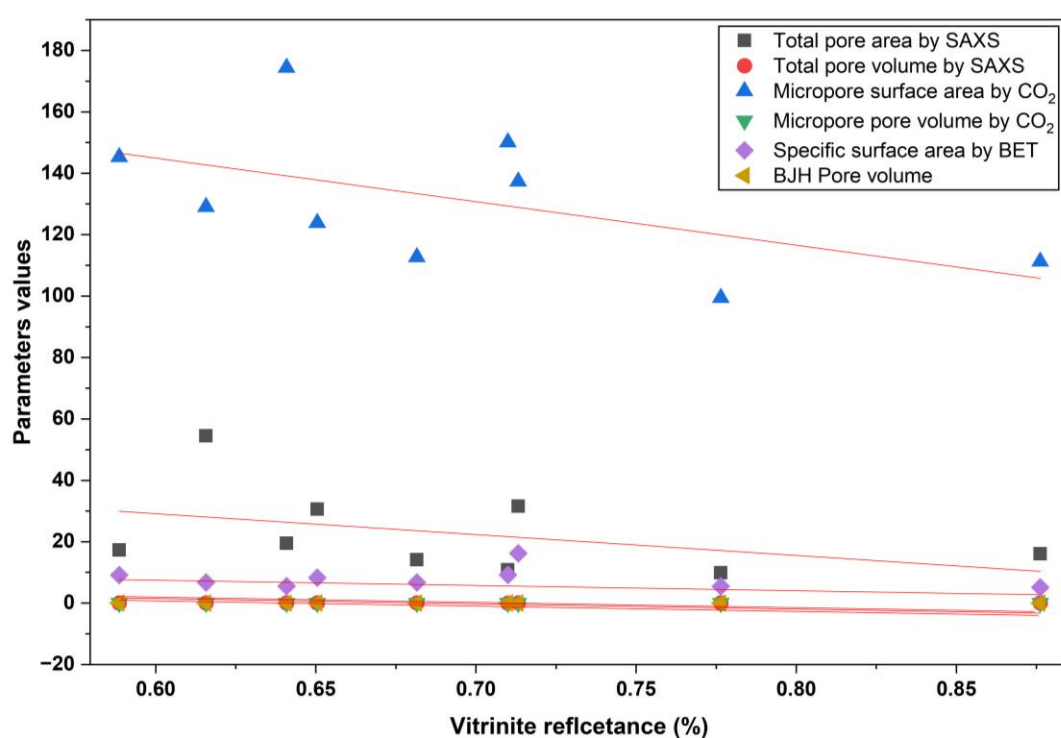


Figure 6.52 Relationship between pore parameter values and vitrinite reflectance values.

When the pore parameters obtained from SAXS and LPGA are plotted against the vitrinite reflectance data, it shows that as the vitrinite reflectance increase the pore parameters value decrease, as shown in Figure 6.52. This suggests that more mature coal has a lower surface area and pore volume for gas adsorption.

6.8.6 Mineral control on pore development

Mineral matter significantly influences pore development, distribution, and preservation in coal by controlling the mechanical behaviour of the coal matrix and the diagenetic evolution of pore systems. The type, abundance, and spatial arrangement of minerals determine whether pores are generated, preserved, or destroyed during burial and coalification (Gan et al., 1972; Clarkson & Bustin, 1999).

Clay minerals play a particularly important role in pore development. Common clay minerals in coal include kaolinite, illite, and mixed-layer illite–smectite. Kaolinite typically occurs as sheet-like or vermicular aggregates that can host abundant intercrystallite pores, contributing positively to mesopore and macropore development (Ward, 2002; Liu et al., 2017). In contrast, illite and illite–smectite often form fibrous or pore-bridging morphologies that reduce pore throat size and connectivity. During progressive diagenesis, the transformation of smectite to illite may further reduce porosity by promoting compaction and cementation, although localized microporosity may also be generated (Zhang et al., 2016).

Quartz and feldspar generally act as rigid framework minerals that help preserve pore structures by resisting mechanical compaction. Detrital quartz grains can maintain interparticle pores and cleat apertures, particularly in mineral-rich coals (Zhang et al., 2018). However, authigenic quartz cement may occlude pores and fractures, reducing effective porosity and permeability. Feldspar dissolution under acidic conditions can generate secondary porosity, but this process is typically less pronounced in coal than in clastic reservoirs (Zhang et al., 2016).

Carbonate minerals, such as calcite, dolomite, and siderite, have a complex influence on pore development. Early-stage carbonate cementation commonly fills primary pores and

cleats, thereby reducing porosity and permeability (Laubach et al., 1998). Conversely, late-stage dissolution of carbonates can generate secondary pores and enhance pore connectivity, particularly along fracture networks and cleat systems (Yan et al., 2019). The overall impact of carbonate minerals, therefore, depends on their timing relative to compaction and organic matter maturation.

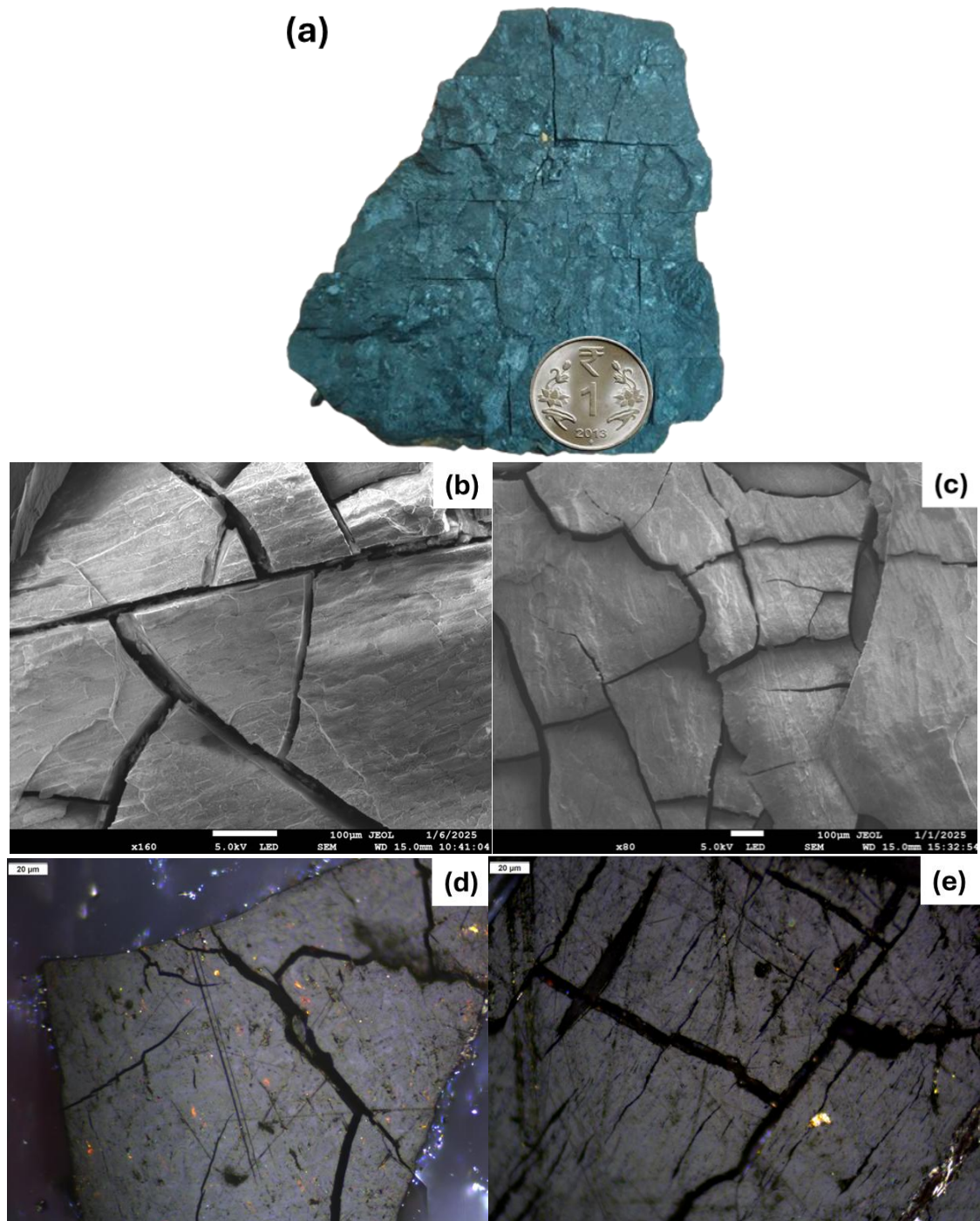
Pyrite and other sulphide minerals influence pore development mainly through their morphology and distribution. Framboidal pyrite may introduce localized microporosity at grain boundaries, whereas massive or euhedral pyrite commonly occupies pore space and reduces effective porosity (Yao et al., 2009). In addition, pyrite fills cracks and reduces permeability.

6.8.7 Fracture cleat and permeability implications

Fractures and cleats constitute the primary pathways for fluid flow in coal reservoirs and therefore exert a dominant control on permeability. Unlike pore systems, which mainly govern gas storage, permeability in coal is largely fracture-controlled and is strongly influenced by cleat geometry, connectivity, mineral infilling, and their relationship with coal fabric and composition (Laubach et al., 1998).

Cleats in coal are typically orthogonal fracture sets comprising face cleats and butt cleats (Figure 6.53a). Face cleats are generally continuous and well developed, while butt cleats terminate against face cleats and display more limited lateral persistence. Field observations and core-scale studies indicate that cleat spacing, aperture, and continuity vary significantly with coal rank, stress history, and lithological heterogeneity (Laubach et al., 1998; Moore, 2012). Natural fractures, including tectonic and shear-related fractures, may further enhance permeability when well-connected. However, they can

also act as sites for mineral precipitation and permeability reduction (Figure 6.53b, 6.53c and 6.53f).



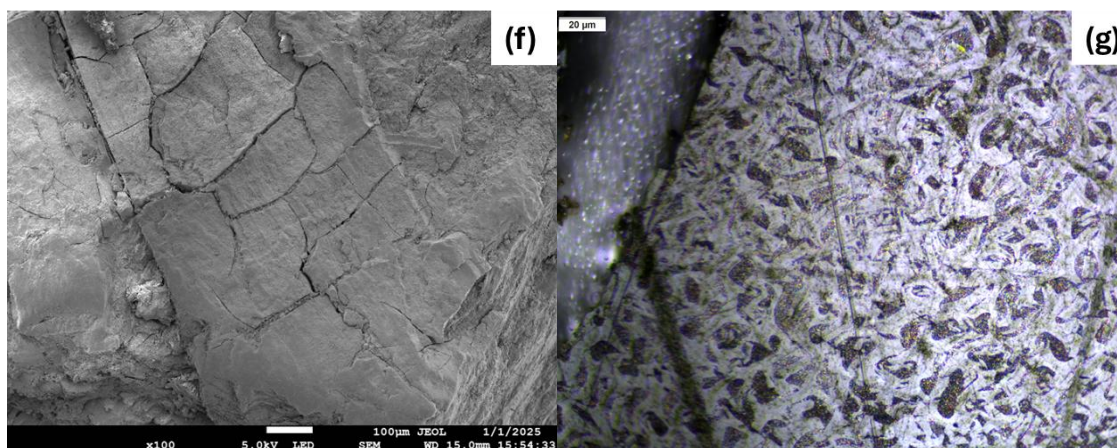


Figure 6.53 Cleats and microfracture present in these coals (a) cleats/microfractures in hand specimen, (b and c) cleats identified under the SEM, (d and e) cleats/microfracture identified under the petrography and (e and f) cleats/fractures and semifusinite grain filled with mineral matter and reducing permeability.

