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Study of Coal-Bearing Heterolithic Units for Reconstructing Marine Pathways in the Eastern Gondwana Basin, India

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Abstract

The Gondwana sequence has traditionally been viewed as resulting from post-glacial fluvio-lacustrine sedimentation within large, elongated rift valleys during the Permian Period. However, doubts have recently been raised regarding its freshwater origin. This research fills that gap through a multidisciplinary approach-incorporating sedimentological study, coal petrography, mineralogy and major and trace element geochemistry demonstrating a dynamic depositional environment controlled by tidal, wave and river interactions. Geochemical proxies viz., CaO/MgO, Sr/Ba, and Th/U ratios, along with MgO and Al_2O_3 trends, reveal fluctuating paleo-salinity conditions from brackish to marine environment. The presence of dolomite, siderite, limited pyrite and alginite macerals further confirms episodic marine influence during peat formation. Heterolithic units, the principal sedimentary facies in the study area, archives tidal bundles, coarsening-upward successions, and wave-ripple-tidalite features, indicative of deposition across supratidal to subtidal salt marsh settings. The coal-bearing heterolithic units form during multiple minor marine transgressions. A regressive shift is marked by the deposition of the Dumerbera and Parsatoli Sandstone units, followed by a major transgression that initiated the ironstone-rich Barren Measure Formation. These transgressions predate the previously documented marine inundation of the overlying Barren Measures Formation, implying that marginal marine conditions developed earlier in this basin than previously thought. This study provides clear evidence of marine influence

during Barakar sedimentation and supports the existence of a near-continuous marine incursion pathway from the Khemgaon–Sikkim corridor to the Satpura Basin, reflecting sustained marine connectivity across Gondwana basins. By refining the regional paleoenvironmental model of Indian Gondwana, this study emphasizes the efficacy of multi-proxy frameworks in decoding complex depositional systems.

Keywords: Barakar Formation, Gondwana marine incursion, Heterolithic units, Trace element geochemistry, West Bokaro basin.

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1 Introduction

Rifting of Gondwanaland during the Late Carboniferous to Early Permian period developed several intracratonic rift basins filled with continental clastic deposits (Mathews et al. 2020). A long episode (Permo-Carboniferous to Early Cretaceous) of fluviatile sedimentation, took place in such rift basins (Tewari and Maejima 2010). All such sediments are grouped under stratigraphic framework as The Gondwana Supergroup. Several of these sediment layers are renowned for their rich fossil flora and fauna, as well as economically exploitable coal seams.

The Permian coal-bearing sediments of India has traditionally been marked as fluvio-lacustrine depositional system, based on sedimentological study and non-availability of marine fossils

(Casshyap 1987; Ray and Chakraborty 2002; Tewari et al. 2012) and many more, however, many researchers (Goswami 2008; Bhattacharya et al. 2021) also encountered the sign of marine intrusions during their deposition. The marine origin of the Barakar Formation has been a longstanding topic of debate across the Gondwana rift.

The initial identification of a marine signature within the predominantly non-marine Gondwana Sequence was made based on the Eurydesma-Productus-Conularia assemblage in the Umaria Marine Bed, as reported by Sinor in 1923 (Goswami 2008). Chatterjee and Hotton (1986) proposed that a large-scale marine transgression occurred through Gondwana rift system, in peninsular India during the lower Permian, as part of their paleogeographic reconstruction work (Chatterjee and Hotton 1986). Subsequently, the marine nature of the Gondwana sediments is also confirmed by the presence of invertebrate fossils from Manendragrah (Chhattisgarh), Daltonganj (Jharkhand), Rajhara (Jharkhand), Ranjit Pebble Slate (Sikkim), Subansiri (Arunachal Pradesh), and Bap Boulder Bed (Rajasthan) (Figure 1) (Venkatachala and Tiwari 1987; Goswami 2008). Most of these sediments also contain acritarchs, leiosphaerids and other palynofossils of marine origin in association with spores and pollen (Venkatachala and Tiwari 1987).

The Gondwana sedimentation began with the deposition of the Talchir Formation, whose marine nature is already well established (Venkatachala and Tiwari 1987). Interestingly, recent studies across various Gondwana basins of India have increasingly highlighted the role of marine influence during the deposition of the Barakar Formation as well (Table 1). Multiple Gondwana basins of India, including Rajmahal, Raniganj, West Bokaro, South Karanpura, Rajhara, Ib River, Talcher and Satpura exhibit compelling evidence of marine influence during the Barakar Formation sedimentation, as indicated by sedimentological, ichnological, palynological, and geochemical data (Gupta 1999; Chakraborty et al. 2003; Ghosh et al. 2004; Goswami 2008; Bhattacharjee et al. 2018; Mathews et al. 2020; Bhattacharya et al. 2021, 2012a; Pillai et al. 2023). These findings collectively suggest that post-glacial sea-level rise led to episodic to sustained marine incursions, resulting in estuarine to peritidal depositional settings across these coal-bearing basins. Recently, the signatures of Permian Tethyan transgression were recorded from Barren Measures Formation, West Bokaro Coalfield (Bhattacharya and Banerjee 2015). Thus, the previous view of predominantly non-marine origin of Lower Gondwana has been challenged.

Table 1: Summary of marine influence and depositional settings of the Barakar Formation across various Gondwana basins of India, highlighting evidence from sedimentological, ichnological, and geochemical indicators as reported in previous studies.

Location	Depositional setting	Reference
Raniganj Basin, West Bengal	Barakar Formation experienced a significant marine incursion, likely due to post-glacial sea-level rise during the Permian. This transgressive event led to the development of estuarine conditions.	(Bhattacharjee et al. 2018; Bhattacharya et al. 2021, 2012b)
Ib river valley and Talcher Basin, Orissa	The presence of sparry calcite cementation, phosphate-bearing peloids, marine ichnotaxa, bioturbated beds, and brackish-water palynofossils in the Barakar Formation strongly supports episodic marine incursions during its sedimentation in the Ib River and Talcher basins.	(Goswami 2008)
Satpura basin, Madhya Pradesh	The Barakar Formation in the Satpura Basin, once considered purely continental, is now reinterpreted as having formed in a tidally influenced deltaic setting. Evidence such as bidirectional cross-strata and tidal rhythmites suggests significant marine influence, highlighting a tidal estuarine environment and revising earlier palaeogeographic models of Gondwanan coal basins.	(Ghosh et al. 2004)
Mohpani Coalfield, Satpura Gondwana Basin, Madhya Pradesh	This study reveals clear evidence of marine incursion during Barakar Formation sedimentation, with tidal signatures identified in mudstone-dominated facies. Features such as flaser bedding, spring-neap tidal cycles, bidirectional foresets, and desiccation cracks indicate deposition in intertidal to supratidal environments, challenging the earlier view of a purely continental braided river system and confirming significant marine influence.	(Chakraborty et al. 2003)
Ramgarh, South Karanpura, and West Bokaro coalfields, Jharkhand	Marine influence in the Barakar Formation has been identified based on trace fossils, sedimentary features, and trace element content. The upper part indicates deposition in a peritidal setting near a broad, shallow epicontinental sea, with storm activity playing a key role during high sea-level conditions.	(Gupta 1999)

Rajhara Coalfeld, Palamu, Jharkhand	Geochemical signatures suggest a brackish palaeoenvironment prevailed during the Late Permian (Artinskian) in the Rajhara Colliery.	(Pillai et al. 2023)

1.1 Necessity of research

From the studies reporting marine incursion during the Early Permian, it seems that nearly all the low-lying embryonic basinal depressions experienced marine transgression from an eastern bay. In the west and northwest, these marine pathways connected with the Arabian Sea and the Salt Range Sea (Chatterjee and Hotton 1986). Evidence of episodic marine transgression into the Middle and Late Permian in central India further necessitates the search for such signatures to establish the remnants of these pathways inside the peninsula. The Bokaro basin is one such gap where marine signatures have yet to be confirmed by multi-proxy tools.

Multi-proxy studies are crucial in sedimentary depositional environment research because they provide a more comprehensive and detailed understanding of past environmental conditions compared to single-proxy approaches. By combining multiple lines of evidence from different proxies, the limitations of individual proxies can be overcome and gain a more nuanced picture of past environmental changes (Birks and Birks 2006; Schroeter et al. 2020; Quamar et al. 2024).

In this study, we attempt to evaluate the paleo-salinity conditions, ichnofossils, paleo-depositional environment, of sandstone–mudstone heteroliths, coal, and claystone of the Early Permian Barakar Formation in the West Bokaro Basin, using sedimentology, organic micropetrographic analysis, and major and trace element geochemistry. Connection with Tethys was established through the same pathways as Early Sakmarian (Mukhopadhyay et al. 2010). By confirming the marine origin of the Barakar Formation in the West Bokaro Basin, this study aims to connect the missing links between the eastern and western marine pathways and contribute to a re-evaluation of Gondwana palaeogeography. The analysis will provide a detailed assessment of the paleo-depositional conditions of the Barakar Formation and reveal the extent of Permian marine inundations in eastern India.

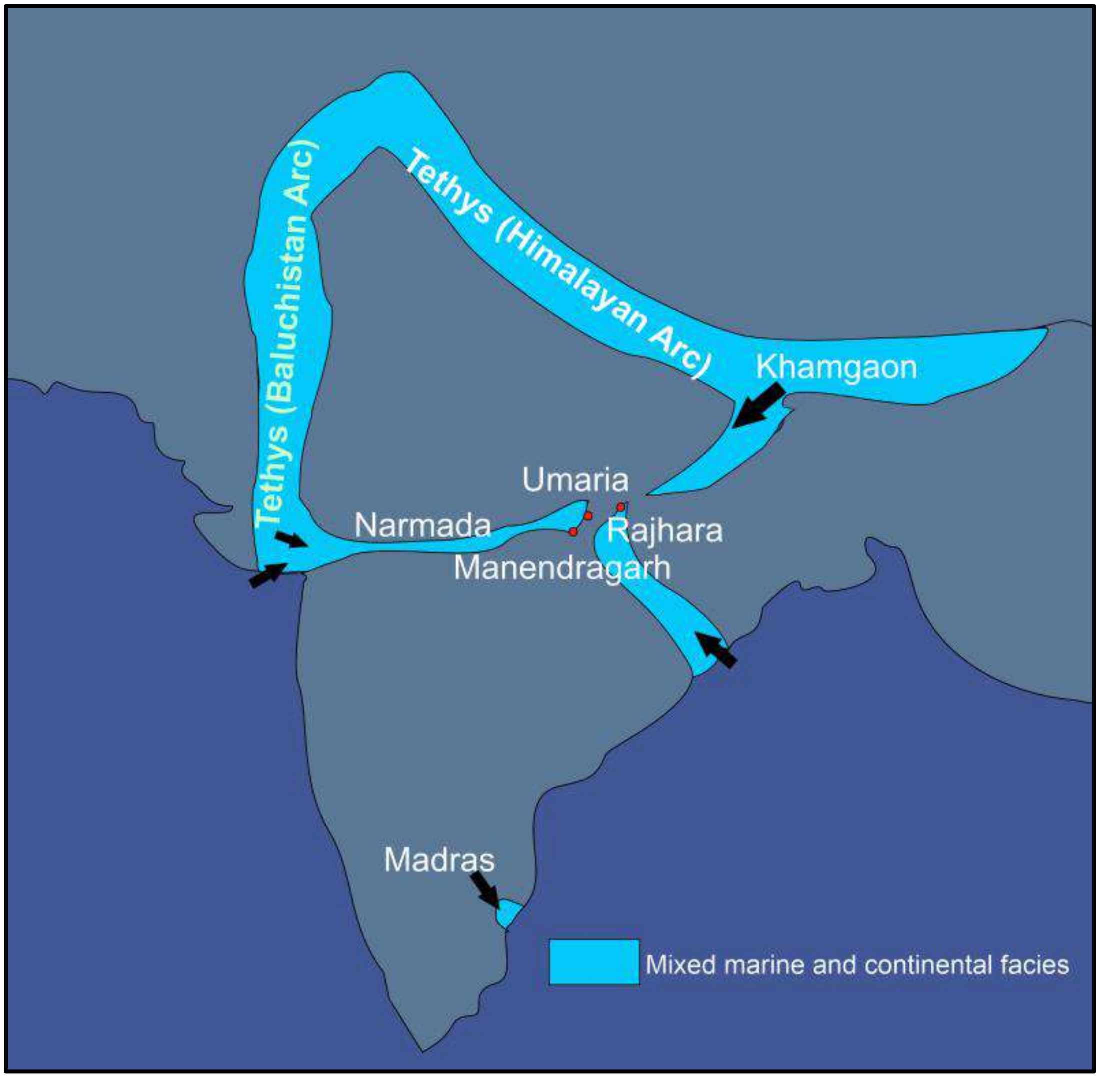


Figure 1: Cartoon Map of India (Not to Scale) exhibiting marine transgression from eastern flank through Khemgaon, Sikkim and western flank through Narmada rift Source: (Chatterjee and Hotton 1986; Mathews et al. 2020).

A prominent sedimentary feature of the study area is the occurrence of coal-bearing heterolithic units, belonging to middle to upper Barakar formation. Heterolithic and tidally influenced depositional systems have been widely documented across various basins worldwide, reflecting diverse marginal marine to estuarine environments (Figure 2). Studies (Table 2) from formations such as the Ediacara Member in South Australia (Jenkins et al. 1983), the Tilje and Cook formations in offshore Norway (Martinius et al. 2001; Ringrose et al. 2005), the McMurray Formation in Canada (Gingras et al. 2016), Beach Formation in Australia (Bann et al. 2004), Ostreaelv Formation in East Greenland (Ahokas et al. 2014), Neslen Formation in Utah USA

(Olariu et al. 2015) and the Mamu and Nanka formations in Nigeria (Dim et al. 2019; Ogbe and Osokpor 2021), reveal the significance of tidal processes in shaping heterolithic successions. These interpretations are supported by sedimentological, ichnological, and stratigraphic evidence, emphasizing the role of transgressive-regressive events, fluvio-tidal interactions, and storm influences in the deposition of these units. (Table 2)

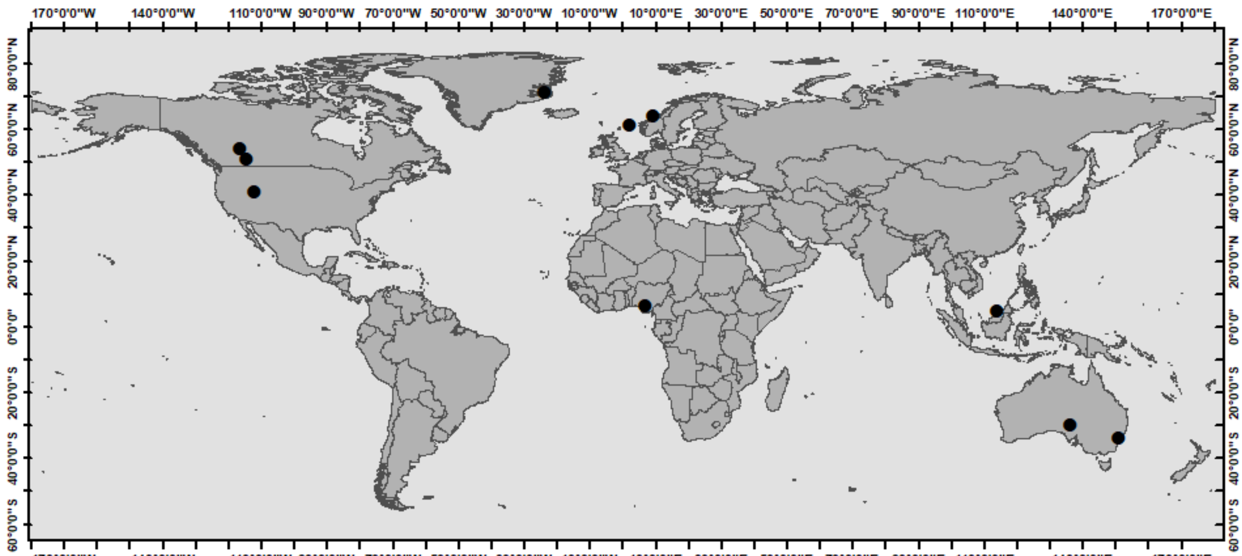


Figure 2: Representative examples of heterolithic units deposited in tidal and fluvio-tidal environments across the globe. (Global shape file Source: https://public.opendatasoft.com/explore/dataset/world-administrative-boundaries/export/, accessed on 26/5/2025).

