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Tectonically deformed coal: Focus on microstructures & implications for basin evolution

Manish Kumar Srivastava [a], Kaushal Kishor [a], Alok K. Singh [a,*], Soumyajit Mukherjee [b], Shivranjan Kumar Bharti [c]

[a] Department of Petroleum Engineering and Geoengineering, Rajiv Gandhi Institute of Petroleum Technology, Jais, 229 304, Amethi, Uttar Pradesh, India
[b] Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai, 400 076, Maharashtra, India
[c] Geological Survey of India, State Unit Jharkhand, Ranchi-2, Jharkhand, India

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ABSTRACT

Traditionally, the Gondwana basins of India were believed to have formed primarily through extensional tectonics that created rift basins. However, recent models propose that strike-slip movements along deep-seated crustal fractures also contributed to their development. This article investigates this theory through a comprehensive structural analysis of the Bokaro Basin, located in the Damodar Valley of eastern India. This study deciphers tectonic history and evolutionary mechanisms of the Bokaro Basin by analyzing its coal samples, especially their structures—a relatively unexplored aspect in Indian coal research. We investigate maceral types, deformation manifestations, and fracture patterns at various scales. This led us to refine the structural classification of (Indian) coals. Deformation imprints were identified using remote sensing for regional features, geological fieldwork for megascopic observations, and petrographic analysis for micro-scale studies. The study utilized ArcGIS for lithology and fault mapping in conjunction with fieldwork in the highly deformed south-western Bokaro Basin. Petrographic analysis revealed coal macerals and deformation signs. This research confirms that the Bokaro Basin's tectonic evolution involved uneven fault distribution, with significant rift and pull-apart mechanism. Coal seams show diverse deformation patterns, from ductile in fusinite to brittle in collotelinite, indicating multiple deformation stages under varying stress regimes. The East Bokaro Basin, with deeper seams, shows stronger deformation than the West. Shear stress, alongside extension, played a role in shaping the basin, with sigmoidal tension gashes from the coals of Barakar Formation, confirming active shearing through or afterwards coalification during or/and after the Early Permian time. The structural classification aids in coal bed methane (CBM) reservoir characterization, highlighting promising potential in cataclastic/tectonically deformed coal reservoirs. Tectonic deformation has affected the coals from the Bokaro Basin, resulting in structures that range from blocky to cataclastic, with some instances of granulation.

1. Introduction

Coal is a unique rock that reacts strongly to variations in temperature and pressure, leaving behind distinct stress imprints throughout its long geological history (Li et al., 2018a,b,c). When subjected to tectonic stress, coal seams and the surrounding rocks develop complex fracture networks and various coal body structures (Lyu et al., 2020). These fractures occur across multiple scales, from meter-sized faults to microscopic intergranular fractures (Pant et al., 2015; Li et al., 2017; Lyu et al., 2020). As a result, variations in coal structure across different parts of a basin can reveal the tectonic history and paleo-stress conditions. When studied together, these structural aspects provide valuable insights into the tectonic evolution of the basin.

Medlicott in 1873, first studied the coal bearing sedimentary sequences of central India and coined the term *Gondwana* for the Paleozoic-Mesozoic rocks deposited within the rift valleys of central and eastern peninsular India (Ghosh, 2002). These rocks unconformably overlie the Mesoproterozoic Vindhyan sedimentary rocks and the Indian Precambrian shield (Oldham, 1873). Subsequently these sequences were termed as the *Gondwana Supergroup* that became well-known for their prolific coal reserves (Ghosh, 2002). Since then, the tectono-sedimentary evolution and basin architecture have been studied

* Corresponding author.
E-mail address: asingh@rgipt.ac.in (A.K. Singh).