The development and distribution of cleats are closely linked to coal fabric, particularly microlithotype composition and banding characteristics. Vitrite and clarite-rich microlithotypes, which are dominated by vitrinite macerals, tend to be more brittle and thus favour the development of well-defined, continuous cleat networks (Figure 6.53d and 6.53e). In contrast, inertinite-rich microlithotypes and durite bands often exhibit reduced cleat density and poorer connectivity due to their higher mechanical strength and heterogeneous texture (Figure 6.53 g).

Mineral matter exerts a critical control on fracture effectiveness through mineral infilling and cementation. Cleats and fractures are commonly partially or filled with clay minerals, carbonates, quartz, or pyrite, as shown in Figure 6.53 (f and g), significantly reducing fracture aperture and connectivity (Laubach et al., 1998; Yao et al., 2009). Clay minerals are particularly detrimental to permeability due to their platy morphology, ductile behaviour, and tendency to swell in the presence of water. Kaolinite may line cleat surfaces and reduce effective aperture, while illite and mixed-layer illite–smectite can bridge cleat openings and occlude pore throats, leading to substantial permeability loss (Zhang et al., 2016).

6.8.8 Role of organic functional group in gas adsorption

Hydroxyl groups are among the most important functional groups in coal macromolecules, as they readily form hydrogen bonds with various hydrogen bond acceptors (Wang et al., 2017). The broad stretching vibration region in the FTIR spectrum, typically associated with hydroxyl groups, highlights their ability to form extensive hydrogen bonding networks within the coal structure. This is particularly significant because hydrogen bonding provides favourable sites for gas adsorption, thereby enhancing the overall sorption capacity of coal matrices (Kishor et al., 2023a; Kumar et al., 2021).

Beyond hydroxyl groups, several other oxygen-containing functional groups play critical roles in gas adsorption processes. For example, carboxyl ($-\text{COOH}$), carbonyl ($\text{C}=\text{O}$), and ether/ester ($\text{C}-\text{O}$) groups contribute polar sites that enhance interactions with adsorbates, particularly CO_2 and CH_4 . Jia et al. (2023), through a slit pore model analysis of different functional groups, demonstrated that the relative adsorption capacity for CH_4 follows the order: $\text{CH}_2-\text{CH}_3 > \text{CH}_3 > \text{O}-\text{CH}_3 > \text{COOH} > -\text{OH} > \text{C}=\text{O}$. This trend highlights the superior sorption potential of aliphatic functional groups compared to oxygen-containing moieties, though the latter still contribute significantly by providing polar sites. Complementary results were reported by Fu et al. (2021), who found that microwave irradiation decreases the maximum CH_4 adsorption capacity of coal. This reduction was attributed to a simultaneous decrease in adsorption pore volume and the degradation of functional groups such as $\text{C}=\text{O}$, $\text{C}-\text{O}$, and $-\text{COOH}$, confirming that these functional groups favour methane adsorption.

As all these functional groups are present in these coals, the resulting coals are favourable for gas adsorption.

6.9 CO₂ sequestration potential in Sohagpur coals

High-pressure CO₂ adsorption experiments on Sohagpur coals show adsorption volumes ranging from 17.024 to 54.075 cc/g, reflecting considerable variability in CO₂ storage capacity. These volumes indicate a moderate to high potential for CO₂ sequestration. This wide variability highlights the heterogeneity of the coal seam. It indicates that certain portions of the coal can serve as efficient CO₂ storage media, while other sections may contribute minimally due to structural or compositional constraints. The higher adsorption values observed, particularly the samples exceeding 50 cc/g, suggest the presence of a well-developed micropore system.

6.9.1 Mechanism of CO₂ storage

In Sohagpur coals, the adsorption onto microporous surfaces is consistent with trends observed in these rank coals. Micropores (<2 nm) provide extremely high specific surface areas that facilitate the physical adsorption of CO₂ molecules through van der Waals interactions, dipole–quadrupole interactions, and, in some cases, oxygen-containing functional groups. Mesopores (2–50 nm) and macropores (>50 nm) contribute less to total adsorption but are crucial for multilayer adsorption and gas transport, allowing CO₂ molecules to access the microporous domains efficiently (Mukherjee and Misra 2018). Additionally, cleat and fracture networks serve as conduits for gas migration, particularly important for injection and field-scale storage, though they contribute minimally to the total adsorption volume.

6.9.2 Interpretation of high-pressure CO₂ adsorption results

Coals and organic-rich shales commonly exhibit a Type I adsorption isotherm under high-pressure CO₂ conditions, as documented by several previous studies (Bakshi et al., 2020; Kumar, 2023; Shukla et al., 2025; Tambaria et al., 2023). A Type I isotherm is

characteristic of microporous solids, in which adsorption is dominated by rapid filling of micropores at low to moderate pressures.

In contrast to this typical behaviour, the CO₂ adsorption isotherm for Sohagpur coal deviates from the expected Type I profile, suggesting that adsorption mechanisms in these coals may be more complex. Such deviations imply that the pore system in Sohagpur coal is not exclusively micropore-dominated but also contains a significant proportion of mesopores and macropores, which become increasingly active at higher pressures. This behaviour has important implications for CO₂ storage capacity, as it suggests that storage capacity may continue to increase beyond the pressure limit.

6.9.3 Pore-Scale Controls on CO₂ Uptake

The efficiency of CO₂ sequestration in Sohagpur coals is strongly controlled by pore size distribution and connectivity, which determine both the total storage capacity and the accessibility of adsorption sites. Micropores (<2 nm) provide most adsorption sites due to their high surface area, but their contribution is strongly dependent on connectivity to mesopores and fractures that facilitate gas transport (Bae and Bhatia 2006; Li et al., 2010). Samples exhibiting the highest adsorption volumes possess a well-developed micropore network with sufficient connectivity, whereas lower uptake corresponds to samples with isolated micropores, collapsed pore structures, or mineral blockage that prevents CO₂ access. Mesopores contribute to multilayer adsorption and act as storage intermediaries between micropores and macropores, which primarily provide pathways for gas movement but contribute minimally to adsorption (Laxminarayan and Crosdale 1999).

6.9.4 Coal composition effect on CO₂ sequestration

Vitrinite-rich layers, characterized by their brittle, planar structure, tend to generate micropores and mesopores more efficiently than inertinite-rich or durite layers, which are mechanically stronger and often less porous. Banding patterns influence pore

connectivity: continuous vitrinite bands allow uniform gas penetration, while inertinite- or clay-rich layers act as barriers, limiting access to micropores in underlying layers (Shukla et al., 2025). Additionally, mineral matter can occlude pore throats, particularly clay minerals such as illite or mixed-layer illite-smectite, thereby reducing effective storage volume. The high-pressure adsorption data reflect these influences, as samples with similar rank may exhibit markedly different CO₂ uptake depending on microlithotype and pore connectivity (Krooss et al., 2002; Premlall et al., 2014).

6.9.5 Microlithotype scale effects on CO₂ sequestration

Microlithotype distribution strongly controls CO₂ uptake in coals. In Sohagpur coals, vitrite and inertite are dominant; vitrite can form micropores, whereas inertinite-rich and durite bands are mechanically stronger, less porous, and provide fewer adsorption sites (Krooss et al., 2002; Gensterblum et al., 2013; Premlall et al., 2014). Banding patterns influence gas accessibility by allowing CO₂ to penetrate continuous vitrinite-rich layers while restricting flow in clay or inertinite-rich bands. This heterogeneity results in highly variable adsorption volumes, as reflected in the experimental data ranging from 17.024 to 54.075 cc/g.

6.9.6 Uncertainties, limitations, and methodological considerations

High-pressure adsorption experiments provide valuable insights but are subject to uncertainties and limitations that must be carefully considered. Sample heterogeneity, small sample size, and preparation methods can introduce significant variability in measured adsorption volumes. Laboratory conditions cannot fully replicate in-situ stress, temperature, and pore connectivity, and coal swelling under CO₂ exposure may alter cleat apertures, further complicating extrapolation to field conditions. The high-pressure CO₂ adsorption experiments were conducted solely to determine the adsorption capacity of the coal samples. Since CO₂ induced coal swelling is a time-dependent process governed

by the diffusion of CO₂ into the coal matrix over periods of days to weeks, and no long-term exposure or dimensional change measurements were performed, the swelling behaviour of the studied coals cannot be evaluated from the present experiments.

6.10 Coalification Trend

Coalification is a complex and progressive process that begins with the accumulation of peat and culminates in the advanced maturation or metamorphism of organic matter to form meta-anthracite, with sub-bituminous, bituminous, and anthracite coals representing intermediate stages. The transformation of plant-derived organic matter into coal occurs through two principal stages: peatification and coalification. Peatification represents the initial stage, during which vegetal material is biochemically altered over geological time to form peat, and is therefore commonly referred to as biochemical coalification. Depending on the oxygen availability, biochemical coalification can be further subdivided into humification, which occurs under aerobic conditions, and gelification, which occurs in anaerobic environments. These processes control the preservation, degradation, and transformation of plant tissues within peat-forming swamps. Following peat formation, continued burial and increasing temperature and pressure lead to the progressive transformation of peat into successive coal ranks, namely lignite, sub-bituminous coal, bituminous coal, semi-anthracite, and anthracite. This stage, referred to as coalification, is dominated by geochemical and thermal processes rather than biological activity. The coalification process is primarily influenced by factors such as bacterial activity during the early stages, burial depth, fluctuations of ground water table, and pH conditions in peat-forming environments (Stach et al., 1982).

The process of coalification is commonly divided into two main phases: biochemical coalification and geochemical coalification (Teichmüller & Teichmüller, 1979). Biochemical coalification occurs during the early stages of peat formation. It is primarily

controlled by the activity of microorganisms, including bacteria and fungi, which facilitate the decomposition of plant material and the formation of humic substances.