Table 2: Compilation of case studies on tidal/fluvio-tidal depositional environments, reported from various global locations. *-Coal reported alongside heterolithic unit.

Geological Description	Location	Paleo Depositional Environment	Reference
Ediacara Member of the Rawnsley Quartzite, context of Ediacara assemblage (Late Precambrian)	South Australia	Heterolithic siltstone/sandstone units represent intertidal deposits	(Jenkins et al. 1983)
Cook Formation; electrofacies analysis (Lower Jurassic)	Gullfaks Field, Offshore Norway *	Tide-dominated estuarine to deltaic setting	(Gupta and Johnson 2001)
Heterolithic unit, Tilje Formation (Early Jurassic)	Offshore mid-Norway	Tide-dominated	(Martinius et al. 2001)

Pebbley Beach Formation; differentiation of estuarine vs offshore marine deposits using ichnology and sedimentology (Permian)	Sydney Basin, Australia	Brackish water to fully marine units	(Bann et al. 2004)
Heterolithic siliciclastic unit with diagenetically altered sandstones	Halten Terrace, mid-Norway *	tide- dominated deltaic and estuarine environments	(Martinius et al. 2005)
Vertical permeability estimation in heterolithic units, Tilje Formation	Offshore mid-Norway	Tidal deltaic sedimentary systems	(Ringrose et al. 2005)
Incised valley fills of Toarcian Ostreaelv Formation; heterolithic succession	Jameson Land, East Greenland	Tide-dominated estuary	(Ahokas et al. 2014)
Campanian Neslen Formation; unusual fluvial-tidal channels with inclined heterolithic strata	Utah, USA *	Tidal influenced fluvial channels	(Olariu et al. 2015)
McMurray Formation; significance of cross-stratified sand, heterolithic unit, bioturbated channel sands.	Alberta, Canada	Bar-top / tidal-flat deposits	(Gingras et al. 2016)
Campano–Maastrichtian Mamu Formation; consists of carbonaceous shales, siltstones, sandstones, heteroliths and coal seams	Anambra Basin, Nigeria *	High frequency transgressive and regressive events in coastal swamps and lagoons, marginal marine environment	(Dim et al. 2019)
The ichnological variation in the heterolithic units, McMurray Formation;	Western Canadian Basin	Fluvio-tidal setting, marginal marine	(Melnyk and Gingras 2020)
Cyclical heterolithic layering, Lambir Formation (Middle Miocene)	Baram Delta Province, north-west Borneo	Fluvio-tidal setting, marginal marine	(Collins et al. 2020)
Nanka Formation of Ameki Group; depositional facies, sequence stratigraphy, reservoir potential (Eocene)	Southeast Nigeria	Tidal mudflat facies, marginal marine	(Ogbe and Osokpor 2021)

2 Geology of the Study area

The Bokaro basin is an E-W trending, linear, isolated depressions located in the eastern side of Indian Gondwana Basin Belt (Jha and Sinha 2022). The major basins of the West Damodar valley are typically synclinal half-basins, generally opening either to the west (such as Ramgarh, and Auranga-Hutar) or to the south (like North Karanpua). The notable exception is the narrow Bokaro

Basin, which is closed at both ends (Dutt 2019). The Lugu Hill, rising to ~ 978 m, is the dominant geomorphic feature that divides East Bokaro from West Bokaro (Murthy 2017) (Figure 3). West Bokaro basin is located in the Ramgarh district of Jharkhand, India (Sinha and Gupta 2020). The coalfield lies between 23°41′ to 23°52′ N latitude and 85°24′ to 85°41′ E longitude, covering an area of 207 sq km (Figure 3) (Tiwari et al. 2016b). We investigated the geological section exposed near Ara and Dumarbera villages in the Ramgarh district (Figure 4).

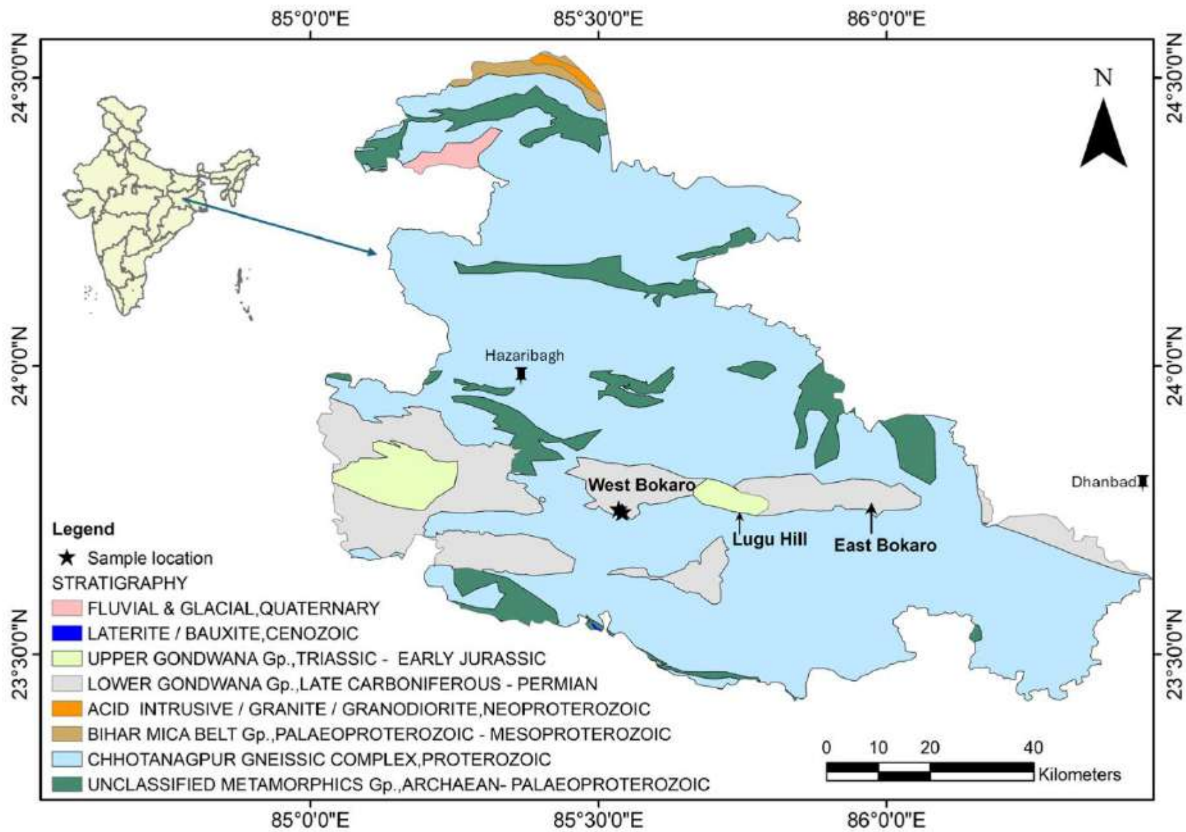


Figure 3: Location map of West Bokaro Basin along with the major stratigraphic unit exposed in the district of Hazaribagh, Ramgarh, and Bokaro, Jharkhand, India. Source: Bhukosh, www.bhukosh.gsi.gov.in (Accessed on 12-April-2025).

The West Bokaro coalfield is divided into two sub-basins by a twin synformal structure, with a northern and southern synform separated by an indistinct central antiform running in an east-west direction. The northern and southern sub-basins are separated by the Archean highland around Mandu (Tiwari et al. 2016b). These three structural axes converge in the eastern part of the coalfield. In the northern limb of the northern synform, the strata typically dip 15° to 25°

southward. In the southern limb of the northern synform, dips vary between 5° to 15° towards the north, except in the sub-basinal structures of the Tapin and Parej blocks. For the southern synform, the southern limb dips northward between 10° to 30°. The tectonic lineaments in these valleys have preserved the oldest rocks, which form the Archean basement complex, with the Permo-Carboniferous to Late Permian age Lower Gondwanan coal deposits overlying these basement rocks (Navale and Saxena 1989). To the North of the Bokaro basin, the Precambrian rocks are separated from the Gondwanas by a boundary fault while to the South and West the Gondwanas generally overlie the Precambrian with a profound unconformity (Raja Rao 1987).

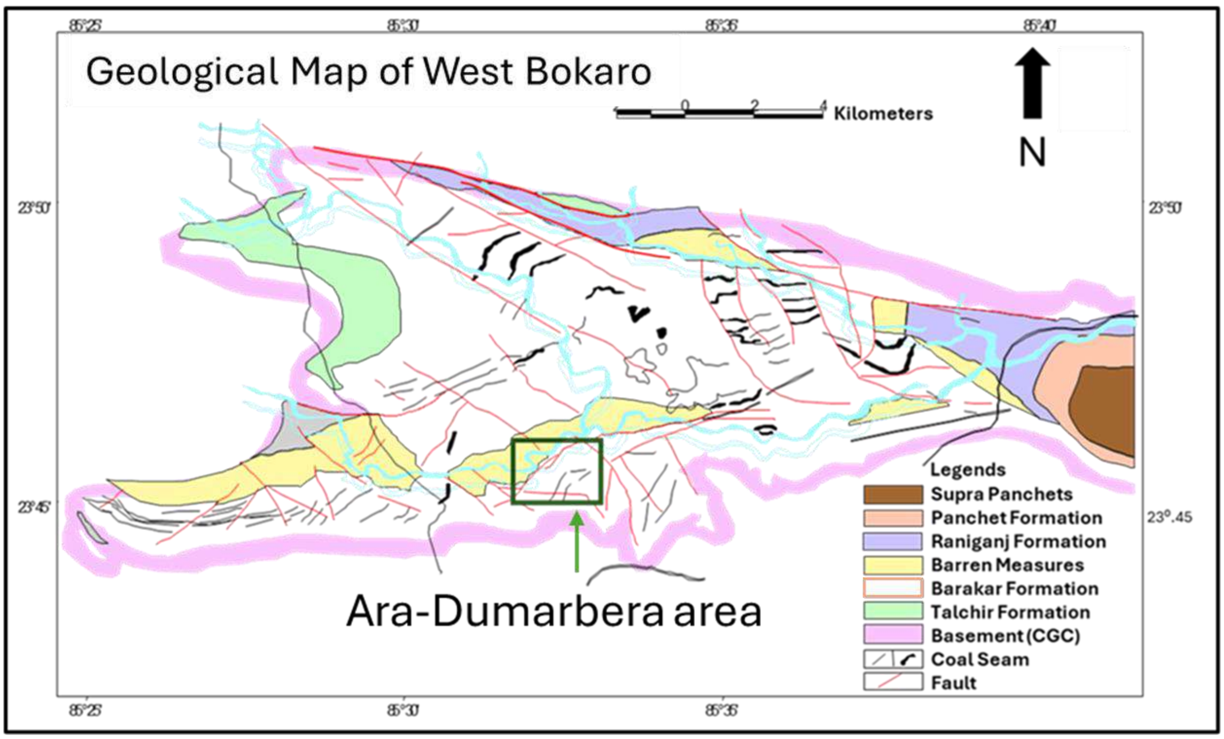


Figure 4: Location map of West Bokaro Basin along with the major stratigraphic unit exposed in the West Bokaro, Jharkhand, India. Reproduced from (Srivastava et al. 2025).

2.1 Sedimentation and marine influence in the Bokaro Basin

The basin features a complete sequence of Lower Gondwana formations resting unconformably on the basement rocks (Tiwari et al. 2016a). It comprises formations including Talchir, Karharbari, Barakar, Barren Measures, Raniganj, Panchet, and Supra Panchet, spanning from the Early Permian to the Upper Triassic (Raja Rao 1987). Gondwana sedimentation begins with the Talchir Formation, which features glacial conglomerates, sandstone, and shales, resting directly on the

Precambrian basement rocks of amphibolite and granitoids, and is well exposed along Dudhi Nala Mahato & Srivastava 2023). The Karharbari Formation, with limited exposure in this region, consists of sandstones, shales, and thin coal seams.

The Barakar Formation (Early Permian) of the Lower Gondwana succession is the predominant coal-bearing litho-unit of the West Bokaro Basin, similar to the rest of the peninsular Indian coal fields. This formation typically features thick coal seam-bearing sedimentary sequences in this region (Bhattacharya and Banerjee 2015; Bhattacharjee et al. 2018). Dominating the area, the Barakar Formation covers a major part of the coalfield and has an aerial extent of ~ 125 km^2. It comprises of coarse to fine-grained sandstones, pebbly conglomerates, gritty sandstones, gray shales, carbonaceous shales, fireclays, and coal seams (Tiwari et al. 2016b). The study area is primarily characterized by the cyclic sequence of Barakar formation, consisting of sandstone of various gain size, carbonaceous and grey shales and coal seams. The full sequence of Barakar Formation in West Bokaro basin contains 14 regionally correlatable coal seams. The Barren Measures Formation is mainly composed of sandstone and shale, while the Raniganj Formation, which overlies the Barren Measures, marks the end of the Lower Gondwana sedimentary sequence. Due to the synclinal structure of this coalfield, which extends in an east-west direction, the Barakar Formation is exposed on both the northern and southern limbs of the syncline, while the younger Barren Measures and Raniganj Formations occupy the central axial region (Sinha and Gupta 2020) (Figure 4). Figure 5 provides the generalized stratigraphic successions of the West Bokaro Basin.