Geochemical coalification dominates at deeper burial and is governed by physical and thermal factors, including lithostatic pressure, basin subsidence, tectonic activity, the geothermal gradient, and the influence of external heat sources. Among these factors, a sustained increase in temperature over geological time is considered the principal driver of coalification (Stach et al., 1982). Throughout this process, organic matter undergoes a series of physical and chemical transformations, including dehydration, bituminization, debituminization, and ultimately graphitization. These transformations result in systematic changes in the chemical composition, molecular structure, and physical properties of coal, reflecting increasing rank and maturity (Flores, 2014).

During the coalification process, methane (CH_4) and carbon monoxide (CO) are initially generated in peat as biogenic gases under low-temperature, microbially mediated conditions. As coalification progresses and moisture content decreases, the expulsion of these gases becomes increasingly restricted. At more advanced stages of coalification, methane is generated again, this time as catagenic methane, resulting from the thermal cracking of organic matter under elevated temperature and pressure conditions (Kopp et al., 2000).

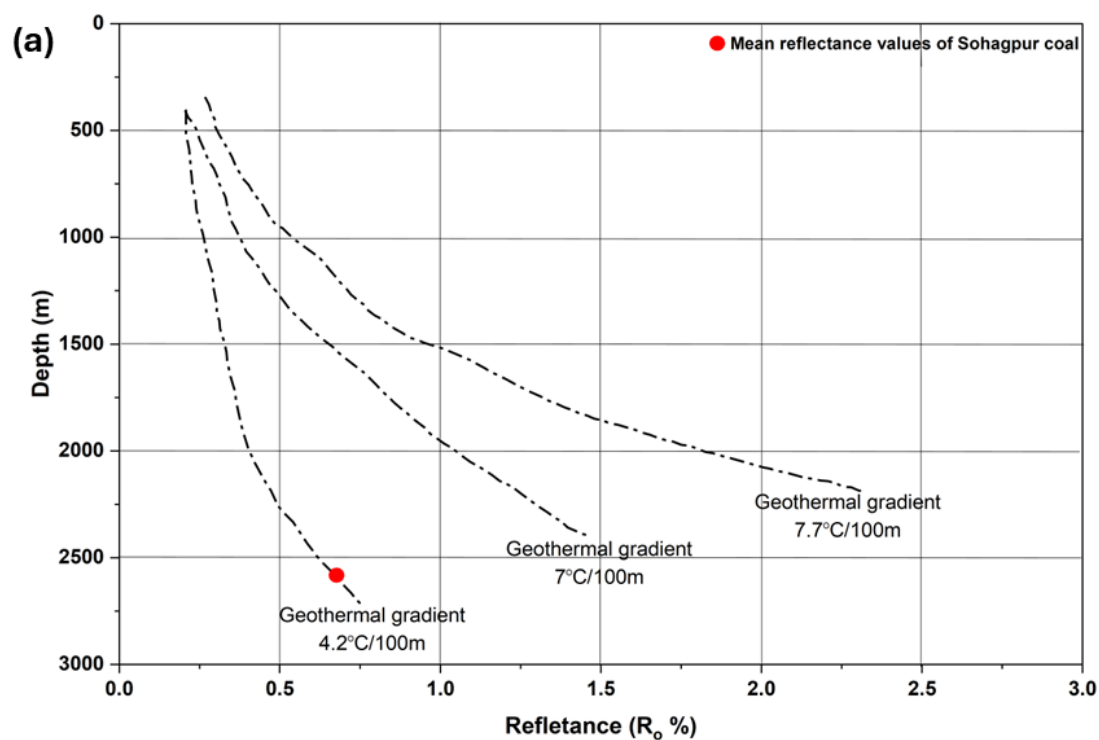
Concomitant with these gas generation processes, significant chemical transformations occur within the coal matrix. Heteroatom-bearing functional groups progressively break down, hydrogen-rich aliphatic side chains are degraded, and the degree of aromaticity increases as coal rank advances (Teichmüller & Teichmüller, 1979; Yao et al., 2011). Fourier Transform Infrared (FTIR) analysis of the studied coals supports this interpretation. Absorption bands observed near 2950 cm^{-1} correspond to aliphatic CH_3 stretching vibrations, while peaks at 2920 cm^{-1} and 2850 cm^{-1} are attributed to aliphatic

CH, CH₂, and CH₃ groups. The band near 1450 cm⁻¹ represents CH₂ and CH₃ deformation modes associated with aromatic ring structures. Notably, the FTIR spectra show higher transmittance intensities for aliphatic functional group peaks compared to those associated with aromatic hydrocarbons. This dominance of aliphatic signatures indicates a relatively lower degree of thermal maturity for the studied coals, consistent with their medium-rank classification (Suggate & Dickinson, 2004; Presswood et al., 2016).

During coalification, plant-derived organic matter undergoes progressive geochemical alteration under the combined influence of increasing temperature and pressure over extended geological timescales. As burial depth increases, thermal maturity and therefore the rank of coal systematically increase. Among the controlling factors, temperature is considered the most critical variable. Localized heat sources, such as nearby volcanic or igneous activity, can induce coalification at comparatively shallow depths and younger geological ages. However, in most sedimentary basins, coal maturation is governed by the regional geothermal gradient of the Earth's crust, which averages approximately 25 °C per 1000 m of burial depth. Under such conditions, bituminous typically forms within a temperature range of 100–150 °C (Stephenson, 2013).

Coal rank shows a strong correlation with the optical properties of macerals, particularly their reflectance values. The mean maximum reflectance of vitrinite, liptinite, and inertinite increases systematically with coal rank, reflecting progressive structural ordering and chemical maturation (Smith & Cook, 1980). Among these, vitrinite reflectance is the most widely used and reliable indicator of coal rank, organic matter diagenesis, and hydrocarbon maturation (Middleton, 1982; Suggate, 1998; Vuković et al., 2016). Measurements of vitrinite reflectance provide a quantitative basis for reconstructing thermal history and coalification pathways.

Knowledge of coal rank derived from vitrinite reflectance data is also fundamental for estimating paleotemperatures, quantifying eroded overburden thickness, and constraining the timing of tectonic deformation relative to coalification processes (International Committee for Coal and Organic Petrology, 1998). Deviations from expected vitrinite reflectance trends may indicate anomalous thermal events, such as exposure to elevated temperatures caused by igneous intrusions, sudden tectonic movements, or abnormal heat flow from the basement (Chandra & Chakrabarti, 1989; Jiang et al., 2011).



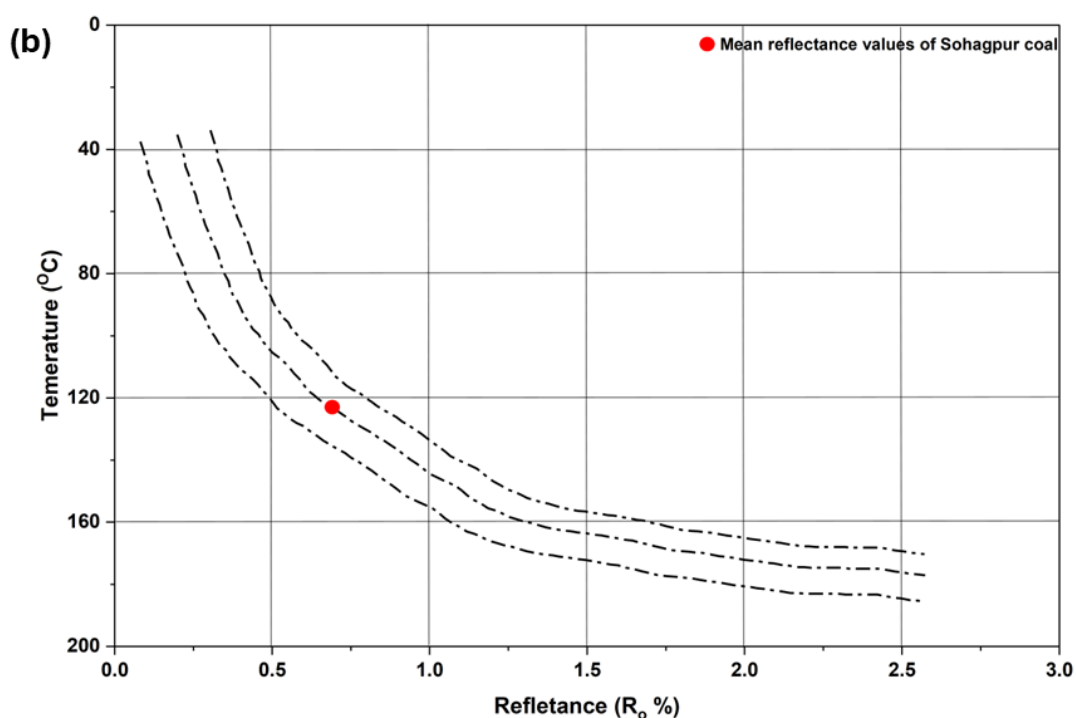


Figure 6.54 Relationship between vitrinite reflectance, depth and rock temperature for the coals of Sohagpur coalfield (after Teichmüller, 1979) (a) R_o versus depth, and (b) R_o versus temperature.

Assuming a relatively uniform geothermal gradient of approximately $40^{\circ}\text{C}/\text{km}$ for the Gondwana basins and an average heat flow of $74 \text{ mW}/\text{m}^2$ (Pandey & Negi, 1995), the burial depth of the Sohagpur coalfield can be estimated using vitrinite reflectance data. Based on a mean vitrinite reflectance value of 0.69%, the maximum burial depth of the Sohagpur coals is inferred to have been in the range of 2500–2700 m, as illustrated in Figure 6.54a. Correspondingly, the coalification temperature for the Sohagpur coals is estimated to lie between 120 and 130°C , as shown in Figure 6.54b. These temperature and depth estimates are consistent with the thermal conditions typically associated with medium-rank (bituminous) coal formation in Gondwana sedimentary basins and support the interpretation of a normal burial-driven coalification history for the Sohagpur coalfield.

6.11 Classification of codes and Utilization potential of Sohagpur coals

Coal has been classified using various schemes to predict the behaviour of unfamiliar coals and to facilitate the selection of appropriate coal types for specific industrial and energy applications. However, the inherently heterogeneous nature of coal, resulting from variations in organic constituents, mineral matter, and coalification history, makes it difficult to develop a single, simple classification system that can provide a globally comparable assessment of coal characteristics. Numerous classification schemes have been proposed over time, but most have been limited in scope, as developed based on coals from specific regions or restricted rank ranges. Consequently, these early classification systems were not universally applicable and failed to gain global acceptance.

To address these limitations, Alpern and Lemos de Sousa (1987) proposed a comprehensive classification framework, later adopted and recommended by the International Committee for Coal and Organic Petrology (ICCP). This system applies to both Laurasian (North Atlantic) and Gondwana coals and provides a standardized approach based on three fundamental parameters: rank, type, and grade. Coal rank represents the degree of coalification and is quantified by vitrinite reflectance. Coal type is determined by maceral composition, reflecting the organic matter assemblage and depositional environment, whereas coal grade is defined by mineral matter or ash content. This multidimensional classification provides a robust and internationally comparable method for characterizing coal properties across diverse geological settings.

Early attempts at coal classification relied primarily on visual appearance and combustion behaviour (Krishnan, 1940). Coals with brown to dark brown colour, visible woody textures, and high moisture content were classified as lignite or brown coal. Coals

exhibiting a black colour, ease of ignition, smoky flame, and agglutinating behaviour upon heating were designated as bituminous coal. In contrast, anthracite was identified by its black, hard, and lustrous appearance, difficulty in ignition, and smokeless combustion. Based on these criteria, the coals from the present study area are classified as bituminous in rank.

Subsequent classification approaches incorporated geochemical parameters, including ultimate and proximate analyses, to provide a more quantitative basis for coal classification. Regnault (1840) pioneered the use of elemental and compositional data for this purpose, which was later refined and expanded by several researchers, notably Parr (1922). These geochemical-based schemes improved objectivity but still exhibited regional and rank-related limitations, reinforcing the need for a globally standardized classification framework.

Several limitations of coal classification are due to the complex and heterogeneous nature of coal. Most classification schemes rely on a limited set of parameters such as vitrinite reflectance, volatile matter, or ash yield. While effective for assessing thermal maturity, these parameters do not adequately capture variations in maceral composition, microlithotype distribution, pore structure, or fracture development, all of which strongly influence coal behaviour and reservoir properties.

Another limitation is scale dependency. Coal classifications are typically based on small laboratory samples that may not represent vertical and lateral heterogeneity within coal seams. Variations in banding, mineral infilling, and cleat development are often averaged out, leading to oversimplified interpretations.

6.11.1 International Organization for Standardization (ISO) classification scheme

The International Organization for Standardization (ISO) has developed a widely accepted coal classification scheme based on random vitrinite reflectance (R_o %), proximate analysis parameters, and petrographic composition, specifically the vitrinite content expressed on a mineral-matter-free (mmf) volumetric basis (ISO, 2005). This multidimensional approach integrates optical, chemical, and petrographic properties to provide a robust and standardized framework for coal classification. Recognizing the need for broader applicability, the ISO revised this system in 2018 through ISO 11760:2018, extending its suitability to coals across the full rank spectrum. However, careful consideration is required when applying this scheme to coals of similar rank or composition, as subtle differences in petrographic characteristics may influence classification outcomes.

Under the ISO classification system, as shown in Tables 6.13 to 6.18, coal rank is broadly divided into three categories based primarily on vitrinite reflectance and inherent moisture content. Low-rank coals, comprising lignite and sub-bituminous coal, are characterized by bed moisture contents of $\leq 75\%$ and R_o values below 0.5%. Medium-rank coals, which include bituminous coals, exhibit vitrinite reflectance values ranging from 0.5% to less than 2.0%. High-rank coals, represented by anthracites, display random vitrinite reflectance values between 2.0% and 6.0%, inclusive of the lower limit. This reflectance-based ranking provides a reliable measure of coalification and thermal maturity.

Table 6.13 Definition of broad rank categories: low, medium, and high rank

Rank	Definition
Low rank A (lignite and sub-bituminous coals)	bed moisture $\leq 75\%$ and $R_o\% < 0.5\%$
Medium rank A	$0.5\% \leq R_o\% < 2.0\%$

(bituminous coals) High rank B (anthracites)	$2.0 \% \leq R_o \% < 6.0 \%$ (or $R_{\max} \% < 8.0 \%$)
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Table 6.14 Subcategories of low-rank coals

Sub-category	Description
Low-rank C (lignite C)	$R_o \% < 0.4 \%$ and bed moisture $> 35 \%$ and $< 75 \%$, ash-free basis
Low-rank B (lignite B)	$R_o \% < 0.4 \%$ and bed moisture $\leq 35 \%$, ash-free basis
Low-rank A (subbituminous coal)	$0.4 \% \leq R_o \% < 0.5 \%$

Table 6.15 Sub-categories for medium-rank coals

Sub-category	Description
Medium rank D (bituminous D)	$0.5 \% \leq R_o \% < 0.6 \%$
Medium rank C (bituminous C)	$0.6 \% \leq R_o \% < 1.0 \%$
Medium rank B (bituminous B)	$1.0 \% \leq R_o \% < 1.4 \%$
Medium rank A (bituminous A)	$1.4 \% \leq R_o \% < 2.0 \%$

Table 6.16 Sub-categories for high-rank coals (anthracites)

Sub-category	Description
High rank C (anthracite C)	$2.0 \% \leq R_o \% < 3.0 \%$
High rank B (anthracite B)	$3.0 \% \leq R_o \% < 4.0 \%$
High rank A (anthracite A)	$4.0 \% \leq R_o \% < 6.0 \%$ (or $R_{\max} \% < 8.0 \%$)

Table 6.17 Classification by the petrographic composition

Vitrinite content% by volume, mineral-free	Vitrinite class category
< 40	Low vitrinite
≥ 40 and < 60	Medium vitrinite
≥ 60 and < 80	Moderately high vitrinite
≥ 80	High vitrinite

Table 6.18 Ash yield classification

Ash yield%	Ash class category
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by mass on a dry basis	
< 5	Very low ash
≥ 5 and < 10	Low ash
≥ 10 and < 20	Medium ash
≥ 20 and < 30	Moderately high ash
≥ 30 and < 50	High ash

6.11.2 Bureau of Indian Standards classification

According to the classification and codification of Indian coals and lignite as outlined in the second revision of IS: 770 (2013), coal rank is determined using a combination of random vitrinite reflectance values, volatile matter content on a dry, mineral-matter-free (dmf) basis, and elemental (ultimate) composition expressed on a dmf basis. This integrated approach incorporates petrological and geochemical parameters to provide a comprehensive and standardized framework for classifying Indian coals and lignites across different rank categories (BIS 2013). The classification schemes based on vitrinite reflectance, volatile matter (dmf basis), and elemental composition (dmf basis) are listed in Tables 6.19, 6.20, and 6.21, respectively.

Table 6.19 Composition of Indian coals/lignite on vitrinite reflectance values.

Mean reflectance (R_o %)	Type of coal
≥0.28-0.38	Lignite
>0.38-0.55	Sub-bituminous
>0.55-0.64	High volatile non- caking bituminous
≥0.64-0.84	High volatile caking bituminous B coal
≥0.85-0.94	High volatile caking bituminous A coal
≥0.95-1.19	Medium volatile caking bituminous coal
≥1.20-1.39	Medium to low volatile caking bituminous coal
≥1.40-1.79	Low-volatile caking bituminous coal
≥1.80-1.99	Low-volatile non-caking bituminous coal
≥2.00-2.5	Semi-anthracite coal

Table 6.20 Composition of Indian coals/lignite on volatile matter values (dmf basis).

Volatile matter % dmf basis	Type of coal
>45	Lignite/ Tertiary high sulphur coals
>37-45	Sub-bituminous/ Tertiary
>37-43	Bituminous high volatile B/ tertiary coals
>32-37	Bituminous high volatile A
>28-32	Bituminous medium volatile

>22-28	Bituminous medium volatile
>15-22	Bituminous low volatile
>10-15	Bituminous very low volatile
<10	Semi-anthracite coal

Table 6.21 Composition of Indian coals/lignite on dmf basis.

Type	Carbon %	Hydrogen %
Lignite	67-72	4.8-5.5
Sub-bituminous (high volatile)	≥75-78	4.5-5.0
Bituminous (non-caking)	>78-83	4.5-5.5
Bituminous high volatile (caking)	>83-86	5.0-5.8
Bituminous high to medium volatile (caking)	>86-91	4.5-5.1
Bituminous (low volatile, non-caking)	>91-92	4.2-4.8
Semi anthracite	>92-93.5	3.7-4.5

6.11.3 Classification of codes for coals of the Sohagpur coalfield

Coal is categorized for multiple purposes, including predicting the behaviour of unfamiliar coal and selecting the most suitable coal for optimal industrial use. Various researchers have periodically presented multiple classification strategies for coal based on its diverse uses. The coals of the Sohagpur coalfield have been categorized using several established schemes, based on petrographic and geochemical characteristics.

6.11.3.1 Based on Fraser classification

The classification of coal into distinct ranks has long been a central focus in coal geology and utilization studies, as the rank determines its industrial applicability, combustion behaviour, and carbonization potential. One of the earliest systematic approaches was proposed by Fraser (1877), who introduced the concept of the fuel ratio (FR) as a fundamental parameter for coal classification. The fuel ratio is defined as the ratio of fixed carbon to volatile matter, expressed as:

$$\text{Fuel Ratio} = \frac{\text{Fixed Carbon}}{\text{Volatile Matter}}$$

This simple but effective parameter provides insight into the degree of coalification and thermal maturity. Coals with higher proportions of fixed carbon relative to volatile matter are more mature and correspond to higher ranks. Conversely, coals with higher volatile matter reflect lower ranks.

Based on fuel ratio values, Fraser (1877) classified coal into four major categories: Bituminous (FR = 0–5), Semi-bituminous (FR = 5–8), Semi-anthracite (FR = 8–12), and Anthracite (FR = 12–100). This classification demonstrates a progressive increase in fixed carbon and a corresponding decrease in volatile matter, reflecting the natural progression of coalification from lower to higher ranks. Although relatively straightforward, Fraser’s classification laid the foundation for subsequent rank schemes and remains useful for preliminary assessments of coal properties.

The Sohagpur coalfield, situated within the Son Valley Gondwana Basin, provides an excellent example of applying Fraser’s classification. Proximate analyses of coal samples from this coalfield reveal fuel ratio values ranging from 1.74 to 2.34 (Table 6.22). These values clearly fall within the bituminous range (FR = 0–5).

Table 6.22 Fuel ratio values of Sohagpur coals.

Sample Name	VM	FC	Fuel Ratio (FR)
Sharda	25.44	52.15	2.05
Dhanpuri	21.86	51.20	2.34
Rajendra	26.20	48.79	1.86
Khairaha VI	25.94	45.71	1.76
Khairaha VII	24.84	49.93	2.01
Damini VI (1st Site)	20.47	41.83	2.04
Damini VI (2nd Site)	22.57	45.37	2.01
Damini V	24.10	41.88	1.74
Bangwar	20.96	38.80	1.85
Amalai	24.10	49.71	2.06

6.11.3.2 Based on Falcon classification

The classification of coal based on maceral composition and rank is a crucial step in understanding its origin, potential for utilization, and industrial significance. While numerous classification schemes have been proposed worldwide, the system initially developed by Alpern (1981) and later modified by Falcon (1986) has been widely recognized for the integration of reactive maceral proportions and vitrinite reflectance (Ro) values. This dual-parameter approach not only reflects the petrographic makeup of coal but also incorporates its maturity, thereby offering a more holistic framework for classification.