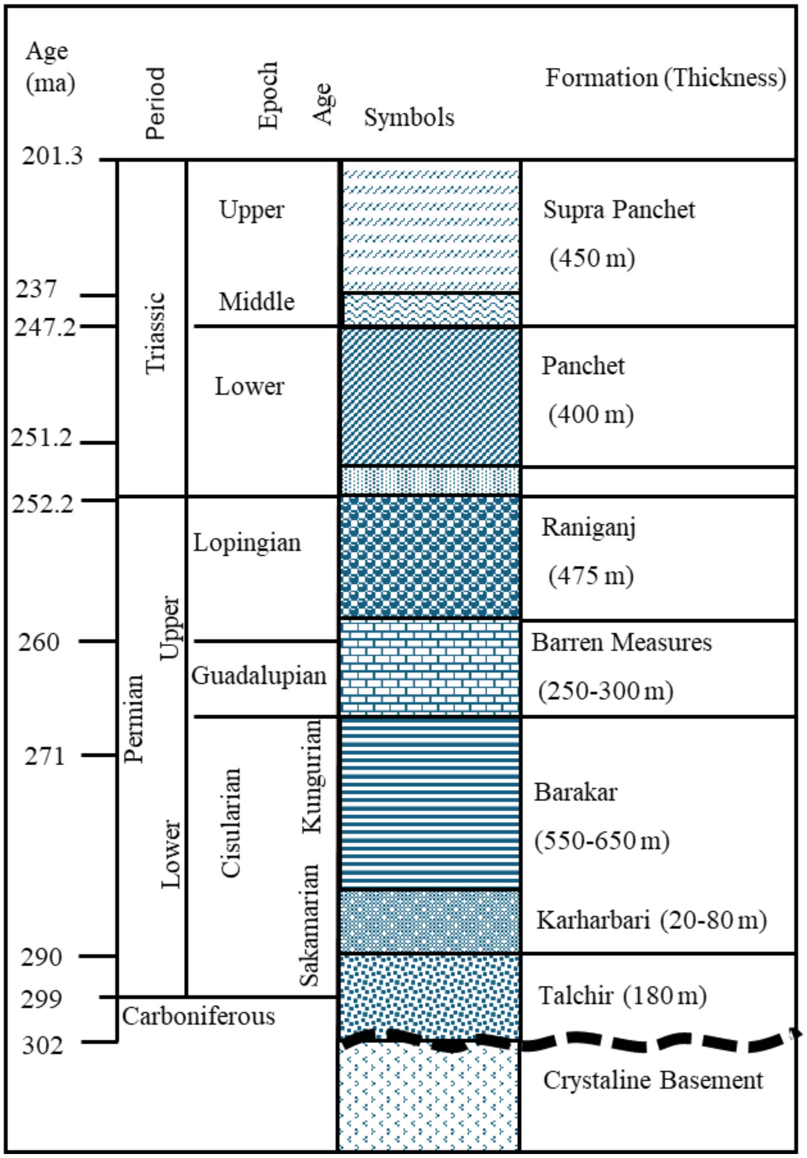


Figure 5: Generalized stratigraphic succession of West Bokaro basin modified after (Murthy 2017).

3 Methodology

Researchers use fossil records, pollen and spores, sedimentological records, geochemical composition and several other tools and techniques to interpret paleo-depositional environments (Spiro et al. 2019). Biological entities, sensitive to environmental changes, provide precise paleoenvironmental information, but their absence in some sediments can hinder predictions. Geochemical entities, while often present, can undergo post-genetic alterations, leading to potential inaccuracies. Therefore, integrating multiple methods offers a comprehensive understanding of the paleo depositional environment, with each technique complementing the others. Hence a holistic multi poxy analysis was considered for the identification of traces of marine transgression, in this region, at the time of sedimentation of the Barakar Formation.

3.1 Field Study: Sedimentology

Fieldwork covered areas along the Chhota Nadi River and coal mining pits near the villages of Ara and Dumerbera, close to Kuju town in Ramgarh District, Jharkhand, India. The area mapped by two of the authors SKB and MKS at the scale of 1:5000 (Figure 6) aiming at the following: (i) Identification of lithological characteristics and their lateral and vertical continuity, as well as the contact relationships with underlying and overlying sequences. (ii) Role of the faults in the disposition of the strata. (iii) Understanding changes in lithological features, such as grain size. This can help to determine whether the sequence is coarsening or fining upward, which can then be interpreted within the context of marine transgression-regression cycles. (iv) Identification of sedimentary and biogenic structures, which can provide essential clues for determining the sedimentary depositional environment. Coal seams are only exposed in the nala section and abandoned quarry. Accordingly, it has been marked in the map.

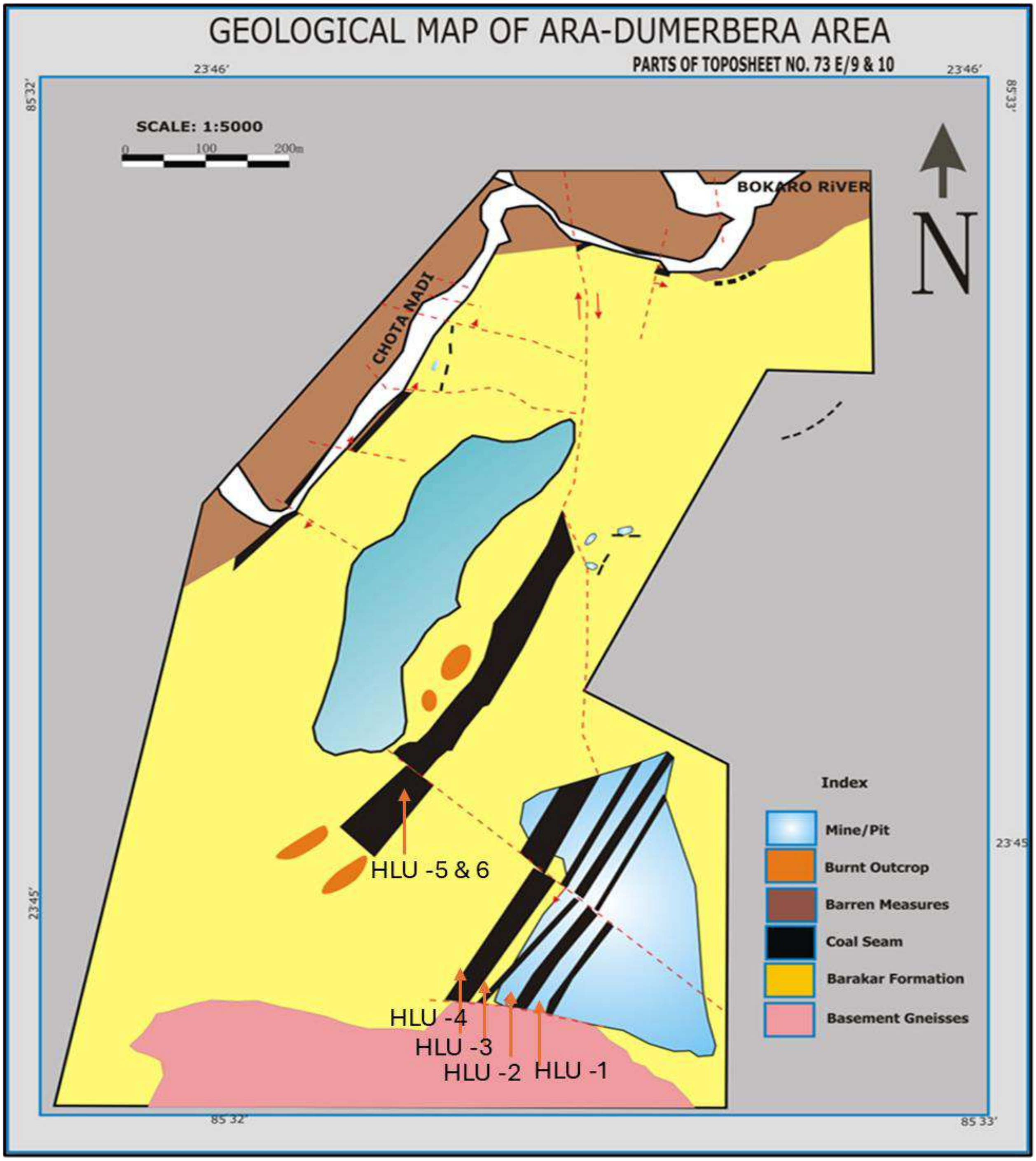


Figure 6: Map of the study area, near Ara and Dumerbera village, Kuju, District: Ramgarh, India.

3.2 Geochemistry:

Rock and coal surfaces were scraped using a mattock. Subsequently, fresh samples were obtained using the pillar sampling method and carefully packed to prevent contamination. A total of 54 coal samples (Heterolithic Unite (HLU) 1=7, HLU 3=15, HLU 5=15, HLU 6=17), 6 shale samples, and 4 sandstone samples were collected (Figure 7). During macroscopic examination, consecutive coal samples with similar characteristics were combined to reduce the sample count. Consequently, the number of coal samples was reduced to 24 (HLU 1=5, HLU 3=6, HLU 5=6, HLU 6=7), and the number of shale samples was reduced to four.

The coal samples were broken into smaller pieces and air-dried at room temperature in the laboratory. Once dried, the samples were crushed with a mortar and pestle, then sieved to achieve two mesh sizes: < 18 and < 72 mesh. A portion of the < 72 mesh samples was further ground to < 100 mesh using a Vibratory cup mill (HVC-2.065).

The samples were analyzed for minerals, major oxides, and trace elements using X-ray Fluorescence Spectroscopy (XRF). For XRF, press pellets were prepared from <100 mesh powdered coal, utilizing the natural moisture present in the coal and shale as a binding agent. XRF was conducted on Malvern Panalytical XRF Spectrometer at the Geology and Geochemistry laboratory, Rajiv Gandhi Institute of Petroleum Technology (RGIPT), Jais, India. This method identified major oxides and trace elements in coal and shale samples.

3.3 Micro-petrography:

For micropetrography, the coal and shale samples were crushed and sieved to a size of < 18 mesh. Particulate pellets were then prepared from these samples using cold-setting material without applying pressure. The sample pellets were polished and examined using an advanced petrological microscope (Leica DMP2700P) equipped with LASv4.6 analysis software and an imaging system. Immersion oil (refractive index of 1.518 at 23 °C) served as the medium between the microscope objective and the sample. The petrography followed the ICCP Classification (ICCP, 1998, 2001; Pickel et al., 2017) and ISO standard (ISO:7404-5, 2004). This analysis provided valuable insights into the mineralogic and maceral composition of coal and shale samples.

3.4 Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDX) Analysis:

The minerals in coal samples were examined through SEM-EDX. A chip of ~ 1 cm in size was extracted from coal sample, coated with gold, and analyzed using the SEM JEOL (Make), JSM-7900F (Model) in an airlock chamber at the Central Instrumentation Facility (CIF), RGIPT, Jais, India. The analysis identified various mineral types. Several line scans were performed on the sample to obtain insights into its elemental composition, facilitating the identification of minerals within the coal samples.

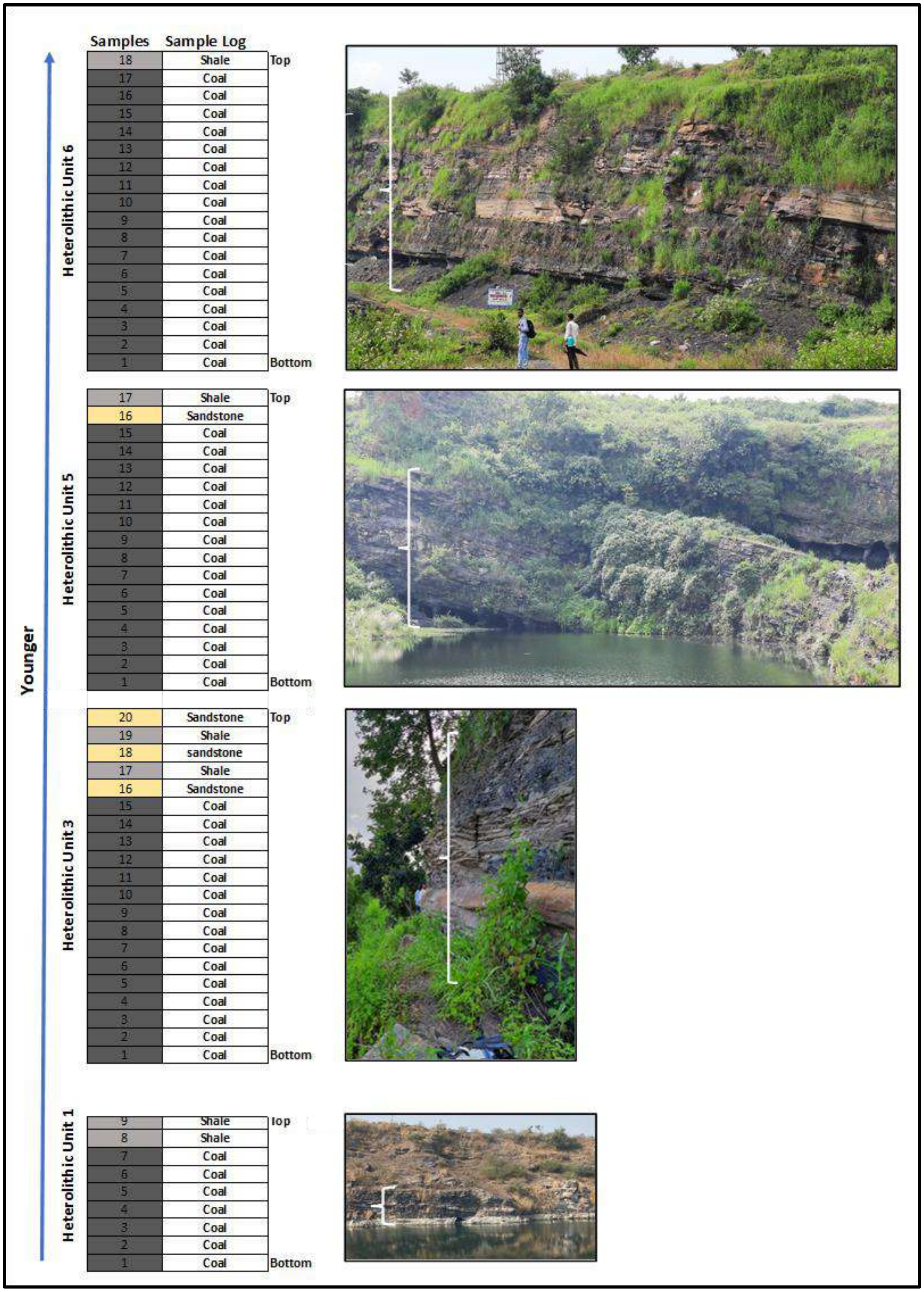


Figure 7: Sampling profile of four heterolithic units (younger at top), and their corresponding field photographs.

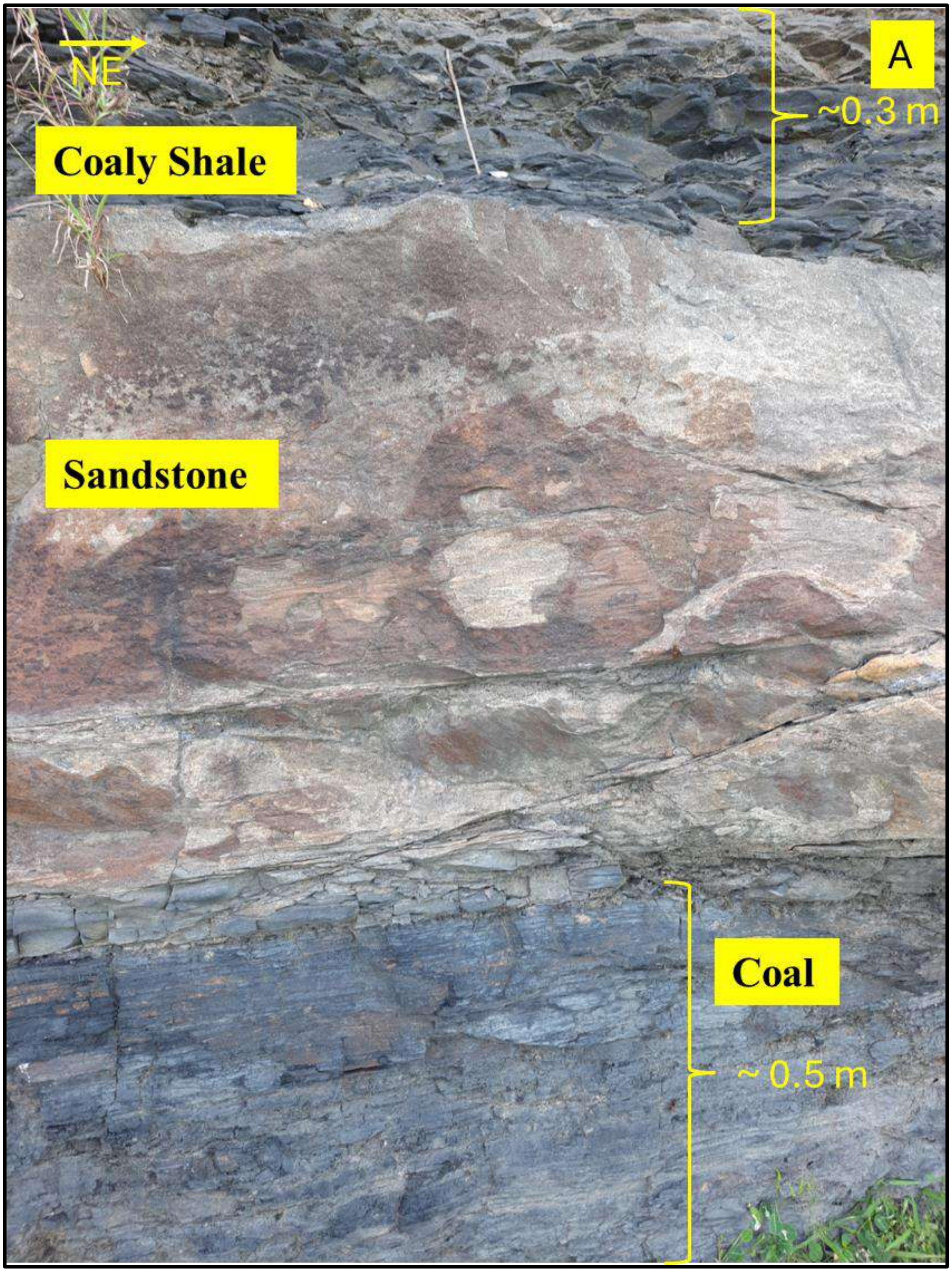
4 Results & Discussions

4.1 Field Evidence

The lithologic, bioturbation, and sedimentary structural characteristics were examined and recorded during the geological field work around Ara Mine, Kuju area. The geological succession is represented by ~ 610 m-thick sedimentary sequence of Barakar Formation. The following sedimentary facies, belonging to upper part of Barakar Formation have been identified in the studied area- *(i)* coal and coaly shale unit, *(ii)* splintery black shale facies; *(iii)* wavy and flaser bedded heterolithic facies *(iv)* sandstone with wave ripple laminated facies; *(v)* hummocky cross stratified fine grained sandstone facies; *(vi)* trough cross stratified sandstone facies; and *(vii)* epsilon cross-bedded sandstone facies. These facies are described below.

4.1.1 Coal and coaly shale facies: These facies are always present at the bottom of the heterolithic unit (Figure 8 A). The coal seam is 1-3 m thick. The coal typically appears dark and somewhat glossy, with a moderate specific gravity. It exhibits interlayer bands of vitrain-clarain and vitrain-durain, with negligible amounts of fusain present. These coals mostly lie in the macro lithotype category of banded to banded bright as per Diesel's classification (Figure 8 B).

Interpretation: The formation of these thick coal seams likely resulted from the accumulation of plant material and minor terrigenous sediments in a marsh environment (Scott 1987). Extensive coal layers developed in low-lying peat mires, where limited siliciclastic input allowed for the prolonged accumulation of vegetation. The brightness of these coals, attributed to the abundance of vitrain, reflects a high vitrinite content. This suggests that the peat swamps had excellent preservation conditions, with a consistently high-water table keeping the organic matter submerged and well-preserved. Periodic influxes of siliciclastic buried the organic material, eventually transforming it into coal. The presence of these facies alongside tidal-flat deposits indicates that the environment was plausibly a supratidal marsh.



289

Figure8: Vertical sections. **A**. Coal and coaly shale facies, and **B** banded to banded bright coal, exposed near Ara-Dumarbera village, Kuju, Ramgarh, India.

4.1.2 Splintery black shale facies: Black coloured carbonaceous shale, 0.5-1 m thick, splintery in nature. Parallel laminated, along the bedding plane an array of plant leaves is well preserved. Sometimes, thin coal units (10-20 cm thick) are present in between these lithofacies (Figure 9).

Interpretation: Deposited due to suspension fall out under stagnant calm water for quite a longer period. However, under deeper water conditions where anoxic conditions exist having input of plant debris (Schieber 1989; Arthur and Sageman 1994).

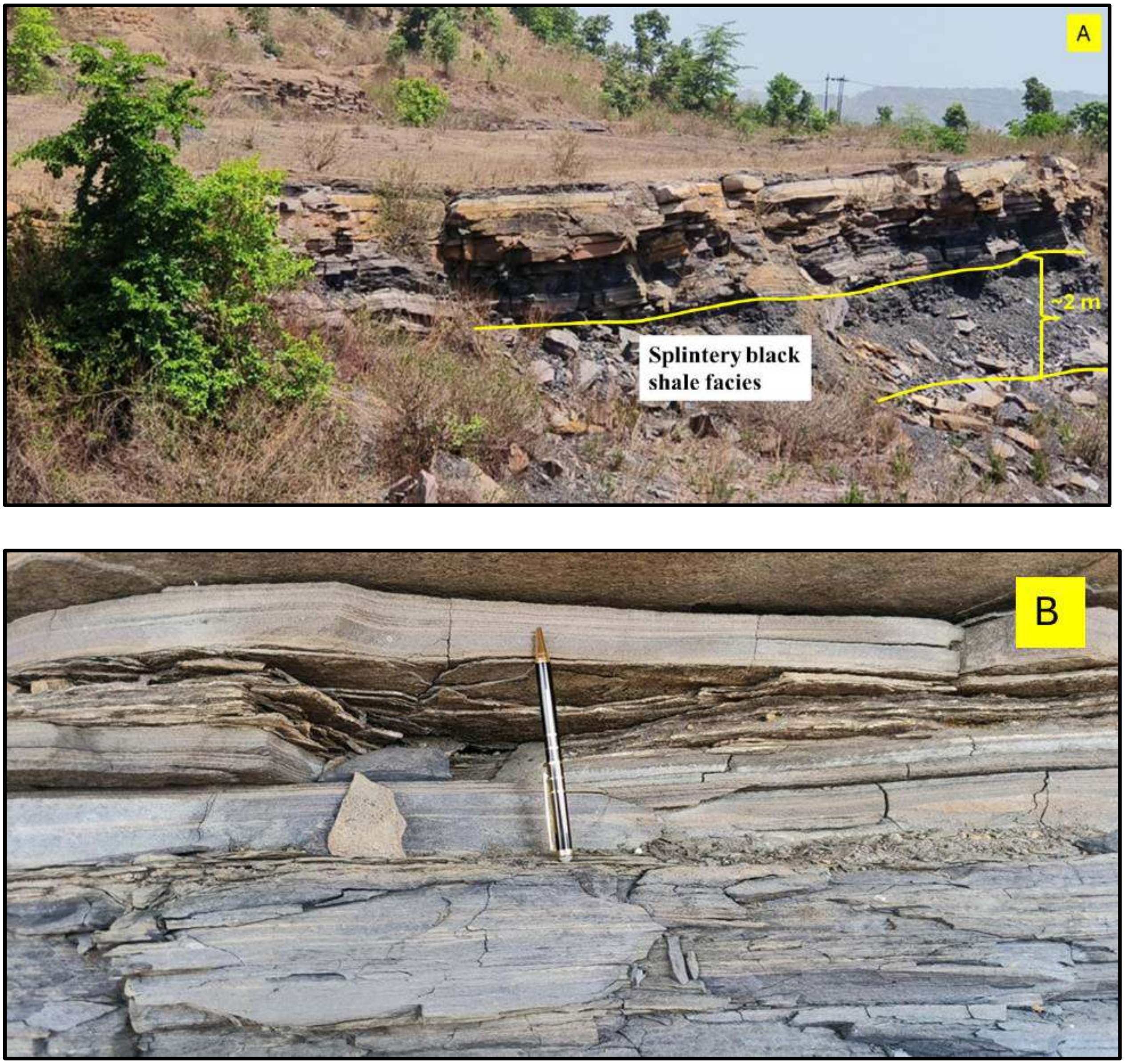


Figure 9: Vertical sections. **A**. Splintery black shale facies (viewing towards NNW) and **B**. Zoomed view of Splintery black shale facies, starting from the base of the pen, Part of HLU-3, exposed near Ara-Dumarbera village, Kuju, Ramgarh, India. (The length of the pen is 14 cm)

4.1.3 Wavy and flaser bedded heterolithic facies: At least 6 to 7 heteroliths were present in this area. Black to dark grey, 10 to 50 cm thick mudstones with thin siltstones and high concentration of plant debris. Falser and wavy bedded mm to cm thick sandstone–mudstone beds and lamination (Figure 10 A), shows systematic changeover between different beddings, present as heterolithic units of 10-20 cm thick. Cyclic sequence of coal, siltstone/black shale, siltstone-sandstone rythmites, and sandstone is commonly present within the heterolithic units. Fine to very fine grained bioturbated sandstone-mudstone heterolith with variety of ichnofossils having thickness of 20-60cm (Figure 10 B and C).

Interpretation: Characteristically formed in intertidal areas by alternate traction load and suspension load deposition (Reineck and Singh 1980). The cyclic sequence represents a tidal bundle characterized by a fluctuating coarsening-upward trend, formed as a result of marine transgression. Fine to very fine grained bioturbated sandstone-mudstone heterolith deposited under low energy calm condition with sub-aerial exposure.

Figure 10: **A**. Wavy and flaser bedded heterolithic facies, facing towards NNW, **B**. Plan view, Bioturbated fine-grained sandstone and mudstone with Diplocriterion, and **C**. Skolithos isp.

ichnofossils from part of HLU-3, Barakar Formation, Dumerbera Village, District: Ramgarh, India.

4.1.4 Sandstone with wave ripple laminated facies: These facies are characterized by fine-to-medium grained relatively well sorted sandstone with symmetrical oscillation ripples. Bundle up-building and mud-drapes are common features of these facies (Figure 11). At places, this unit also occurs as a part of the heterolithic facies.

Interpretation: Symmetrical ripples i.e. wave ripples formed by the oscillation of shallow waves with intermittent aerial exposures in an open shore environment (Reineck and Singh 1980).

Figure 11: Wave generated cross laminations, HLU-5 (demarcated by yellow arrow, facing towards N), Dumarbera village, Kuju, District: Ramgarh, India.

4.1.5 Hummocky cross-stratified fine-grained sandstone facies: These facies are comprised of moderate to well-sorted, fine-grained, buff, and light to dark pink color sandstone beds of couple of meters in thickness and of less lateral extension. The total thickness of these facies varies from 0.5 to 1 m and have discontinuous mud drapes. Mica flakes, mainly muscovite, is one of the dominant constituents of sandstone. Small scale wave ripples are also associated with these facies and are dominant at the upper part of these facies. In the Lower part, below Dumerbera Sandstone a Hummocks and Swales are preserved having ~ 1.5 m trough length (Figure 12 A, B).

Interpretation: Deposition might have taken place under storm generated oscillatory flows below fair-weather wave base i.e. mainly at sub-tidal zone of shoreface. The presence of mica flakes indicates deposition mainly under calm and quite condition where settling is dominated with an impulsive storm wave effect.

Figure 12: **A**. Hummocky cross stratified sandstone, (HLU-3), facing towards NNW. **B**. Zoomed view of hummocky cross-stratified sandstone, facing towards N (HLU-5), Barakar Formation, (paleocurrent direction demarked by yellow arrow), Kuju, District: Ramgarh, India.

4.1.6 Trough cross stratified sandstone facies: It is a coarse-grained, medium to poorly sorted, feldspathic sandstone, 1-2 m thick beds with scoured lower bounding surfaces having pebbles and conglomerate at the base. Two large-scale trough cross stratified sandstone beds were identified in the study area. The Dumarbera sandstone displays the characteristics of these facies and is exposed extensively in this area (Figure 13). The upper sandstone litho-unit is known as Parsatoli sandstone, which overlies the heterolithic unit.

Interpretation: It might be produced by the downstream migration of 3-D sub-aqueous dunes under relatively high flow regime (Leclair 2002). Scoured base has been formed because of erosion by the huge bed load under a high energy condition.

Figure13: Large-scale trough cross-bedded sandstone lithofacies showing unidirectional palaeocurrent (demarked by red arrow), Dumarbera Sandstone bed; Near Dumarbera village, Kuju, District: Ramgarh, India. (Facing towards ESE)

4.1.7 Epsilon cross-bedded sandstone facies: These facies are mainly observed in the Chota Nadi Section at the top of upper Barakar i.e. Parsatoli Sandstone. This is characterized by the large-scale trough cross stratified, multi-storied, coarse to very coarse-grained sandstone with lateral accretion surfaces. (Figure 14).

Interpretation: Lateral accretion surfaces formed as a product of the migration of point bar deposit under meandering channel (Willis and Tang 2010).

Figure 14: Epsilon crossbedding, present in Parsatoli sandstone beds, topmost part of the Barakar Formation, located on the right bank of the Chhota Nadi. (Facing towards N)

4.2 Geochemical evidence:

The presence and distribution of specific clay minerals, major oxides and trace elements are influenced by the depositional environment. As a result, their compositions and ratios can serve as indicators to reconstruct ancient depositional settings (Srivastava et al. 2024). A multiproxy approach has been chosen for the reconstruction of paleo depositional, as no specific proxy is robust enough to be used individually (Wei and Algeo 2020).

4.2.1 Major element geochemistry: Vassilev et al. (2010) documented in detail that certain oxide ratios have been employed in the literature as geochemical markers for coal formation, based on geochemical data derived from coal originating from diverse geologic settings (Vassilev et al. 2010). For instance, coal with low ratios of $CaO + MgO/K_2O + Na_2O$ and CaO/MgO indicates deposits influenced by marine or brackish conditions, saline lakes, or organic matter rich in algal remains (Ameh 2019; Vassilev et al. 2010). Elevated Mg concentrations in certain minerals are characteristic of coal beds affected by marine transgressions (Stach et al. 1982). Vassilev et al. (2010) reported that CaO/MgO ratios between 0.9 and 1.4 were found in coals influenced by marine or brackish water or enriched in algal remains, while coals with higher ratios were of non-marine origin (Vassilev et al. 2010).