In this system, coals are first categorized into types based on the relative proportions of reactive macerals (vitrinite and liptinite) versus inert macerals (inertinite). A higher proportion of reactive macerals generally indicates greater coking potential, higher hydrogen content, and suitability for processes such as liquefaction and gasification. The second criterion is the coal rank, which is primarily assessed using vitrinite reflectance (Ro). This parameter reflects the degree of coalification and is directly related to the thermal maturity of the coal-bearing strata. Falcon's modification refined the ranges for maceral types and vitrinite reflectance categories, allowing for more accurate placement of coals within the classification framework.

Type- Intermediate

Rank- Hypo Bituminous

When applying this scheme to the Sohagpur coalfield, the coals show a distinct placement within the intermediate type of category. The reactive maceral content of Sohagpur coals ranges between 46.55% and 63.78%, which fits well within Falcon's defined limits for intermediate-type coals. This suggests that the coals contain a balanced mixture of reactive macerals and inertinite, thereby possessing moderate reactivity. Such a composition makes them versatile for application, as they can be used for both energy

generation and certain metallurgical processes, though with limitations compared to high-reactivity or coking coals. The rank assessment, based on vitrinite reflectance, further places the Sohagpur coals in the Hypo-bituminous category. The mean R_o values range from 0.5 to 1.0, which corresponds to low- to medium-rank bituminous coal. This indicates that the coals have undergone moderate coalification, reflecting their geological history within the Gondwana basins.

6.11.3.3 Based on ISO classification

According to the ISO coal classification scheme, coal rank and type are determined using a combination of random vitrinite reflectance (R_o %), vitrinite content expressed on a mineral-matter-free (mmf) basis, and ash yield measured on a dry mass basis. These parameters collectively provide a standardized assessment of the degree of coalification, organic composition, and mineral matter content.

For the Sohagpur coal samples, the average random vitrinite reflectance is 0.69%, indicating a medium level of thermal maturity. The vitrinite content averages 43.41 vol.% (mmf basis), suggesting a medium class of vitrinite macerals, while the ash yield is 20.58 wt.%, reflecting a moderately high mineral matter content. When evaluated together within the ISO classification framework, these values classify the Sohagpur coals as medium-rank C (bituminous C).

Rank subcategory- Medium rank C (Bituminous C)

Vitrinite class category- Medium class

Ash yield- Moderately high ash

6.11.3.4 Based on the BIS classification

According to the BIS coal classification scheme, coal rank and type are determined using a combination of random vitrinite reflectance (R_o %), volatile matter dmf basis, and carbon and hydrogen composition on a dmf basis. These parameters collectively provide

a standardized assessment of coalification. According to BIS (2013), coals of the Sohagpur coalfield are classified as follows-

Class- Bituminous

Type- Highly volatile

Nature- Caking

6.11.3.5 Based on West German (DIN) and North American (ASTM) classification

The West German (DIN) and North American ASTM coal classification schemes, as described by Stach et al. (1982), utilize volatile matter content on a dry, ash-free (daf) basis and random vitrinite reflectance (R_o %) as the principal parameters for coal rank classification. According to the West German (DIN) system, the Sohagpur coals fall within the rank range of Gas coal to Gas-Flamm coal (Steinkohle), as illustrated in Figure 6.55. This classification reflects their relatively high volatile matter content and gas-generating characteristics. Consistently, the random vitrinite reflectance values of the Sohagpur coal samples range from 0.59% to 0.88%, placing these coals within the high-volatile bituminous rank under both the DIN and ASTM classification systems. The values of volatile matter and reflectance, based on DIN and ASTM classifications confirms the medium-rank maturity of the Sohagpur coals.

Rank		Reff Rm Oil	V.M. d.a.f. %	Carbon d.a.f. %	Bed Moisture	Cal. Value Btu/lb (Kcal/kg)	Rank Ref oil	Rank VM daf%	Applicability of different rank parameter		
German	USA										
Torf	Peat	0.2	68								
Welch	Lignite	0.3	60	75							
Matt	Sub C Bitu B	0.4	52			7200 (4000)					
Glanz		0.5	48	25		9900 (5500)					
Flam	A	0.6	44								
	C	0.7	40	8-10		12600 (7000)					
Gas flamm	B	0.8									
Gas	A	1.0	32								
Fett	Mid. Volt. Bituminous	1.2	28			15500 (8650)					
Ess	Low Volt. Bituminous	1.4	24								
Marger	Semi	1.6	16								
Anth.	Anthracite	2.0	12								
Meta		3.0	8								
Anth.	Anthracite	4.0	4								
Meta Anth.	Meta Anth.										

Figure 6.55 Rank of coals from Sohagpur coalfield, based on Vitrinite reflectance (R_o %) and V.M. (daf basis) in the scheme representing the different stages of coalification according to North American (ASTM) and West German (DIN) classification and their distinction based on different physical and chemical parameters. The last column shows the applicability of various rank parameters to different coalification stages (Stach et al. 1982).

6.11.4 Industrial utilization potential of Sohagpur coals

Coal utilization studies rely heavily on petrographic and geochemical classification models that link maceral composition and chemical properties to industrial suitability. One widely applied model is that of Falcon (1986), originally proposed for South African coals, which employs reactive maceral percentages and vitrinite reflectance values (R_o %) as the primary criteria. These parameters provide a robust framework for categorizing coal into groups based on their metallurgical and industrial potential. According to Falcon's model, coals with higher proportions of reactive macerals and moderate vitrinite reflectance values are placed within the blend coking coal category, which denotes suitability for use in metallurgical coke production, either independently or in blends with prime coking coals.

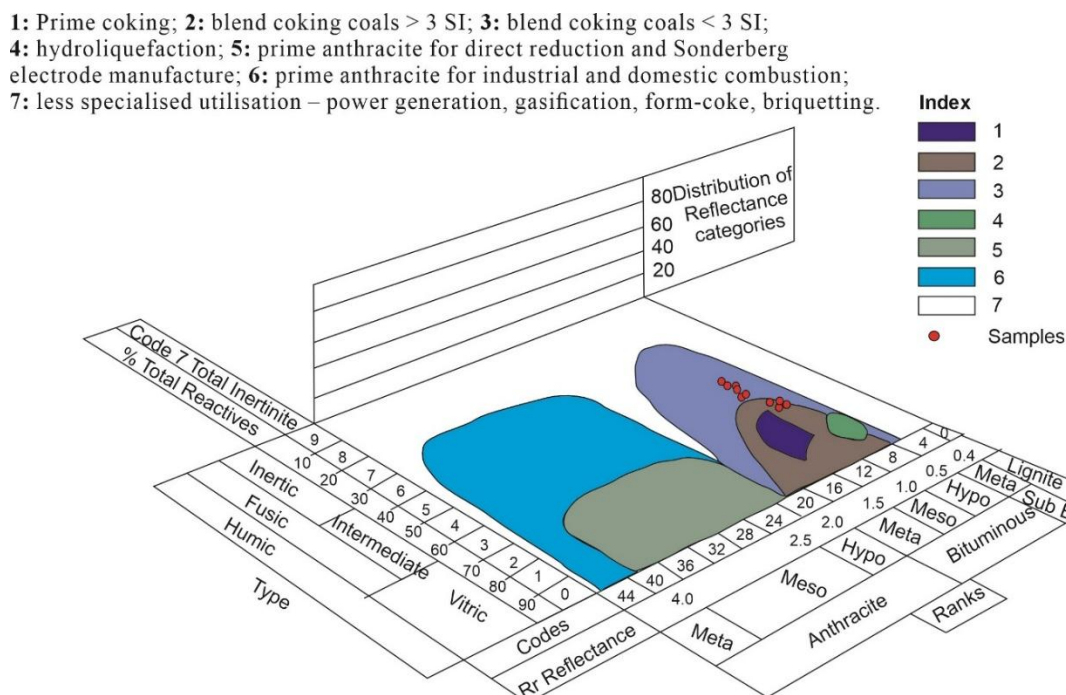


Figure 6.56 Industrial utilization classification of Sohagpur coals based on the reactive macerals (vitrinite + liptinite) and Vitrinite reflectance (Modified after Falcon 1986).

When the Sohagpur coal samples are assessed against Falcon’s model, the results indicate that most samples fall within the blend coking coal < 3 SI category, while a smaller subset plots in the blend coking coal > 3 SI field. The “SI” here refers to the Swelling Index, a measure of coal’s caking ability during carbonization. The < 3 SI group suggests weaker coking characteristics, whereas > 3 SI implies comparatively better swelling properties. This variation is consistent with the mixed petrographic makeup of Sohagpur coals, which contain moderate amounts of reactive macerals but are not highly enriched in vitrinite. Such classification highlights their potential for use in coke blends (Figure 6.56).

Table 6.23 Reactive macerals (vol.%), R_o %, C %, and H % on dry ash-free values of Sohagpur coals.

Sample Name	Reactive macerals (vol. %)	R _o %	C % (daf)	H % (daf)
Sharda	60.18	0.71	84.29	5.16
Dhanpuri	51.93	0.78	81.93	4.74
Rajendra	63.63	0.62	81.54	4.51
Khairaha VI	63.78	0.59	79.99	4.34
Khairaha VII	50.24	0.64	80.50	3.97
Damini VI (1st Site)	63.27	0.87	78.91	4.19
Damini VI (2nd Site)	54.36	0.88	80.03	4.92
Damini V	46.55	0.68	78.48	4.42

Bangwar	52.87	0.64	71.47	4.49
Amalai	46.91	0.71	81.67	4.34

To provide a more detailed evaluation of industrial applicability, the Sohagpur coals were also examined using the model proposed by Snyman (1989). Unlike Falcon's maceral-reflectance approach, Snyman's classification is based on elemental composition, specifically the proportions of carbon and hydrogen on a dry ash-free (daf) basis obtained from ultimate analysis. This model is particularly valuable in determining whether coals are best suited for producing char or for gasification.

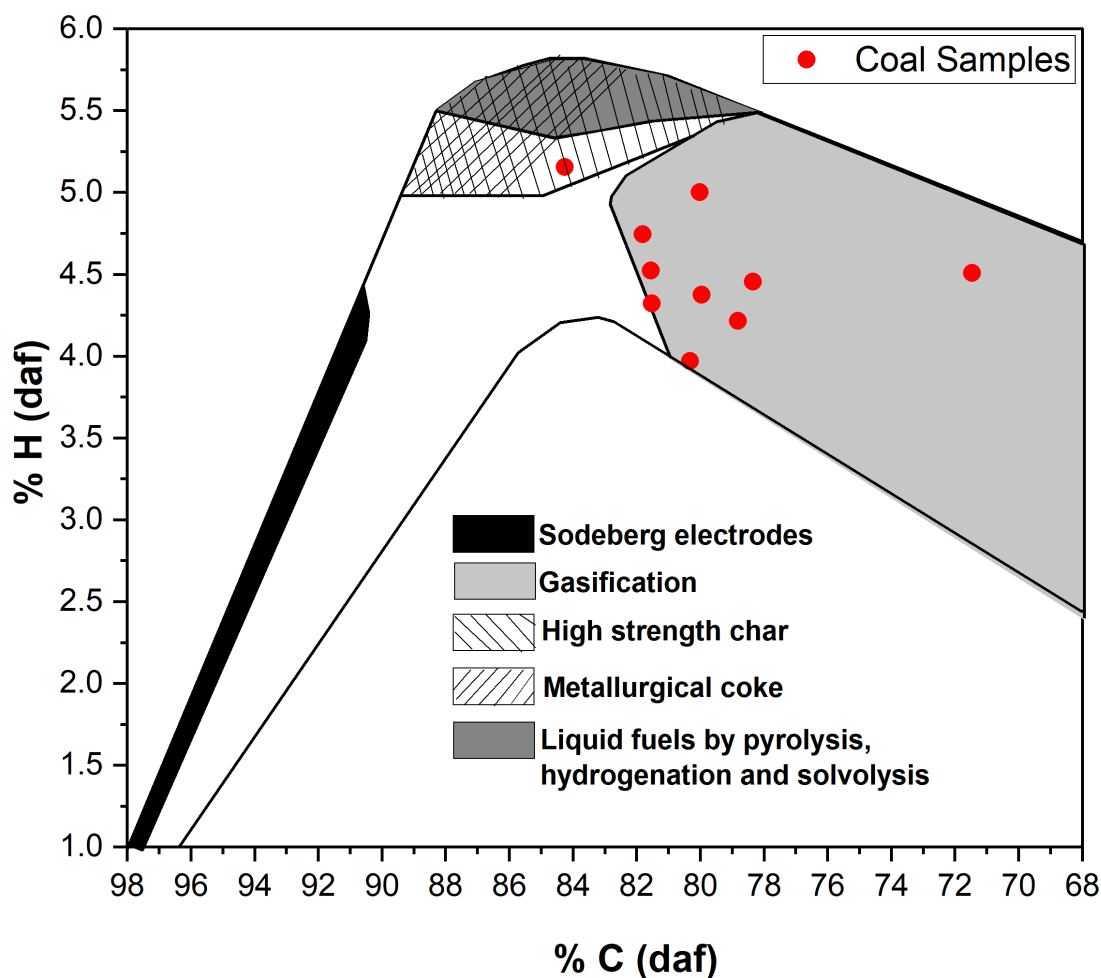


Figure 6.57 Seyler diagram modified by Snyman (1989) for South African coals has been modified for the Sohagpur coal samples.

In the present study, the carbon (daf) content of Sohagpur coals ranges from 71.47% to 84.29%, while the hydrogen (daf) content ranges from 3.97% to 5.16% (Table 6.23). When plotted on Snyman's classification diagram (Figure 6.57), the samples show

distinct groupings. The Sharda coal seam falls within the field indicative of high-strength char production, reflecting its higher carbon content and more favourable hydrogen composition. This finding implies that the Sharda seam coals possess the structural integrity required to produce chars with superior strength, making them valuable for metallurgical processes such as ferroalloy smelting or blast furnace applications.

In contrast, the remaining samples fall within the field designated for gasification coals. Their relatively lower carbon content and higher hydrogen content make them more suitable for syngas ($\text{CO} + \text{H}_2$) production via gasification. Although successful Underground Coal Gasification (UCG) field trials suggest that coal having these parameters- depth should be 30 to 580m, thickness of coal seams should be 2 to 5m, ash yield should be falls within 2 to 34%, moisture content should be in the range of 7 to 35%, volatile matter content should be 27 to 44% and fixed carbon within range of 12-38% are better for UCG (Khadse et al. 2007). As most of these parameters match with Sohagpur coals, these coals are suitable for UCG. The application of Falcon's and Snyman's models demonstrates the dual industrial potential of Sohagpur coals. While their petrographic and reflectance characteristics support their classification as blend coking coals, their elemental composition emphasizes their greater suitability for gasification and char production. These results provide valuable insights into optimal utilization strategies for Sohagpur coalfield resources, balancing traditional metallurgical applications with emerging clean coal technologies.

Chapter: 7

Conclusions and recommendations for further work

7.1 Conclusions

This study provides a thorough assessment of the petrological, geochemical, mineralogical, and pore-structural attributes of Gondwana coals from the Sohagpur Coalfield in the Son Valley Basin, central India. It effectively fulfils its principal aims regarding the depositional environment, the development of the paleo-mire, coal rank, and the prospects for energy and environmental resources. The analysis employs diverse methodologies, including megascopic observations, comprehensive maceral analysis, bulk geochemistry, Rock–Eval pyrolysis, SEM-based pore characterization, and relevant interpretations concerning adsorption. The conclusions are well-supported by several proxy datasets and offer new insights into the origins of the Sohagpur coals and their potential uses, as explained below.

7.1.1 Depositional Environment and Provenance

This study conclusively establishes that peat accumulation in the Sohagpur Coalfield occurred within a warm, humid paleoclimatic context that promoted extensive chemical weathering in the source area. Signatures of major, trace, and rare-earth elements indicate that most of the detrital material in peat originated from intermediate igneous and metamorphic source rocks.

High levels of terrigenous elements such as Al, Si, and Ti indicate that substantial clastic material entered the peat as it formed, especially when water was flowing. The combination of sedimentological indicators and geochemical proxies demonstrates that coal was deposited in a dynamic fluvio-deltaic system, at times influenced by lakes. Changes in redox-sensitive elemental ratios indicate that the environment shifted from

oxic to suboxic, and sometimes even anoxic. These changes had a big impact on how well organic matter was preserved and how well macerals grew. These results collectively improve existing depositional models for the Son Valley Basin by highlighting substantial spatial and temporal variability in peat-forming conditions.

7.1.2 Paleo-mire Evolution and Organic Matter Characteristics

Petrographic studies indicate that mire conditions have undergone systematic transformation from predominantly ombrotrophic, forested peat swamps to increasingly rheotrophic, groundwater-influenced wetlands. The hydrological regime, sediment supply, and the position of the water table have all changed, which is why this happened. The high levels of vitrinite and liptinite suggest that a lot of woody and hydrogen-rich plant materials were used.

Inertinite, on the other hand, indicates periods of oxidation and wildfires. The maceral assemblages, microlithotype distributions, and maceral-based indices suggest that the Sohagpur coals contain Type III kerogen. This type of kerogen indicates that the organic matter is mostly gas-prone, which aligns with the interpreted depositional environments and the evolution of the paleo-mire.

7.1.3 Coal Rank and Hydrocarbon Generation Potential

ASTM standards say that the Sohagpur coals are bituminous based on vitrinite reflectance measurements. Falcon says they are between intermediate and hypo-bituminous. These rank characteristics indicate that the coal is suitable for gasification. The Rock–Eval pyrolysis results and total organic carbon values indicate significant potential for thermogenic gas production, but only moderate to little potential for liquid hydrocarbon production. The high Type III kerogen content and the known coal rank indicate that these coals major hydrocarbon potential lies in the production of methane.

7.1.4 Coalbed Methane and Pore-Structure Characteristics

The study clearly shows that the Sohagpur coals have good properties for coalbed methane (CBM) production. The high vitrinite content and well-developed micropores and microfractures, as demonstrated by SEM and porosimetry tests, make a strong framework for storing and adsorbing methane.

The composition of macerals and the pore size distribution are closely linked to changes in adsorption capacity. This shows how important petrographic controls are for CBM potential. These results not only confirm the Sohagpur Coalfield's potential for CBM development but also highlight the need for seam-specific evaluation, as variations in maceral composition and pore architecture can significantly influence gas distribution and producibility.

7.1.5 Utilization Potential and Environmental Implications

From an industrial perspective, the Sohagpur coals have moderate sulphur content and medium to high ash content. These traits make them good for metallurgical processes, for making electricity from heat after beneficiation, and as a possible feedstock for underground coal gasification (UCG).

The integrated quality assessment in this study provides scientists with a method to enhance the utilization of coal in the region. The petrological features of the coals examined, especially the prevalence of microporous vitrinite and inertinite, indicate a significant capacity for CO₂ adsorption, alongside energy utilization.

These qualities suggest that abandoned or depleted coal seams in the Sohagpur Coalfield might be good places to store CO₂. This could help slow down climate change and make it easier to deal with coal seam gas.

The key contributions of this research can be summarized as follows:

- Presentation of the first integrated petrographic, geochemical, and pore-structural evaluation of Sohagpur coals with specific emphasis on CBM and CO₂ sequestration potential.
- Refinement of paleo-mire and depositional models for the Son Valley Basin using combined maceral, geochemical, and redox indicators.
- Establishment of clear relationships between maceral composition, pore characteristics, and methane adsorption capacity.
- Identification of Sohagpur coals as a dual-purpose resource for energy production and long-term CO₂ storage.

7.1.6 Limitations of this study

Key limitations include the absence of in-situ gas content measurements, reservoir pressure- temperature constraints, permeability and cleat characterization at the reservoir scale, and hydrological data parameters that directly influence producibility. Where such data are not part of the dataset, the thesis distinguishes clearly between (i) adsorption/storage potential inferred from lab measurements and (ii) field-scale deliverability, which requires additional measurements. Interpretations are presented with these boundaries stated explicitly to avoid overextension.

7.2 Recommendations for Further Research

This study provides an extensive petrological, geochemical, and pore-structural analysis of Permian coals from the Sohagpur Coalfield, precisely assessing their paleoenvironmental significance and coalbed methane (CBM) potential. Nonetheless, numerous significant opportunities for additional research persist. To augment and elaborate on the findings of this study, the following recommendations are presented:

7.2.1 Comparative Studies at the Basin and Regional Levels

This research focuses on the extractable coal seams of the Sohagpur Coalfield. Subsequent studies should employ similar multi-proxy petrological, geochemical, and pore-characterization methodologies on deeper, non-viable seams, as well as on adjacent Gondwana coalfields within the Son–Mahanadi basin system, including Singrauli, Umaria, and Pench–Kanhana. Comparative studies at the basin scale would enhance our understanding of regional variations in coal genesis, rank progression, depositional environments, and coalbed methane (CBM) potential, ultimately leading to more sophisticated exploration and exploitation strategies.

7.2.2 Molecular Geochemical and Isotopic Studies

This study effectively uses bulk geochemical methods; however, future research should incorporate more comprehensive molecular geochemical analyses. This should encompass the examination of biomarkers through gas chromatography–mass spectrometry (GC–MS) and stable carbon and hydrogen isotope analyses.

These methods will help us figure out where organic matter comes from, how old the thermal levels are, and how hydrocarbons form. These methods will also help us distinguish between thermogenic and microbial contributions to methane production.