In the studied coal samples, the value of Ca and Mg ranges up to 0.92 % (mean 0.39%) and 0.10 % to 0.53 % (mean 0.23%) respectively, whereas the CaO/MgO ratio ranges from 0 to 3.44 (mean 1.51). These values suggest that the coal seams may have experienced episodic marine / brackish water influence during peat accumulation or might have got contributions from algal remains.

The MgO/Al_2O_3 ratio also serves as an effective geochemical indicator for distinguishing marine from non-marine influences. MgO is typically more abundant in marine deposits, whereas Al_2O_3 is characteristic of continental weathered debris, often resulting from the breakdown of feldspar. The relationship between $\log(K_2O/Al_2O_3)$ and $\log(MgO/Al_2O_3)$ can be utilized to distinguish marine sediments from non-marine ones (Bhattacharjee et al. 2018). The studied samples plotted on the aforementioned graph clearly indicate that sediments were deposited in a marine environment (Figure 15).

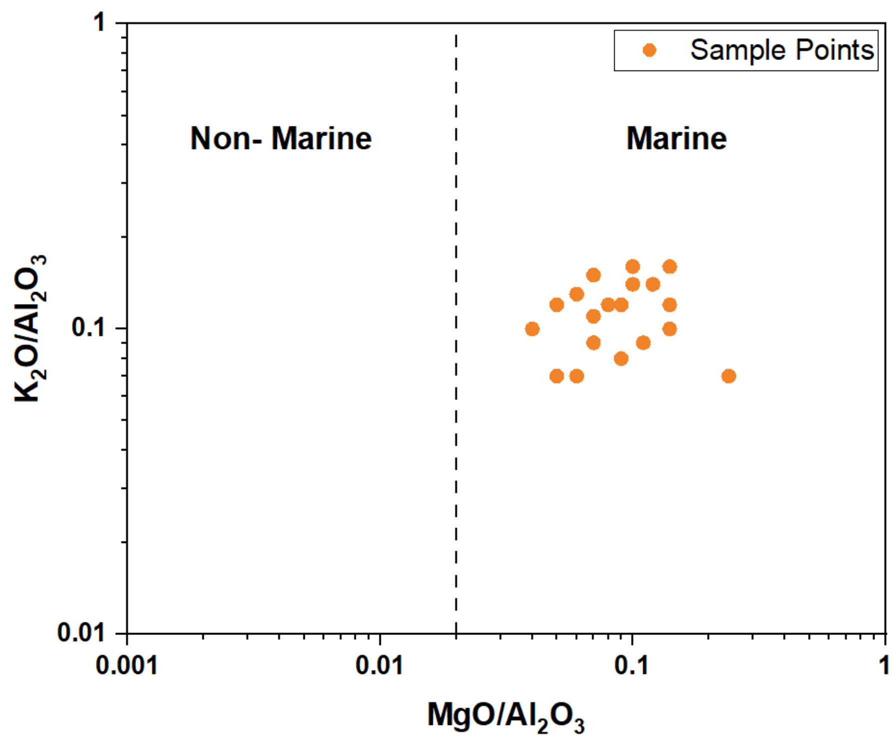


Figure 15: Log-Log Cross-plot between (MgO/Al_2O_3) and (K_2O/Al_2O_3) (as in Bhattacharjee et al. 2017) depicts the depositional environment of all the studied samples.

4.2.2 Trace element geochemistry: Strontium (Sr) and barium (Ba) are reactive alkaline earth metals frequently found on Earth as either sulfates ($SrSO_4$ and $BaSO_4$) or carbonates ($SrCO_3$ and

$BaCO_3$). In seawater, barium can appear as Ba^{2+} ions, $BaSO_4$ (barite), or as particulates in sediments. The concentrations of Sr and Ba are influenced by seawater chemistry and geological settings. Sr is more soluble in seawater compared to Ba and has a higher solubility product. Barium's concentration remains relatively stable in seawater due to lateral circulation, except in regions of upwelling or significant freshwater input (such as at large river mouths). Increased salinity promotes the precipitation of Sr over Ba, thereby elevating the Sr/Ba ratio (Zuo et al. 2020). Therefore, the Sr/Ba ratio serves as a geochemical marker for estimating paleo salinity levels. A ratio > 1 indicates seawater, between 1 and 0.6 suggests brackish water, and < 0.6 connotes freshwater (Li et al. 2018) . Concentration of Sr and Ba ranges from 0.02 % to 0.35 % (mean 0.12 %) and 0.05 % to 0.71 % (mean 0.23 %) respectively. The Sr/Ba ratio of the studied samples (0.25-1.12, mean of 0.6) suggests that the Barakar Formation experienced a variable depositional environment influenced by seawater, brackish water and freshwater inputs.

In another exercise, the concentrations of Sr and Ba (in ppm) marked on a Sr-Ba cross-plot, shows that the data points are dispersed within the marine facies to brackish water facies (Figure 16). The data in the plot depicts that heterolithic unit 3 was deposited entirely under seawater inundation, whereas heterolithic units 1, 5, and 6 were deposited in a transitional zone environment with lower salinity. This distribution indicates that the Early Permian coals of the Barakar Formation were predominantly deposited under the influence of marine transgression-regression cycle.

The Th/U ratio is often used as a geochemical proxy to infer paleoenvironmental conditions, including paleo-salinity, though it provides an indirect determination. This ratio is particularly valuable in sedimentary geology for assessing paleo-redox conditions. Typically, reducing conditions are associated with freshwater or low salinity, while oxidizing conditions are linked to marine environments. Thorium (Th) is relatively immobile in low-temperature surface environments and remains in a constant oxidation state (Wei et al. 2023), whereas Uranium (U) is more mobile and can exist in multiple oxidation states (Cumberland et al. 2016). In reducing (anoxic) environments, U is often reduced to U^{4+} and precipitates out of solution, resulting in higher Th/U ratios. Conversely, under oxidizing conditions, U remains as U^{6+} and is more soluble (Borch et al. 2010), leading to lower Th/U ratios. Thus, a high Th/U ratio indicates reducing or freshwater geological settings, while a low Th/U ratio indicates oxidizing or marine conditions. Typically, a Th/U ratio > 7 suggests a terrestrial freshwater environment, a ratio between 2-7 indicates a brackish water environment, and a ratio < 2 points to a marine/saline environment (Fu et al. 2018). The Th/U ratio of the studied samples ranged from 0.93 to 4.78 (mean 2.53), indicating a brackish to saline water condition was prevailing at the time of deposition of the Barakar Formation.

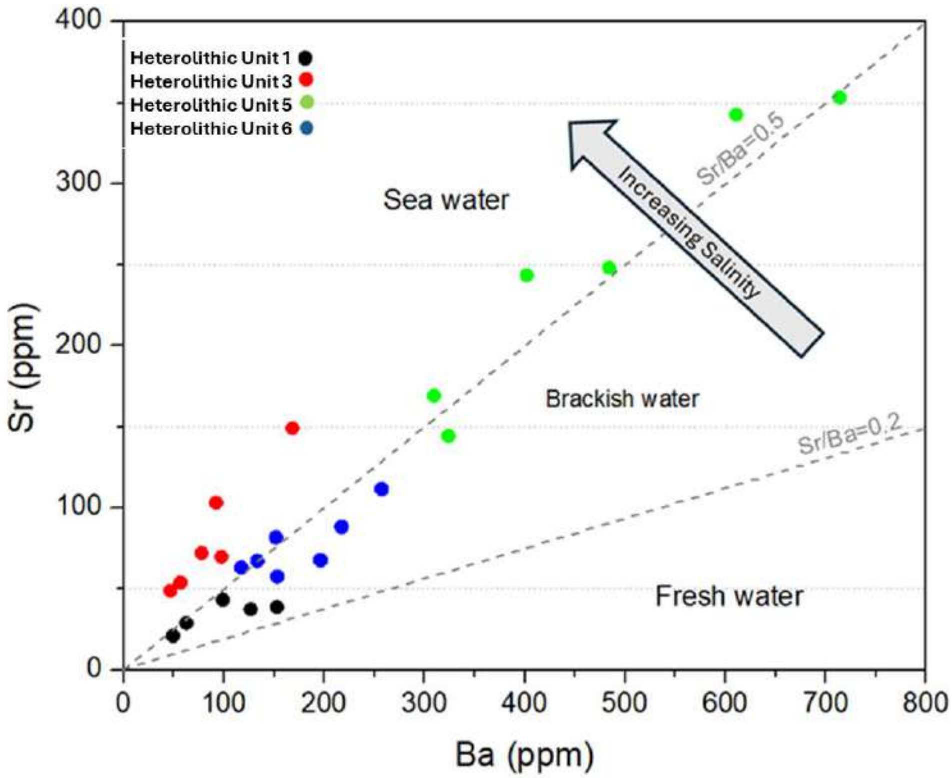


Figure 16: Plot of concentrations of Sr and Ba (Cao et al. 2022). show salinity in the coal samples collected from different heterolithic units in the study area.

In another cross-plot analysis between Th/U and Sr/Ba, a similar interpretation can be drawn: heterolithic unit 3 falls entirely within the seawater region, whereas heterolithic units 1, 5, and 6 fall between the seawater and brackish water regions. This supports the notion of a fluctuating depositional environment with frequent seawater inundation (Figure 17).

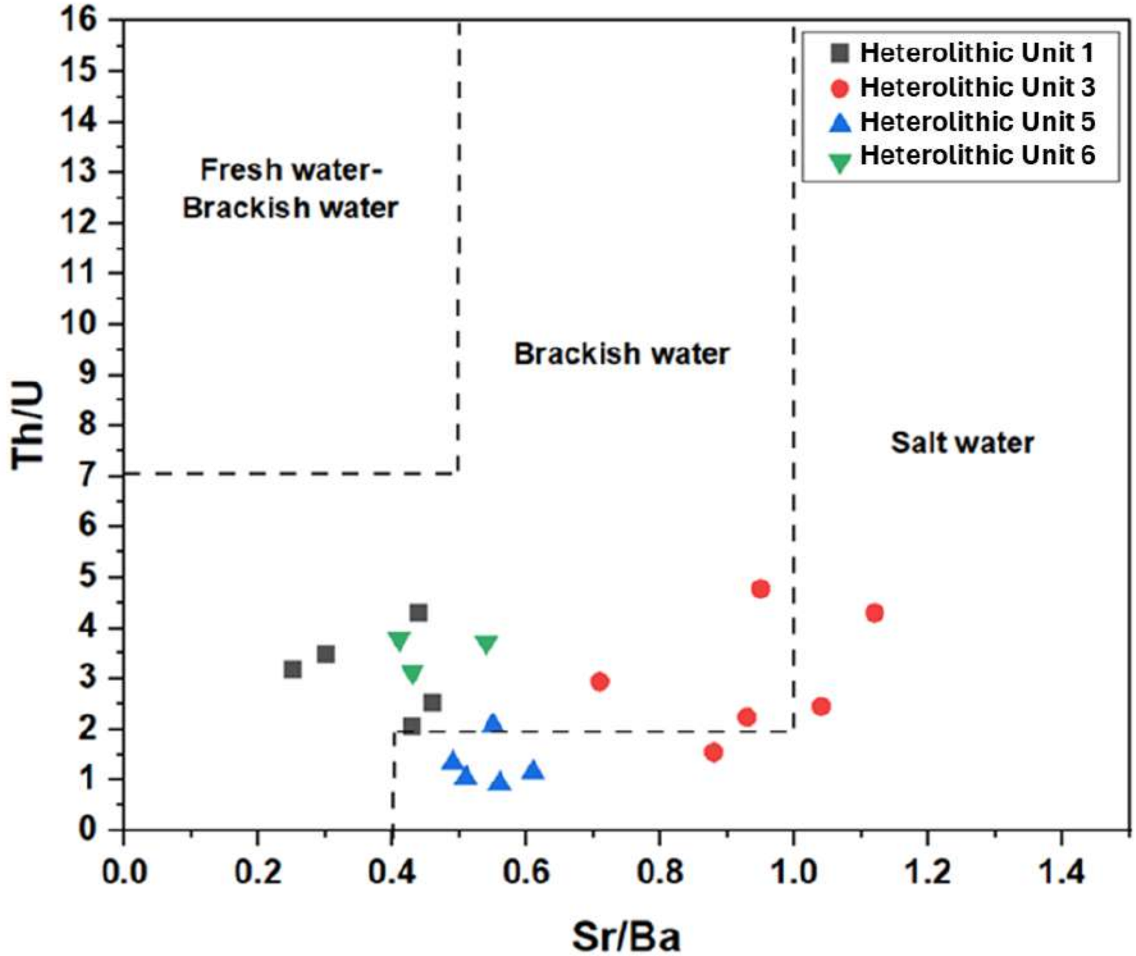


Figure 17: Cross-plot between (Th/U) and (Sr/Ba) (Pillai et al. 2023) depicting the depositional environment of the samples studied.

4.3 Mineralogical Evidence:

Carbonates are characteristic authigenic minerals in these coals, as evident from reflected light petrography (Figure 19 A-F). They most often either embed macerals, particularly collotelinite, or appear as crack-filling material in collotelinite or chamber-filling material in fusinite. The occurrence patterns of authigenic carbonates in coal sometimes indicate multiple phases of formation, spanning major syngenetic and epigenetic stages (Vassilev and Vassileva 1996). As observed during reflected light petrography, siderites are mostly present either as independent concretions (Figure 19 F) or show growth over collotelinites, whereas dolomites mostly embed collotelinite, reflecting a precipitation structure covering collotelinite or other macerals. The calcites are mostly present as crack-filling or chamber-filling material. Observation from the samples studied indicates that siderite and dolomite are syngenetic types, consistent with their recognized global occurrence in coal deposits (Taylor et al. 1998).

4.3.1 Dolomite: The SEM-EDX analysis of coal samples from the study area reveals the presence of various minerals and macerals. Line scans across several mineral assemblage groups indicate the presence of minerals such as clay, silicates, and most notably, carbonates (Sample S3/B4). In some areas, calcite was identified, and nearby, dolomite was also detected (Figure 18). Additionally, the XRF analysis shows a high magnesium content in most samples, with exceptionally high levels observed in a few specific samples. The high Ca and Mg levels are linked to various causes including (1) formation of Mg-rich carbonates and sulfates; (2) Mg bound to organic matter; (3) biogenic sources e.g., plants and fossils; (4) weathering of sulfides and precipitation from water; and (5) detrital minerals e.g., montmorillonite, chlorite, and authigenic minerals like brucite(Vassilev et al. 2010).