7.2.3 Advanced CBM Evaluation in Reservoir Conditions

This study has assessed the potential of coalbed methane (CBM) through empirical formula-based methodologies. Future research should concentrate on advanced experimental studies that emulate reservoir conditions. This means conducting high-pressure adsorption tests on methane and carbon dioxide, as well as moisture-controlled and temperature-dependent gas sorption tests. We can learn more about gas-in-place and

how easily it can be produced by combining adsorption data with permeability, cleat system characteristics, and stress-sensitivity parameters.

7.2.4 Modelling of Multiscale Pore Networks and Gas Migration

Although comprehensive analyses of pore-size distribution and connectivity have been performed, future research should incorporate three-dimensional pore network characterization techniques, such as nanocomputed tomography (nano-CT), focused ion beam–scanning electron microscopy (FIB-SEM), and digital rock physics modelling. By combining these datasets with numerical simulations of multiphase gas flow, researchers can learn more about how gas moves and how petrographic components, pore structure, and gas transport behaviour are all connected.

7.2.5 Studies on the Use of Clean Energy and the Storage of CO₂

The petrographic, geochemical, and functional group characteristics identified in this study suggest that further research should evaluate the suitability of Sohagpur coals for advanced utilization technologies, including coal gasification, coal-to-liquid (CTL) processes, and underground coal gasification. Furthermore, conducting comprehensive research on the CO₂ sequestration potential in unmineable coal seams, including examining competitive adsorption dynamics and long-term storage stability, could enhance climate mitigation strategies and promote sustainable resource utilization.

7.2.6 Modelling the Basin and Thermal Maturation

Future research should integrate petrological and geochemical datasets with basin and thermal modelling to elucidate burial history, heat-flow dynamics, and the chronology of hydrocarbon and methane production. This kind of modelling would help us understand how gas is formed, how it remains in the Sohagpur Coalfield and the basins around it, and how porosity changes over time.

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Curriculum Vitae

Kaushal Kishor

Geologist | Conventional & Unconventional Energy Resources

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Professional Profile:

- Dynamic professional with a strong foundation in academic research, seeking to leverage expertise in the Conventional & Unconventional Energy Resources sector to tackle innovative challenges and drive impactful solutions.

Professional & Research Experience:

Research Scholar - Geology / Energy Geoscience

Rajiv Gandhi Institute of Petroleum Technology (RGPT) | August 2021 – March 2026

- Performed detailed petrographic, geochemical, and mineralogical characterization of Permian coal deposits.
- Evaluated coal rank, pore structure, cleat systems, and gas adsorption behaviour relevant to CBM and CO₂ storage.
- Conducted geological fieldwork, including coal sampling, field logging, and lithological documentation.
- Integrated Rock-Eval, XRF, petrography, and mineralogical datasets for energy resource assessment.
- Prepared research articles and industry-style technical reports, datasets, and documentation for applied geoscience studies.

Academic Qualifications				
Year(s)	Qualification	Board/Subjects	College/ Institute	%/ CGPA
2021-2026	Ph.D.		Rajiv Gandhi Institute of Petroleum Technology	8.42/10
2019-2021	M.Sc.	Geology	Bundelkhand University, Jhansi	8.23/10
2016-2019	B.Sc.	Geology, Physics, Mathematics	BSNV PG College, University of Lucknow	68.33%
2016	Class XII	U.P. Board	Saraswati Vidya Mandir Inter College, Gola- Kheri	86.60%
2014	Class X	U.P. Board	Saraswati Vidya Mandir Inter College, Gola- Kheri	88.50%

Achievements & Awards:

1. **Creative Research Poster Award** in the 40th Convention of the **Indian Association of Sedimentologists** & National Conference on An Odyssey of Sedimentology from Precambrian to Anthropocene: Significant Contributions in Environmental Climatic and Energy Research, organized by the **Birbal Sahni Institute of Palaeosciences**, Lucknow (11-13 December 2024).
2. Qualified **IIT-JAM** (Geology).
3. Qualified **GATE -2021, 2022, 2023, 2025** (Geology).
4. Joint **M.Tech-PhD** Admission offer from **IIT Kharagpur** and **M.Tech** admission offer from **IIT Kanpur**.
5. Qualified and appeared for document verification in the Staff Selection Commission Selection Post Phase IX (2021) and Phase XII (2024) for the positions of Junior Geographical Assistant and Senior Technical Assistant (Hydrology), respectively.
6. Completed the Level 1 Programme (English) by the International Well Control Forum.

M.Sc. Dissertation:

- **Title:** Morphotectonic Analysis of Ken Basin using advanced techniques of ArcGIS.
- **Synopsis:** To evaluate the neotectonic activity in the Ken River basin, using ArcGIS to determine the Morphotectonic features of the area. (Based on these findings, a research article published in Total Environment Advances-<https://doi.org/10.1016/j.teadva.2023.200088>).

Ph.D. Thesis:

- **Title:** Petro-chemistry of Permian Coal Deposits from the Sohagpur Coalfield, Son Valley, Central India: Implications for Paleoenvironments and Coal Bed Methane (CBM) Potential.
- **Synopsis:** The objective was to perform a petrographic and geochemical analysis of coal deposits in the Sohagpur Area. This includes determining the coalification trend over time and space and deciphering the paleo-depositional conditions. These characteristics also be useful for gas adsorption behaviour and Coal Bed Methane (CBM) potential. The findings recommend the most favourable use of coal in industrial utilization.

Geological fieldwork:

- Geological fieldwork and coal sample collection for PhD work from the Sohagpur Coalfield, Son Valley, Madhya Pradesh.
- 6 days of geological fieldwork in Ajmer, Kishangarh, and the surrounding areas of Rajasthan.
- 10 days of geological fieldwork in Jhansi, Babina, Mauranipur, the Amola Valley of the Bundelkhand Craton, and the Vindhyan Basin.

Skills:

Software	ArcGIS, ArcGIS Pro, Origin Pro, Adobe Illustrator, X'pert Highscore, MSP 200, Corel Draw, Gwyddion, ImageJ, and Leica Application Suite v4.6.
MS Office	MS Word, Excel, and PowerPoint.

Instrument	Proximate Analyzer, Bomb Calorimeter, Petrological Microscope, Polishing Machine, Rock-Eval, X-ray Fluorescence, Ultimate Analyzer, Ash Fusion Tester, and Atomic Force Microscopy.
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Member of Societies:

- Geochemical Society (Member ID: **502175**).
- International Association of GeoChemistry (Member ID: **77300690**).
- International Association for Gondwana Research.
- European Association of Geoscientists & Engineers (Membership No. - **M2024-123822**).
- The Paleoclimate Society.
- Structural Geology and Tectonic Studies Group of India.

Peer Reviewer:

- International Journal of Coal Preparation and Utilization.
- Journal of Petroleum Exploration and Production Technology.
- Evolving Earth.
- Open Journal of Soil Science.
- Discover Geoscience.
- Journal of Petroleum Geology.
- Journal of Saudi Chemical Society.

Workshops, Seminars and Webinars Attended:

1. Workshop on Carbon Capture and Storage *organized by the Department of Earth and Environmental Sciences, IISER Bhopal (13-16th October 2025)*.
2. Webinar "Streamline your research workflow" *organized by ACS Publications designed for institutions participating in One Nation One Subscription (Virtually- 29th August 2025)*.
3. Scientific Writing Workshop *organized by ACS Publications designed for institutions participating in One Nation One Subscription (Virtually- 26th August 2025)*.
4. Navigating Peer Review *organized by WILEY (Virtually- 9th October 2024)*.
5. Peer Review 101: Build Expertise, Become a Peer Reviewer *organized by Taylor and Francis Group (Virtually- 24th September 2024)*.
6. How to Do Research and Get Published - How to respond to reviewer comments *organized by Sage (Virtually- 18th September 2024)*.
7. National Workshop on Geochronology *at Inter-University Accelerator Centre, New Delhi (3-4 October 2023)*.
8. Capacity Building in Scientific Writing & Communication Skills *organized by Banaras Hindu University & Geochemical Society (Virtually- December 2022)*.

Research Articles:

1. Srivastava, M. K., **Kishor, K.**, Singh, A. K., Bharti, S. K., & Mukherjee, S. (2025): Study of Coal-Bearing Heterolithic Units for Reconstructing Marine Pathways in the Eastern Gondwana Basin, India. *Geological Journal* [10.1002/gj.70173](https://doi.org/10.1002/gj.70173)
2. Kori, R. K., Bhatt, S. C., Singh, M. M., Singh, S. K., Patel, A., Kumar, D., & **Kishor, K.** (2025). Identification of groundwater potential zones in a hard rock terrain of Central India. *Proceedings of the Indian National Science Academy*. <https://doi.org/10.1007/s43538-025-00652-3>
3. Tripathi, G.P., **Kishor, K.**, Srivastava, M.K. & Singh, A.K. (2025): Review on

- unconventional hydrocarbon and CO₂ storage potential in organic rich tertiary shales of Assam Arakan basin. *Discover Geoscience* 3, 201. <https://doi.org/10.1007/s44288-025-00320-5>
4. **Kishor, K.**, Srivastava, M.K., Tripathi, G.P. Singh, A.K. & Mukherjee, S. (2025): Paleoenvironmental and Paleodepositional Reconstruction of the Permian coals from Burhar Seam IV of Sohagpur Coalfield, India: Using Integrated Mineralogical, Geochemical, and Petrographic Proxies. *Geological Journal* 10.1002/gj.70113
 5. Srivastava, M.K., Vikram, K., **Kishor, K.**, Singh, A. K. (2025): Rank-Dependent Amphiphilicity of Coal: Insights into Combustion and Beneficiation Mechanisms. *ACS Omega* <https://doi.org/10.1021/acsomega.5c03877>
 6. Srivastava, M.K., Vikram, K., **Kishor, K.**, Singh, A. K., Mukherjee, S., & Singh, R. K. (2026): Unraveling coalification dynamics: A comprehensive spectroscopic study on the chemical and microstructural evolution from lignite to semi-anthracite. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 345, 126765. <https://doi.org/10.1016/j.saa.2025.126765>
 7. Srivastava, M.K., **Kishor, K.**, Singh, A.K., Kumar, A., Mustapha, K.A., Saxena, A. (2025): Multi-analytical assessment of shale gas potential in the West Bokaro Basin, India: A clean energy prospect. *Energy Geoscience* 6, 100434. <https://doi.org/10.1016/j.engeos.2025.100434>
 8. **Kishor, K.**, Srivastava, M.K. & Singh, A.K. (2025): Pore characteristics and Gas Adsorption Properties of Permian Coals in Sohagpur Coalfield, India: A Comprehensive Multi-Analytical Study. *Energy & Fuels*. <https://doi.org/10.1021/acs.energyfuels.4c04722>
 9. **Kishor, K.**, Srivastava, M.K. & Singh, A.K. (2025): Characterisation of surface and structural properties of Permian coals from Sohagpur Coalfield, India: a comprehensive analysis. *Int. J. Oil, Gas and Coal Technology*. Vol. 38, No. 3, pp.339–357. [10.1504/IJOGCT.2025.10072868](https://doi.org/10.1504/IJOGCT.2025.10072868)
 10. Srivastava, M. K., **Kishor, K.**, Singh, A. K., Mukherjee, S., & Bharti, S. K. (2024): Tectonically Deformed Coal: Focus on Microstructures & Implications for Basin Evolution. *Marine and Petroleum Geology*, 107223. <https://doi.org/10.1016/j.marpetgeo.2024.107223>
 11. Srivastava, M. K., **Kishor, K.**, & Singh, A. K. (2024): A comprehensive petrochemical study of coals of Jaintia Hills: unveiling their industrial applicability and potential as hydrocarbon source rocks. *International Journal of Coal Preparation and Utilization*, 45(4), 822–836.. <https://doi.org/10.1080/19392699.2024.2353130>
 12. Srivastava, M. K., **Kishor, K.**, Nath, M., & Singh, A. K. (2024). Inorganic geochemical attributes of Jaintia Hills coals, India: Implications for paleo-depositional conditions. *Kuwait Journal of Science*, 51(3), 100227. <https://doi.org/10.1016/j.kjs.2024.100227>
 13. Bhatt, S.C., Patel, A., Pradhan, S.R., Singh, S.K., Singh, V.K., Tripathi, G.P. & **Kishor, K.** (2023): Morphometric and Morphotectonic Attributes of Ken basin, Central India: Depicting Status of Soil Erosion, and Tectonic activities. *Total Environment Advances*. <https://doi.org/10.1016/j.teadva.2023.200088>
 14. Kumar, M., Srivastava, M. K., **Kishor, K.**, & Singh, A. K. (2023). An Assessment of the Environmental Impact of Coal Mining through Acid Mine Drainage and Soil Degradation from Makum Coalfields, Upper Assam, India: A Case Study. *Journal of the Geological Society of India*, 99(8), 1113–1120. DOI: [10.1007/s12594-023-2437-3](https://doi.org/10.1007/s12594-023-2437-3)