However, in this case the elevated levels of Mg are mostly attributable to the deposition of syngenetic Mg-rich carbonate (dolomite). Source of Mg^{+2} that transforms calcite to dolomite comes from marine or diagenetic environments. The dolomites in this case appear mostly in the form of independent micro nodules or embedded coal particles. The possibility of diagenetic alteration of calcite is less probable as no signs of active hydrothermal fluid were found by the elemental geochemical analysis ($Al/(Al+Fe+Mn)>0.4$ and $(Fe+Mn)/Ti<15$). The elevated concentration of magnesium indicates a saline environment, often associated with saline lakes or coal deposits influenced by marine transgressions (Vassilev et al. 2010). Marine influence in the dolomitization of coastal peat swamps occurs when magnesium-rich seawater infiltrates the swamp environment during high tides, storm surges, or sea-level changes. This introduces magnesium into the peat swamp, transforming calcium carbonate (from shell debris or plant material) into dolomite. The interaction between marine waters and organic-rich sediments can create conditions favorable for dolomitization, especially in areas where saline and freshwater mix, altering the geochemistry of the swamp and influencing mineral deposition.

4.3.2 Siderite: Siderite was identified in only a few samples (S5/B3, S5/B4) (Figure 20) during micropetrography, but where present, it appeared in abundance. It is commonly observed forming on collotelinite grains or nucleating around other macerals, with typical radiating structure or concretions embedded on a maceral (Figure 20).

Sideritization refers to the formation of the mineral siderite ($FeCO_3$) through the interaction of iron with dissolved CO_2, which is often produced by the decomposition of organic material. This mineralization typically occurs in reducing settings with low sulfur content, such as coal seams or organic-rich sediments. It is particularly characteristic of coal deposits formed in freshwater environments, where sulphate-rich seawater and sulfide ions are absent, and under conditions that promote strong reduction (Vassilev et al. 2010). However, the presence of siderite in modern salt marshes, such as one present in Norfolk, UK, (Pye 1984; Pye et al. 1990) indicates that the precipitation of siderite is more complex than previously assumed and might get affected by the microbial activity (Lin et al. 2020a).

Siderite can only form in specific environmental conditions. It needs an oxygen-free (anoxic) environment because dissolved iron (Fe^{2+}) reacts with carbonate ions (CO_3^{2-}) to create siderite, but iron quickly oxidizes in the presence of oxygen. Additionally, hydrogen sulfide prevents siderite formation by reacting with dissolved iron to form other minerals (Lin et al. 2020a).

For siderite to form, pH must be between 6.0 and 7.2; lower pH delays carbonate precipitation, while higher pH favors the formation of other minerals like calcite. The process usually involves microbial activity that generates dissolved iron and alkalinity, but just having bacteria that reduces iron often raises the pH too high for siderites to form. So, additional conditions are needed for the siderites to develop (Lin et al. 2020a). Siderite can form in the environments where iron reduction takes place faster than sulfate reduction, resulting in an insufficient amount of dissolved sulfide to bind with all the available ferrous iron in the solution (Pye et al. 1990). Thus, based on comparisons with modern sedimentary environments, such as intertidal marsh and sandflat sediments of Norfolk, England (Pye et al. 1990; Lin et al. 2020b;), it is likely that these siderites also formed in an intertidal setting.

4.3.3 Pyrite: Fe sulfides are typical authigenic minerals in many coals (Vassilev and Vassileva 1996). However, in the currently studied samples, pyrite is relatively scarce (S3/B1 and S6/B5). Despite its low abundance, it appears in various forms, most commonly as isolated crystals dispersed within collotelinite macerals or, on several occasions, as encrustations in the cell lumens of fusinite, where mineral deposits are preserved in the plant cell structure. In rare cases, pyrite is also observed filling cracks within collotelinite (Figure 21). Based on its mode of occurrence, pyrite appears to be syngenetic. Its crystallization is likely associated with pH shifts in the micro-environment during and after coal formation. While the limited presence of pyrite does not strongly support a conclusion in favor of marine incursion, their intermittent occurrence in the sample column suggests a shifting micro-environment within the swamp.

Dolomite (S3/B4) and siderite (S5/B3, S5/B4) are not found together in the same sample; rather, each dominates the mineral assemblage in separate samples, with one being dominated by siderite and little to no dolomite (S5/B3), and vice versa. Based on the present mineralogical investigation, the authors suggest that the coal-bearing heterolithic units of the Barakar Formation were likely deposited in a marginal marine environment. Coastal lagoons or salt marshes, separated from the open sea by a barrier, may have experienced periodic seawater intrusion driven by fluctuations in relative sea level.

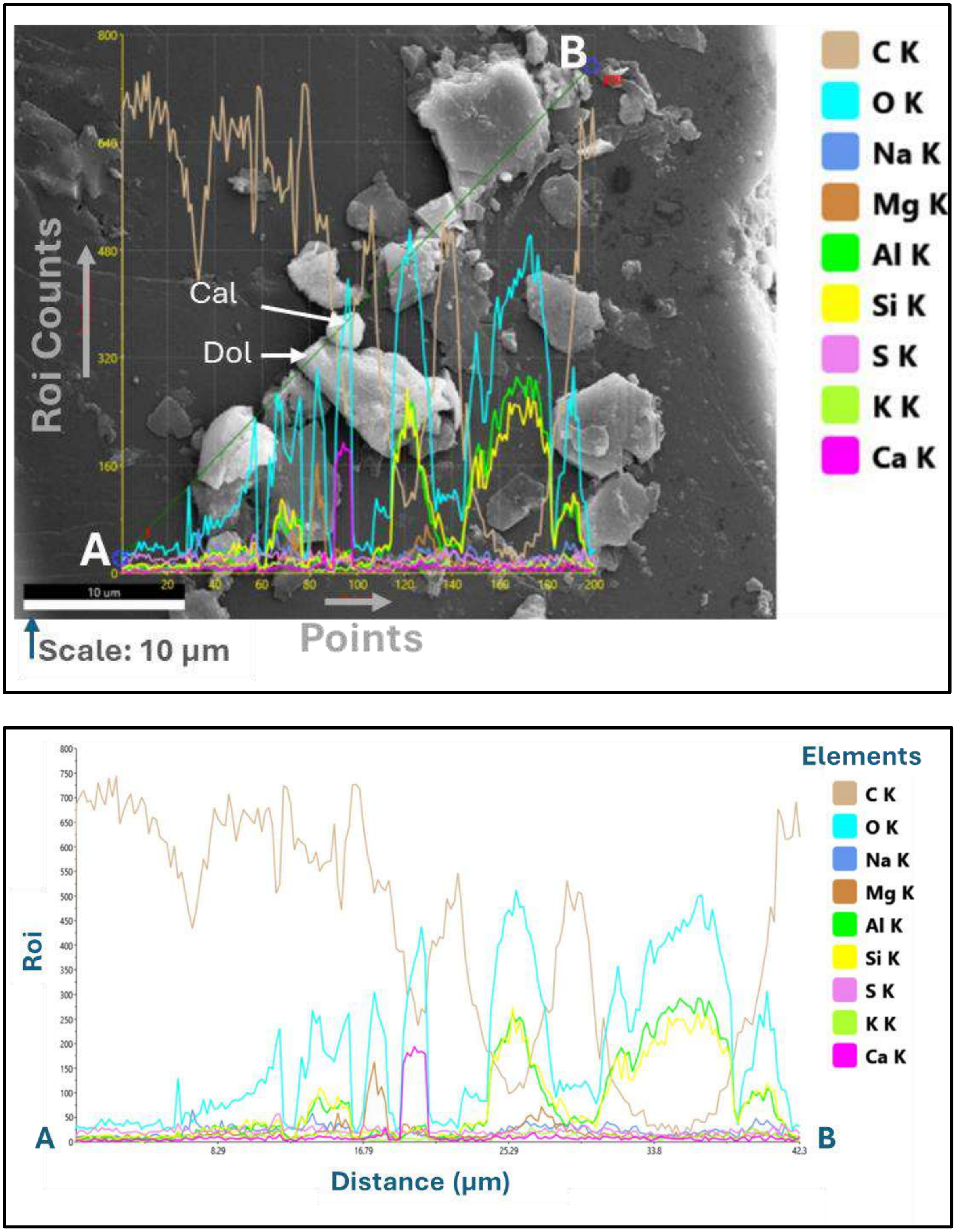


Figure 18: Line scan across line A and B, and corresponding spectra depicting different elements (Cal- Calcite, Dol- Dolomite), using SEM EDS profiling.

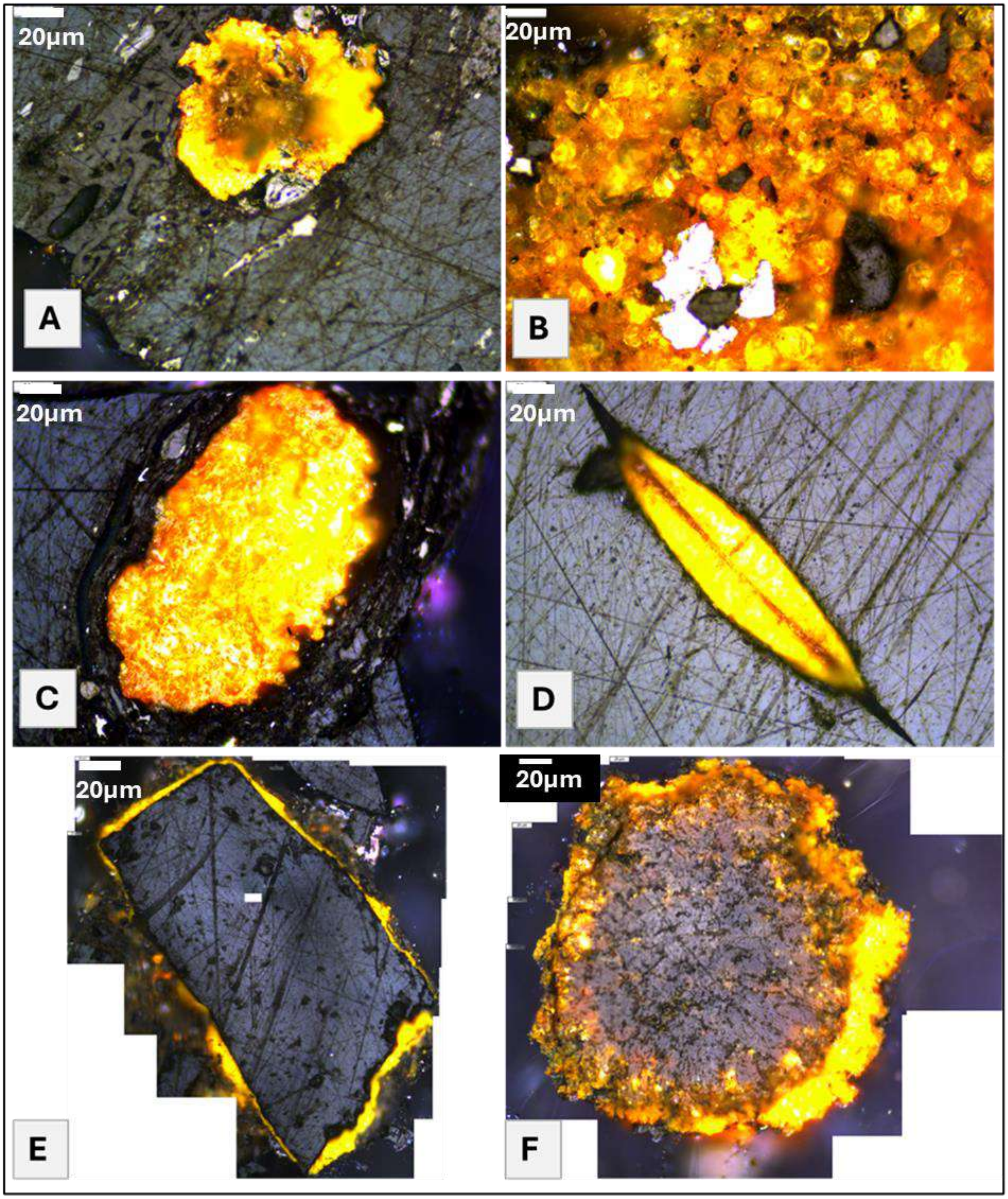


Figure 19: Coal micro-petrography image of **A**. Fe bearing Calc nodule precipitated on collotelinite, **B**. Calc nodule in cluster, **C**. Calcite precipitated on collotelinite, **D**. Calcite filling the elliptical crack in collotelinite, **E**. Euhedral collotelinite embedded in carbonate, and **F.** Siderite nodule

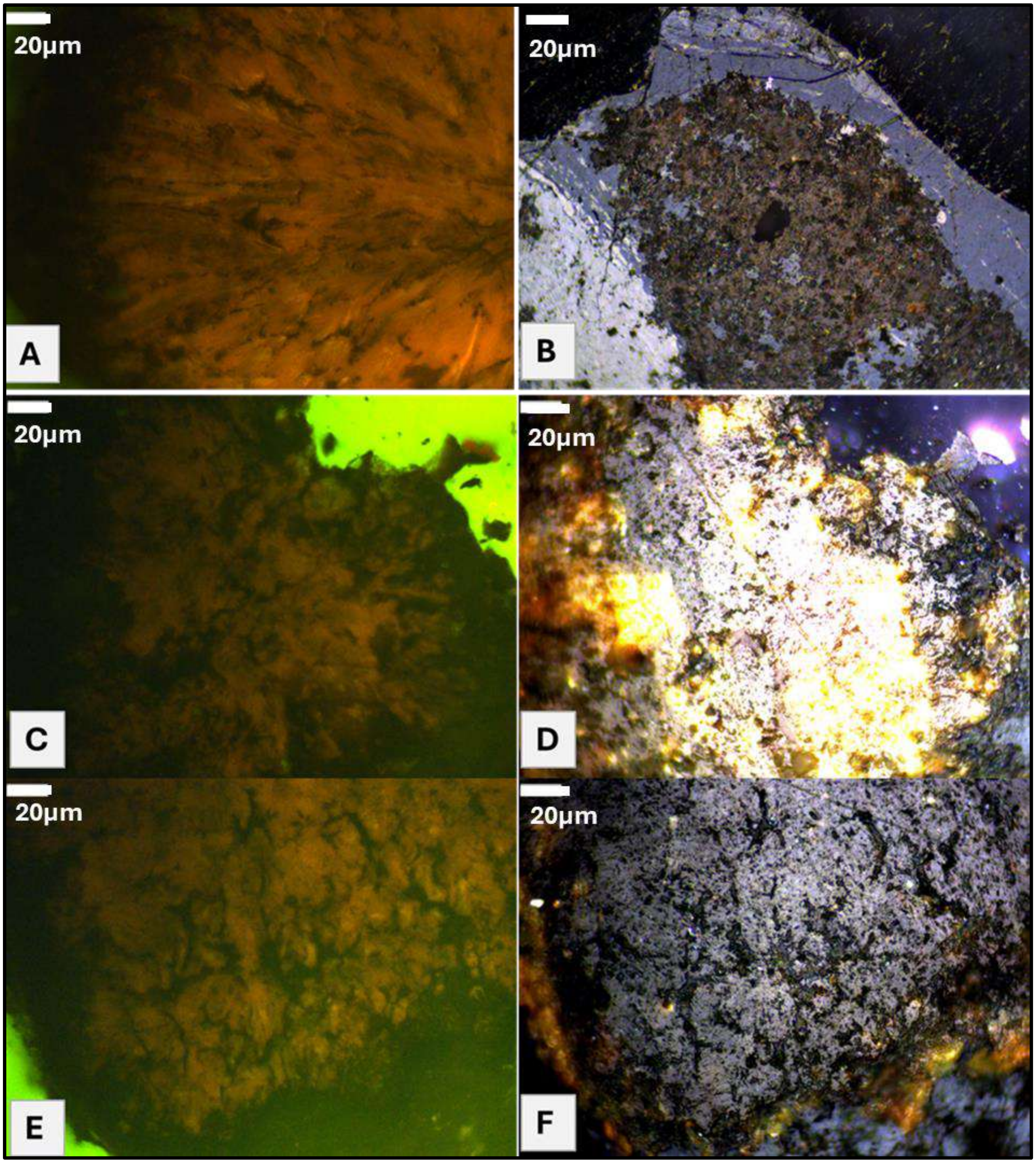


Figure 20: Coal micro-petrography: **A**., **C**., and **E**. are images of siderite in fluorescent (Blue light) with typical radiating structures in the nodules, and **B**., **D**., and **F**. are images of siderite nodule in white light.

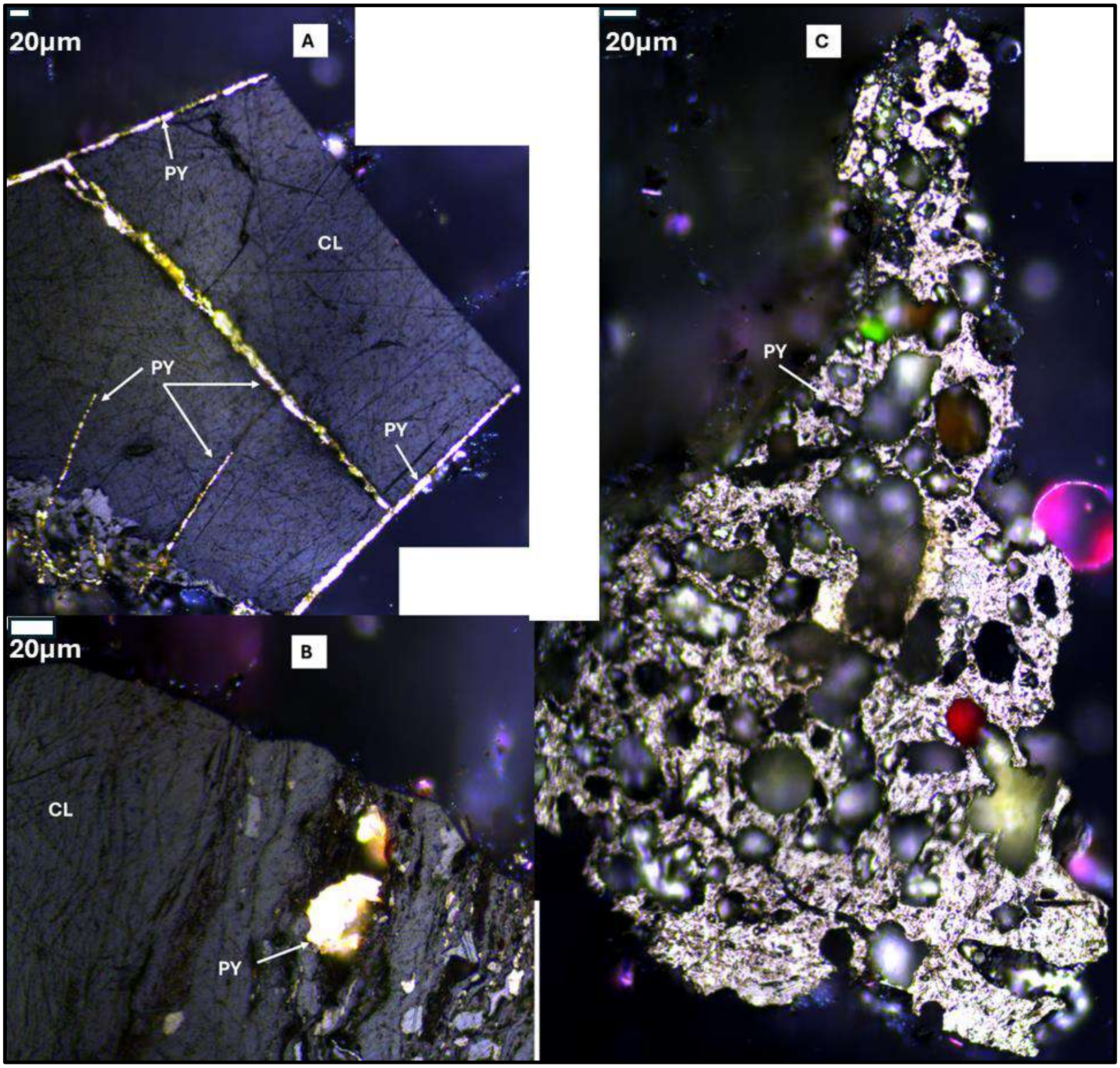


Figure 21: Coal micro-petrography: **A**. Collotelinite (CL) cracks filled with pyrite, **B**. Irregular pyrite (PY) crystal developed on collotelinite, and **C**. Encrustations of pyrite on the cell lumens in fusinite.

4.4 Organic micro-petrographic evidence:

Coal samples for the study area are dominated by Vitrinite followed by Inertinite and Liptinite group of macerals. The collotelinite is the most abundant sub-maceral, followed by Vitrodetrinite and Collodetrinite among the vitrinite group. Among Inertinite, Fusinite is most abundant followed by Semifusinite, Inertodetrinite, Scleoritinite and Macrinite. Micrinite were also present at several locations. A wide variety of liptinite macerals were observed, among which Sporinite, Cutinite, and Alginite are abundantly present. A rare occurrence of Suberinite was discovered from Seam 6. Megasporinite and Fluorinite were also present in several samples.

The abundance of alginite in the limited coal samples suggests that the mire developed under subaquatic conditions. Out of the two alginite types identified, lamalginite was more prevalent than telalginite. Telalginite consists of discrete algal bodies, both colonial and unicellular, such as Botryococcus, Tasmanites, and Gloeocapsomorpha (a primitive blue-green algae). In contrast, lamalginite comprises benthonic or pelagic lamellar algae (green or blue green) that occur as finely laminated bands, interbedded with mineral matter either finely or coarsely (Singh and Singh 2004). According to Misra et al. (1998), the presence of alginite in coal and lignite deposits indicates a mixed marine environment, typically nearshore settings (Misra et al. 1998). They further noted that the mode of occurrence, frequency, and preservation state of alginite reflect seasonal paleoenvironmental fluctuations, particularly variations between oxidizing and reducing conditions during the accumulation of vegetal matter (Misra et al. 1998). The coal seam is associated with heterolithic units 3 and 5, where alginite is frequently observed as a liptinite sub-maceral (Figure 22). This suggests that at least these units developed under marine-influenced conditions. The maceral analysis aligns well with geochemical data, both clearly indicating that heterolithic units 3 and 5 were affected by marine transgression.

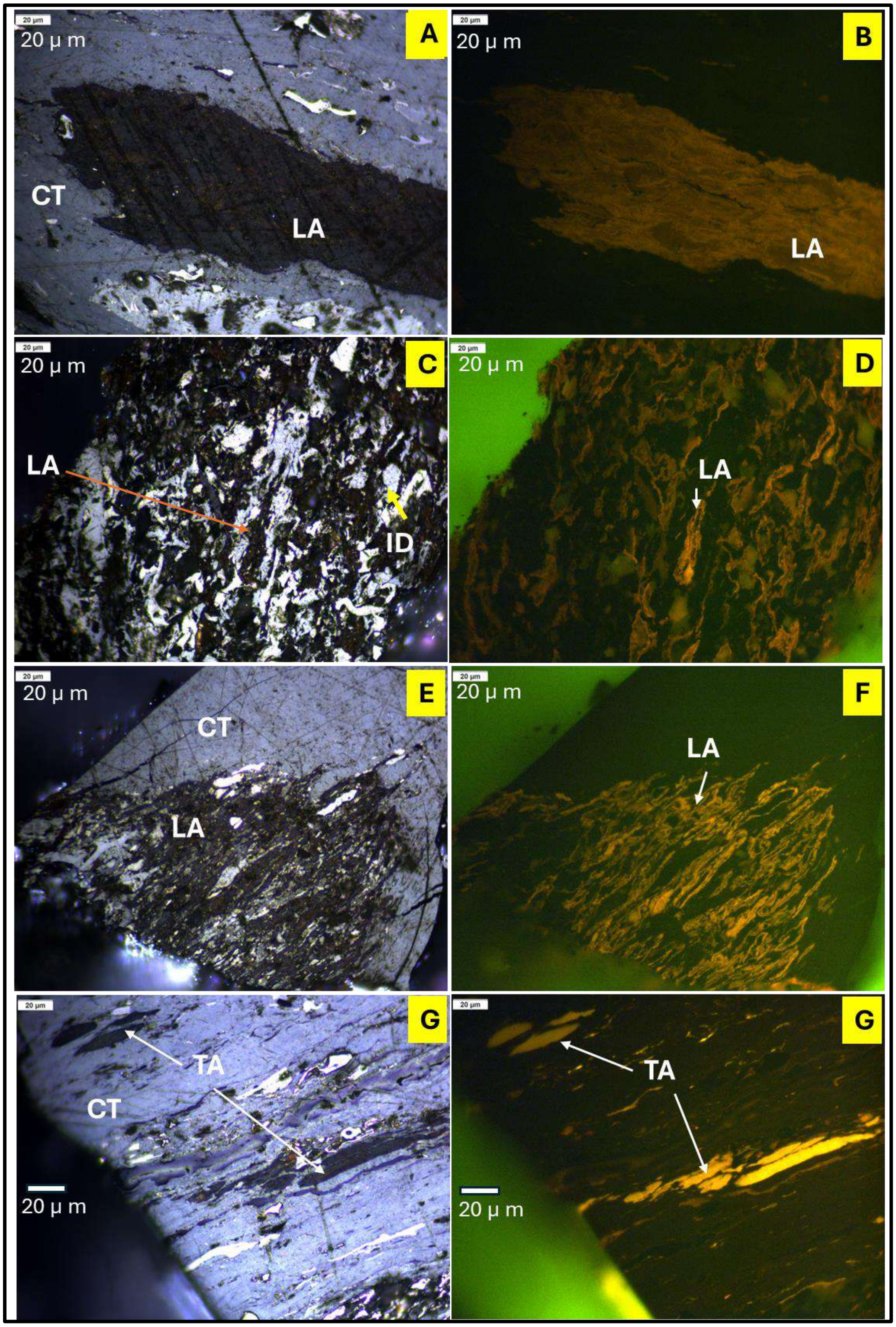


Figure 22: Micro-photograph **A**., **C**., **E**., and **G**. under white incident light, and **B**., **D**., **F**., and **G**. under blue incident light where, LA=Lamalginite, TA=Telalginite, CT=Collotelinite, ID= Inertodetrinite, coal sample from seam 3 (heterolithic unite 3) and 5 (heterolithic unite 5).

5 Depositional Model:

The Gondwana basins of India preserve a nearly 200 Ma long geological archive within Peninsular India. Initially formed as sag basins, they later transitioned into fault-controlled systems due to widespread tectonic reactivations, mainly linked to pan-Gondwanan geodynamic events. The sedimentary fill is largely siliciclastic and was primarily deposited in continental environments. However, distinct marine signatures are evident within the Early and middle Permian sequences across several Gondwana basins. Detailed investigations of the Indian basins indicate that sedimentation within the Gondwana Basins was shaped by a dynamic interaction of tectonic faulting, sea-level fluctuations, and climatic variations (Mukhopadhyay et al. 2010).

Talchir Formation exposed in the northwestern part of the West Bokaro basin, has already been established as a glaciogenic deposition with marine influence at the top (Sengupta; et al. 1999). In contrast, the overlying Karharbari Formation shows no evidence of marine influence and is interpreted as a fluvio-lacustrine deposit (Bhattacharya et al. 2005). The HLU, representing the middle to upper part of the Barakar Formation and covering the major portion of the study area, appears to have been deposited in a marginal marine environment, as revealed by the present multi-proxy approach. This interpretation is supported by field studies, geochemical proxies, mineral and macerals assemblage of coal samples.

Geochemical markers in the studied coal samples suggest intermittent marine or brackish water influence during peat accumulation. The CaO/MgO ratio (ranging from 0 to 3.44, with a mean of 1.51) aligns with values reported for marine-influenced coal deposits. Additionally, the MgO/Al_2O_3 ratio further supports marine influence, as MgO enrichment is characteristic of such environments. The log (K_2O/ Al_2O_3vs. log (MgO/ Al_2O_3) plot confirms that the sediments were deposited under marine conditions. These findings indicate that the coal seams experienced multiple episodes of marine transgression or contributions from algal remains during their formation. Geochemical proxies, including Sr/Ba and Th/U ratios, indicate that the Barakar Formation experienced a dynamic depositional environment influenced by fluctuating seawater, brackish water, and freshwater conditions. The Sr/Ba ratio (0.25 to 1.12, mean 0.6) suggests variable salinity levels, with HLU-3 deposited under full marine inundation, while HLU-1, HLU-5, and HLU-6 represent transitional brackish settings. Similarly, the Th/U ratio (0.93 to 4.78, mean 2.53) confirms brackish to saline conditions, supporting a marine transgression-regression cycle.

Cross-plot analyses further reinforce this interpretation, highlighting periodic marine incursions that shaped the depositional environment of the Early Permian Barakar coals.

The presence of authigenic carbonates (Figure 19), including dolomite (Figure 18) and siderite, in the studied coal samples suggests deposition in a marginal marine environment. Dolomite formation indicates periodic marine influence, likely through seawater infiltration into coastal peat swamps, while siderite rich coal (Figure 20) deposits typically associated with freshwater conditions, low sulfur content, absence of sulfate-rich seawater and sulfide ions, and strongly reducing environments (Vassilev et al. 2010). In contrast, they may also get deposited on salt marshes e.g. Norfolk coast, UK. Their mutually exclusive occurrence suggests fluctuating depositional conditions, influenced by sea-level changes. Limited pyrite (Figure 21) occurrence further supports intermittent marine incursions. Overall, the coal-bearing heterolithic units of the Barakar Formation were likely deposited in a coastal lagoon or salt marsh setting, periodically affected by seawater intrusion. The existence of alginite maceral (Figure 22), a transformational product of algae, suggests deposition in a stagnant water condition in a peat swamp environment, likely within a supratidal salt marsh (Figure 24).

Sedimentological studies exhibit subtidal to supratidal facies, influenced by intermittent fluctuations of wave energy, ranging from strong to weak, due to open marine storms, and at least at two interval fluvial systems prevailed and resulted in the deposition of two thick trough cross stratified sandstone locally named Dumarbera and Parsatoli Sandstone (Figure 5,13 and 14). The coexistence of wave ripples and tidalites (Figure 10, 11, and 23B) in the HLU suggests an environment where low-energy wave and storm processes interacted with tidal currents. These conditions favored the deposition of fine- to medium-grained sandstones and heterolithic facies, typical of tidal flats, with sedimentary structures reflecting shifting energy conditions. Further, at least five coarsening upward sequences have been reported from the HLU-5 and 6 exposed under quarry no 18 D (Figure 23A), which exhibits tidal bundles, where coal/shale/siltstone present at the bottom of the sequence represents supratidal condition, sandstone- siltstone rhythmites represents intertidal and sandstone represents subtidal condition (Figure 23B). Typically, coal swamps formed due to marine regression, in this case they developed as a result of marine transgression. Similar to the current scenario in the North Sea, the advancing sea pushes the rising groundwater table landward, leading to the formation of new swamp belts. Tidal flat or coastal marine swamps, in particular, become inundated by the sea during transgressive events (Taylor et al. 1998).