15. **Kishor, K.**, Kumar, M., Srivastava, M.K. & Singh, A.K. (2023): Geochemical and microstructural analysis of coals from Sohagpur Coalfield with reference to adsorption behavior: An assessment for CO₂ sequestration. *International Journal of Coal Preparation and Utilization*, 44(7), 941–952. DOI: [10.1080/19392699.2023.2232721](https://doi.org/10.1080/19392699.2023.2232721)
16. **Kishor, K.**, Srivastava, M.K. & Singh, A.K. (2023): Geochemical Study of Coals from Sohagpur Coalfield, India, and Its implication to CBM Potential. *International Journal of Coal Preparation and Utilization*, 44(6), 614–625. DOI: [10.1080/19392699.2023.2212611](https://doi.org/10.1080/19392699.2023.2212611)

Book chapters:

1. Bhatt, S.C., Singh, M.M., Rana, P., Patel, A., Rana, N.K., Singh, S.K., **Kishor, K.** (2025): Estimation of Morphometric and Morphotectonic Indices of the Kanhan River Basin, Central India, Implication for Susceptibility of Soil Erosion and Groundwater Potential. In: Pal, S.C., Chatterjee, U. (eds) *Surface, Sub-Surface Hydrology and Management. Springer Geography. Springer, Cham.* https://doi.org/10.1007/978-3-031-62376-9_13

Conference Papers & Posters:

1. Srivastava, M.K., **Kishor, K.**, Singh, A.K., Mustapha, K.A., Bharti, S., and Saxena, A. 2025: Fault-Induced Thermal Maturation and Pore Development in Barakar Formation Shales, West Bokaro Basin: Insights for Shale Gas Exploration in *International Seminar Unearthing the past, shaping the future: 175 years of Geological Survey of India organized by Geological Survey of India, Jaipur Rajasthan India (20-21 November 2025)*.
2. Tripathi, G.P., **Kishor, K.**, Srivastava, M.K., and Singh, A.K. 2025: SEM and FTIR characteristics of Upper Assam Tertiary Shale, India: Implication for Clean Energy in *International Seminar Unearthing the past, shaping the future: 175 years of Geological Survey of India organized by Geological Survey of India, Jaipur Rajasthan India (20-21 November 2025)*.
3. Srivastava, M.K., **Kishor, K.**, Singh, A.K., Vikram, K. and Saxena, A. 2025: Spectroscopic Evaluation of Coal Wettability: A Robust Alternative to Contact Angle Measurement in *International Conference on Petroleum, Hydrogen & Decarbonization (ICPHD 2025) Advances, Challenges & Opportunities for Sustainable Future organized by Rajiv Gandhi Institute of Petroleum Technology, Jais, Amethi, Uttar Pradesh (7-9 November 2025)*.
4. Tripathi, G.P., **Kishor, K.**, Srivastava, M.K., and Singh, A.K. 2025: Integrated FTIR, XRD, and N₂ Adsorption Study of Shales: Insights into Specific Surface Area and Gas Adsorption Capacity in *International Conference on Petroleum, Hydrogen & Decarbonization (ICPHD 2025) Advances, Challenges & Opportunities for Sustainable Future organized by Rajiv Gandhi Institute of Petroleum Technology, Jais, Amethi, Uttar Pradesh (7-9 November 2025)*.
5. Srivastava, M.K., Tripathi, G.P., **Kishor, K.** and Singh, A.K. 2025: Evidence of Tectonically Deformed Paleogene Coal of Kalakot, Jammu, India: Insights from macroscopic to microscopic study in *International Conference on Geodynamic Evolution of Himalaya (Crustal Architecture, Climate, Resources, and Disaster) organized by Department of Geology (Centre of Advanced Study), Kumaun University, Nainital and Geological Society of India (6-10 October 2025)*.

6. Tripathi, G.P., Srivastava, M.K., **Kishor, K.** and Singh, A.K. 2025: Study of Hydrocarbon Functional Groups of Tertiary Kopili Shales from Northeastern Himalaya: A case study from Upper Assam Basin in *International Conference on Geodynamic Evolution of Himalaya (Crustal Architecture, Climate, Resources, and Disaster)* organized by Department of Geology (Centre of Advanced Study), Kumaun University, Nainital and Geological Society of India (6-10 October 2025).
7. Singh, A.K., **Kishor, K.** and Srivastava, M.K. 2025: Multiscale Characterization of Cleats in Permian coals of Sohagpur coalfield: Insight from Microscopic to Field-Scale Observations in *UrjaVarta 2025*, organised by Directorate General of Hydrocarbons at Bharat Mandapam, New Delhi, India (17th July 2025).
8. **Kishor, K.**, Srivastava, M.K., Tripathi, G.P. and Singh, A.K. 2024: Multi-analytical approach to investigate paleoclimate and paleo-depositional conditions of coal samples from Sharda coal mine of Sohagpur coalfield, India in *40th Convention of Indian Association of Sedimentologists & National Conference on An Odyssey of Sedimentology from Precambrian to Anthropocene: Significant Contributions in Environmental Climatic and Energy Research* organized by Birbal Sahni Institute of Palaeosciences, Lucknow (11-13th December 2024).
9. **Kishor, K.**, Srivastava, M.K., Tripathi, G.P. and Singh, A.K. 2024: Hydrocarbon Potential of Sohagpur Coal Seams: Unlocking Sustainable Energy Prospects through Pore and Fracture Characterization in *8th National Geo-Research Scholars Meet at Shri Mata Vaishno Devi University, Katra*, organized by Wadia Institute of Himalayan Geology, Dehradun, India (22-25 November 2024).
10. **Kishor, K.**, Srivastava, M.K. and Singh, A.K. 2024: Multiscale Pore and Microfracture Characterization of Permian Coals of India: Implications for CO₂ Sequestration Potential in *International Conference on Transforming Upstream: Breakthrough Technologies and Sustainability at Rajiv Gandhi Institute of Petroleum Technology Jais, Amethi- Uttar Pradesh, India* (30th September to 1st October 2024).
11. Tripathi, G.P., Srivastava, M.K., **Kishor, K.**, Jaiswal, H. and Singh, A.K. 2024: Application of Modern tools to identify Unconventional hydrocarbon potential and CO₂ Sequestration possibility in Assam-Arakan basin in *International Conference on Transforming Upstream: Breakthrough Technologies and Sustainability at Rajiv Gandhi Institute of Petroleum Technology Jais, Amethi- Uttar Pradesh, India* (30th September to 1st October 2024).
12. Srivastava, M.K., **Kishor, K.**, and Singh, A.K. 2024: From Raw Samples to Refined Views: A cost-effective way of Coal Mount Preparation for Micro-petrography in *International Conference on Transforming Upstream: Breakthrough Technologies and Sustainability at Rajiv Gandhi Institute of Petroleum Technology Jais, Amethi- Uttar Pradesh, India* (30th September to 1st October 2024).
13. **Kishor, K.**, Srivastava, M.K. and Singh, A.K. 2024: Genesis and characteristics of Cleat system in Coal and its impact on coal porosity and permeability in *National conference on Geosciences for Sustainable World -2024 at Department of Geophysics, Banaras Hindu University, Varanasi-India* (6th and 7th March 2024).

14. Ismail, M.H, Srivastava, M.K, **Kishor, K.**, and Singh, A.K. 2024: A comprehensive study on the different ranks of Indian coals to test the stability of different formulas given to predict the gross calorific value (GCV) *in National conference on Geosciences for Sustainable World -2024 at Department of Geophysics, Banaras Hindu University, Varanasi-India (6th and 7th March 2024).*
15. **Kishor, K.**, Srivastava, M.K. and Singh, A.K. 2023: A geochemical study of coal seam from Sohagpur coalfield and its implications for paleo-climate estimation *in 7th National Geo-Research Scholars Meet at Wadia Institute of Himalayan Geology, Dehradun-India (12-14th September 2023).*
16. Srivastava, M.K, **Kishor, K.**, and Singh, A.K. 2023: Geochemical assessment for hydrocarbon source rock potential of Jaintia Hill coals, Meghalaya, India *in 7th National Geo-Research Scholars Meet at Wadia Institute of Himalayan Geology, Dehradun-India (12-14th September 2023).*
17. Srivastava, M.K and **Kishor, K.** 2023: Deciphering Gondwana Coal Macro Lithotypes: Insights into Paleoclimate Dynamics *in The Paleoclimate Society Meeting 2023 at London, United Kingdom (5-6th September 2023, Virtual).*
18. **Kishor, K.**, Srivastava, M.K. and Singh, A.K. 2023: Macro Lithotype and Proximate Analysis: A tool to check Coal Bed Methane Potentiality of Sohagpur Coalfield, India *in National Seminar on Conventional, Renewable Energy Sources and Climate Change Perspective at Nagpur, India (23-24 June 2023).*