During the transgressive phase, the landward migration of the shoreline resulted in a coarsening-upward sequence (Figure 23 A, 24). This is observed in the case of the HLU, where coal and coaly shales present at the base were deposited in a supratidal marsh environment (Figure 23 B). The middle part of the sequence, characterized by rhythmic interbedding of siltstone and shale, represents an intertidal setting, whereas the overlying sandstone reflects subtidal conditions (Figure 23 B). Accordingly, HLU-1 to HLU-4 are interpreted to have been deposited during a transgressive phase over a tidal flat. The Dumarbera Sandstone, a trough cross-bedded sandstone unit, was likely deposited by meandering or braided streams that developed over the supratidal flats during a regressive phase. A renewed marine transgression is marked by the deposition of HLU-5 and HLU-6, followed by the Parsatoli Sandstone unit, which represents another regressive phase. A more extensive marine transgression subsequently led to the deposition of the Barren Measures Formation, as previously demonstrated by Bhattacharya and Banerjee (2015) (Figure 25) (Bhattacharya and Banerjee 2015).

The Bokaro Basin, a sub-basin within the larger Damodar Basin, lies between regions where marine influence during the Early to Middle Permian has already been established, from the underlying Talchir Formation and overlying Barren Measures above (Bhattacharya and Banerjee 2015; Bhattacharya and Mukherjee 2020). Surrounding basins such as Rajmahal and Raniganj to the northeast and east, respectively; and Karanpura, Rajhara, Ramgarh, up till Satpura basin to the west, have also revealed evidence of marine conditions during Barakar sedimentation (Gupta 1999; Chakraborty et al. 2003; Ghosh et al. 2004; Goswami 2008; Bhattacharjee et al. 2018; Mathews et al. 2020; Bhattacharya et al. 2021, 2012a; Pillai et al. 2023).. Even within the West Bokaro Basin itself, marine signatures have been identified at the transition from the upper Barakar to the Barren Measures (Pathak et al. 2024). However, a definitive record of marine incursion during the Barakar deposition in this basin remained unresolved. The present study addresses this gap by documenting clear evidence of marine influence during Barakar sedimentation in the West Bokaro Basin. This contribution helps delineate a near-continuous marine incursion pathway-extending from the Khemgaon, Sikkim corridor through Rajmahal and Raniganj, reaching as far west as the Satpura basin, indicating a sustained marine connection across Gondwana basins during Barakar deposition.

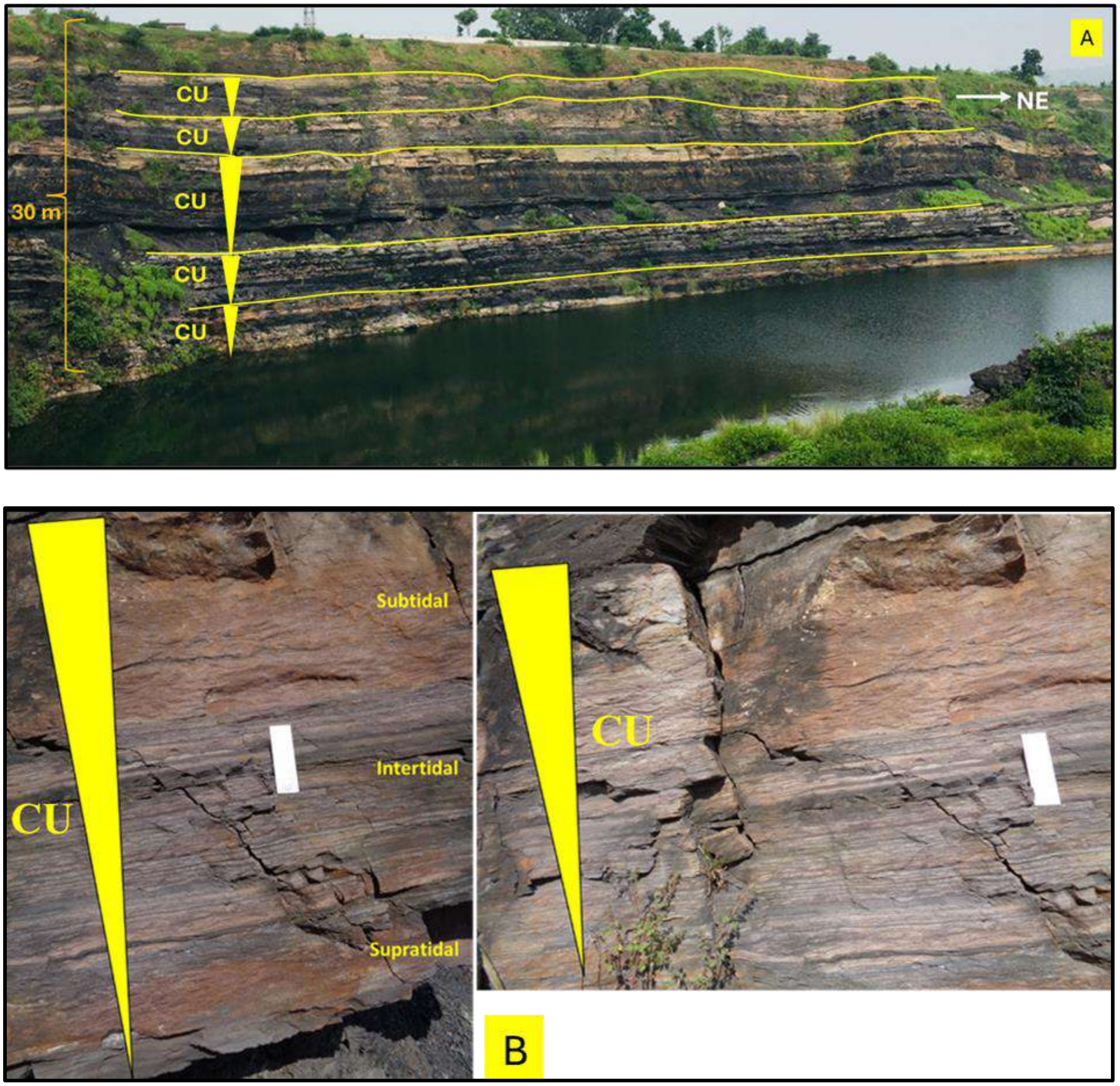


Figure 23 A. Heterolithic coal bearing unit near Quarry no. 18D, (HLU-5 and 6, CU=Coarsening upward), **B**. Closeup view of coarsening upward tidal bundle.

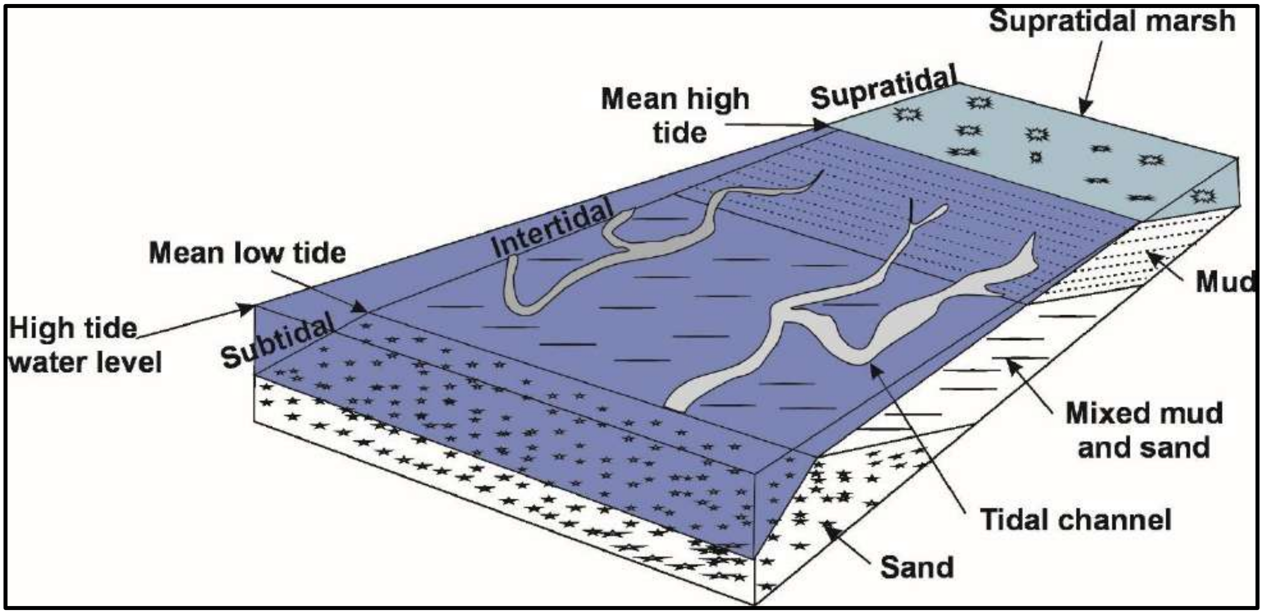


Figure 24: Coexistence of wave ripples with tidalites indicate low-energy wave/storm interference with tidal currents. after (Boggs 2006).

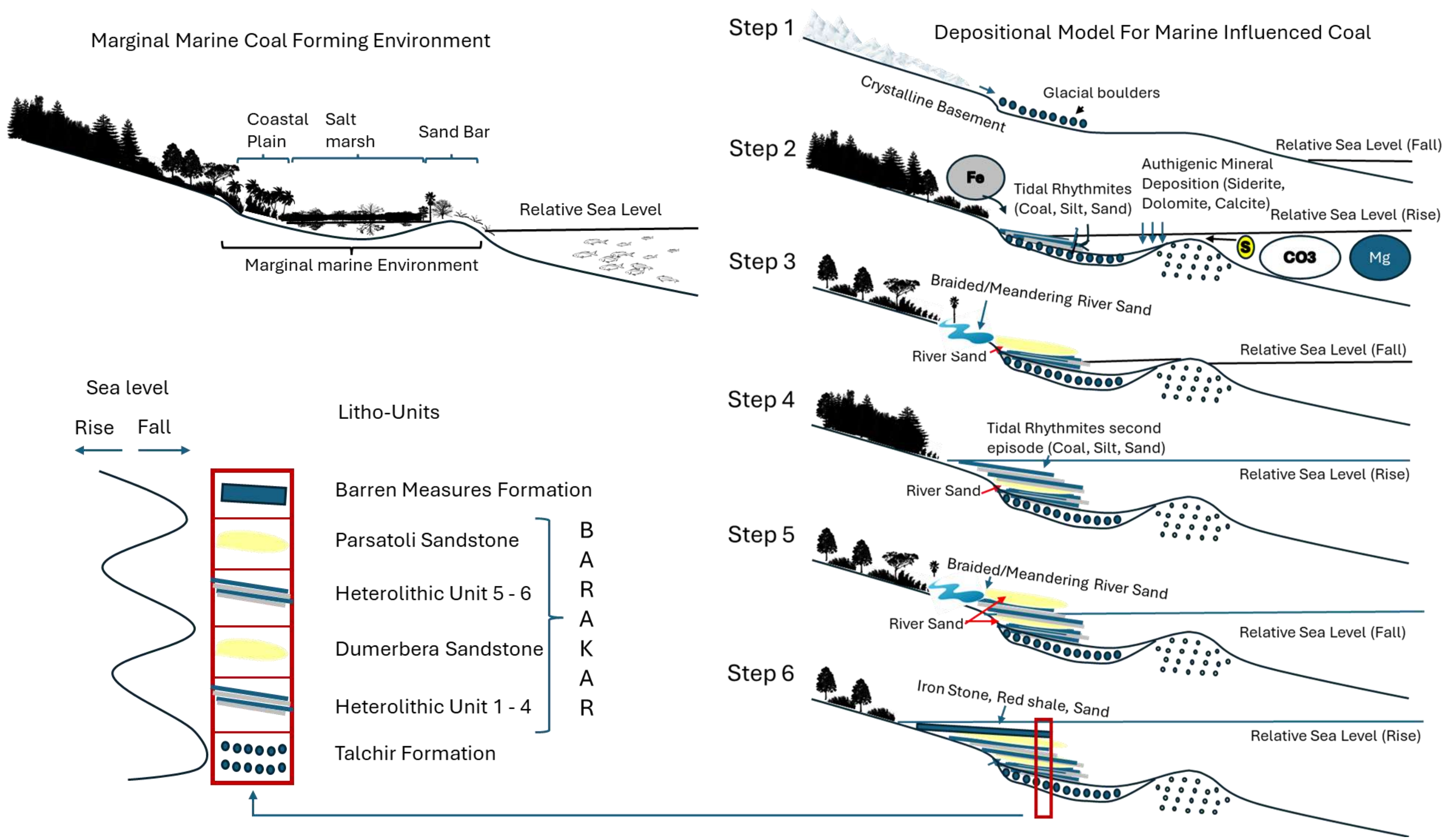


Figure 25: Depositional model for marine influenced coal-bearing heterolithic units of Barakar Formation, Near Ara-Dumerbera, from West Bokaro basin.

6 Conclusion

This depositional model indicates an influence of dynamic coastal environment where tidal and wave interactions played a crucial role in sediment distribution and stratigraphic architecture during the deposition of upper part of the Barakar Formation in the West Bokaro Basin. Evidence suggests that the peat-forming swamps of the Barakar Formation evolved atop supratidal salt marshes. The coal-bearing HLUs of the part of middle to upper Barakar Formation were deposited during multiple episodes of relatively minor marine transgressions. One in the middle of these HLUs and another toward the end of Barakar deposition, a sudden shift toward regression is evident by the deposition of the Dumerbera Sandstone unit and Parsatoli Sandstone unit. This was followed by a significant marine transgression, marking the onset of the Barren Measure Formation, characterized by ironstone-dominated deposits. Integrating previous studies on the Barren Measure Formation in the West Bokaro Basin, it can be inferred that marginal marine conditions in the study area developed earlier than previously reported. The present study establishes definitive evidence of marine influence during Barakar sedimentation in the West Bokaro Basin, thereby confirming a near-continuous marine incursion pathway extending from the Khemgaon-Sikkim corridor through Rajmahal and Raniganj to as far west as the Satpura Basin. This highlights a sustained marine connection across multiple Gondwana basins during the Barakar sedimentation.

Abbreviations:

CU- Coarsening upward

CT- Collotelinite

E- East

ESE- East Southeast

HLU- Heterolithic Unit

ICCP- International Committee for Coal and Organic Petrology

ID - Inertodetrinite

LA- Lamalginite

N- North

NNW- North Northwest

SEM-EDS- Scanning electron microscopy–energy dispersive spectroscopy

TA- Telalginite

XRF- X-ray Fluorescence

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