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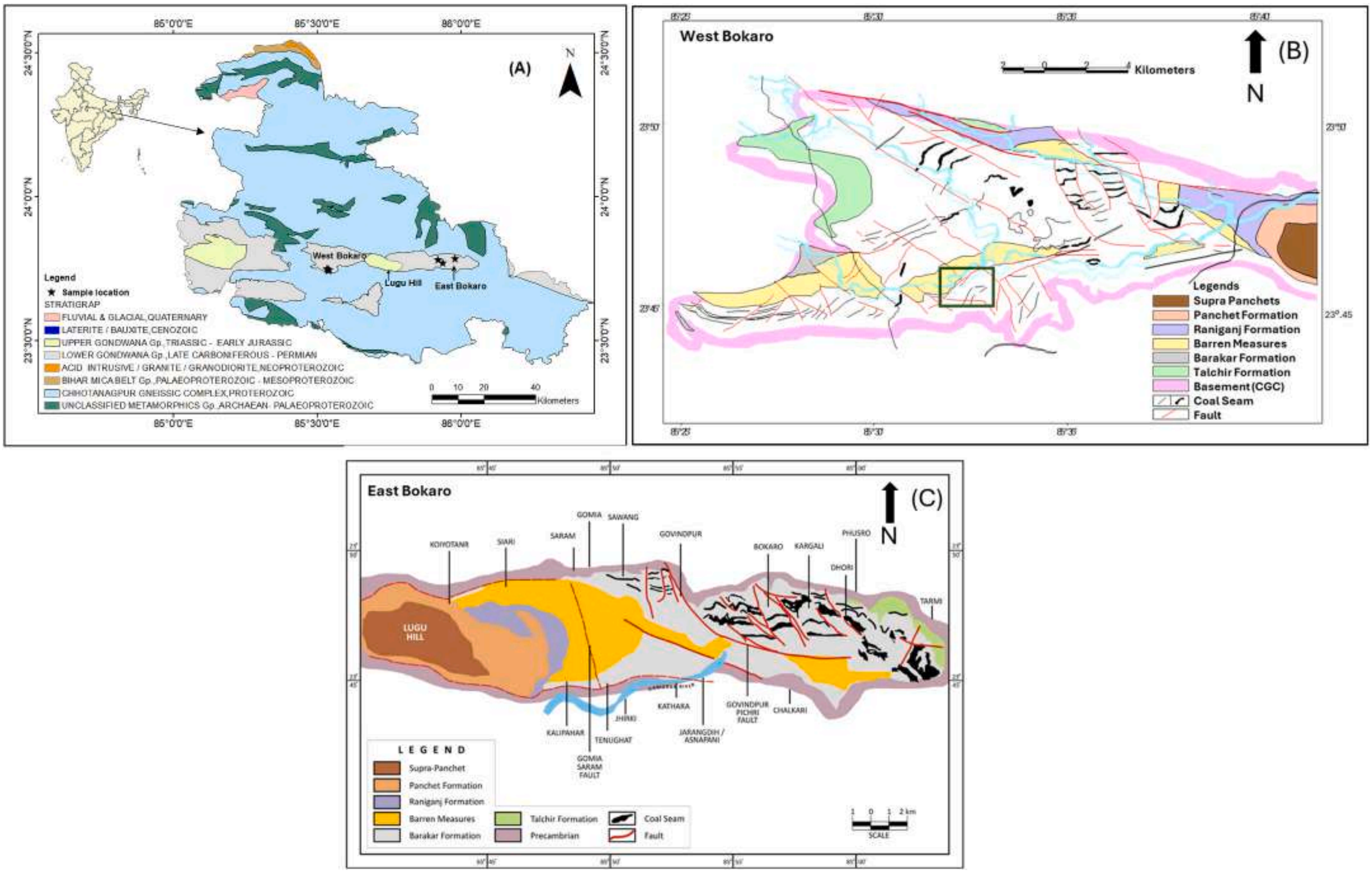

Fig. 1. (A) Location map of Bokaro basin. Reproduced after (Raja Rao, 1987). Inset map of India shows Jharkhand state indicating the study area, along with the sampling location with a star mark, (B) Tectonic-Stratigraphic map of West Bokaro basin. The detail study area is covered by a square, after Geological Survey of India, Source: Bhukosh @ www.bhukosh.gsi.gov.in, (C) Tectonic-Stratigraphic map of East Bokaro basin. Map reproduced after (Dutt, 2019). (D) Major fault distribution map across the Gondwana basins of India, Map reproduces from (Chakraborty et al., 2003b).

by several researchers.

Gondwana basins are either isolated or continuous but are located along belts that parallel the ancient structural lineaments. These linear belts formed at the junction of Archean cratons and distributed across four primary belts: *(i)* ENE-WSW to E-W trending Trans Indian basin belt, *(ii)* NW-SE trending Godavari-Pranhita-Wardha Valley basin belt, *(iii)* NNW-SSE trending Mahanadi Valley basin belt, and *(iv)* N-S trending Purnea-Rajmahal basin belt (Roychowdhury, 2015). Each belt comprises multiple sub-basins, which display diverse lithological characteristics and can either be isolated or linked by thick post-Permian strata (Roychowdhury, 2015). The typical sedimentary configuration and basin architecture are classified as extensional rift basins, usually characterized by a half-graben structure with a boundary fault on one side and a homoclinal tilt of the basin towards that fault (Dutt, 1963). Besides the boundary faults, each basin features a complex network of intrabasinal faults, with one set aligned along the basin axis and the other set oriented transversely (Fig. 1D) (Ghosh, 2002). Reactivation of these faults during sedimentation created accommodation space for the deposition of ~5 km thick predominantly continental sediments. This syndepositional faulting probably stressed the previously deposited strata leading to deformation.

This study aims to provide a detailed characterization of Bokaro Basin coals, focusing on their structural properties, an aspect that so far received limited attention. Alongside this, the investigation seeks to decipher the tectonic deformation history of the basin through fieldworks, fault analysis using remote sensing, and microstructural studies. By comparing samples from both the margin and interior of the basin, this research offers new insights into the composition and deformation processes of Bokaro coals including the micro-kinematic structures.

The Bokaro coalfield has been researched for coalbed methane (Mendhe et al., 2017a) hydrocarbon generation potential of shale rocks (Varma et al., 2014), gas storage potential (Mendhe et al., 2017a,b; Shaw and Mukherjee, 2022), geochemical characterization (Equeenuddin et al., 2016), water resource prospect (Mahato et al., 2022), hydraulic fracturing treatment (Banerjee, 2024) etc. These aims can be accomplished when detailed structural geological studies of the Bokaro field are made. Additionally, new fault identifications from the Bokaro coalfield will lead to more robust machine learning assisted classification of its coal (Banerjee et al., 2024). Therefore, the coalfield deserves structural geological characterization.

2. Geology of the study area

2.1. Origin of Gondwana basin

The Indian Gondwana basins, including the Bokaro Basin originated during the Permo-Carboniferous Period (Acharyya, 2019; Chakraborty et al., 2003a). Two schools of thought have been proposed related to the genesis of the Indian Gondwana basin. The first one proposes that these basins formed due to local extensional tectonics that developed grabens. This hypothesis cannot account for the need for kinematic compatibility amongst the basins, which should arise from a singular tectonic regime (Chakraborty et al., 2003a; Acharyya, 2019).

The second school proposes that the Gondwana basins, including the

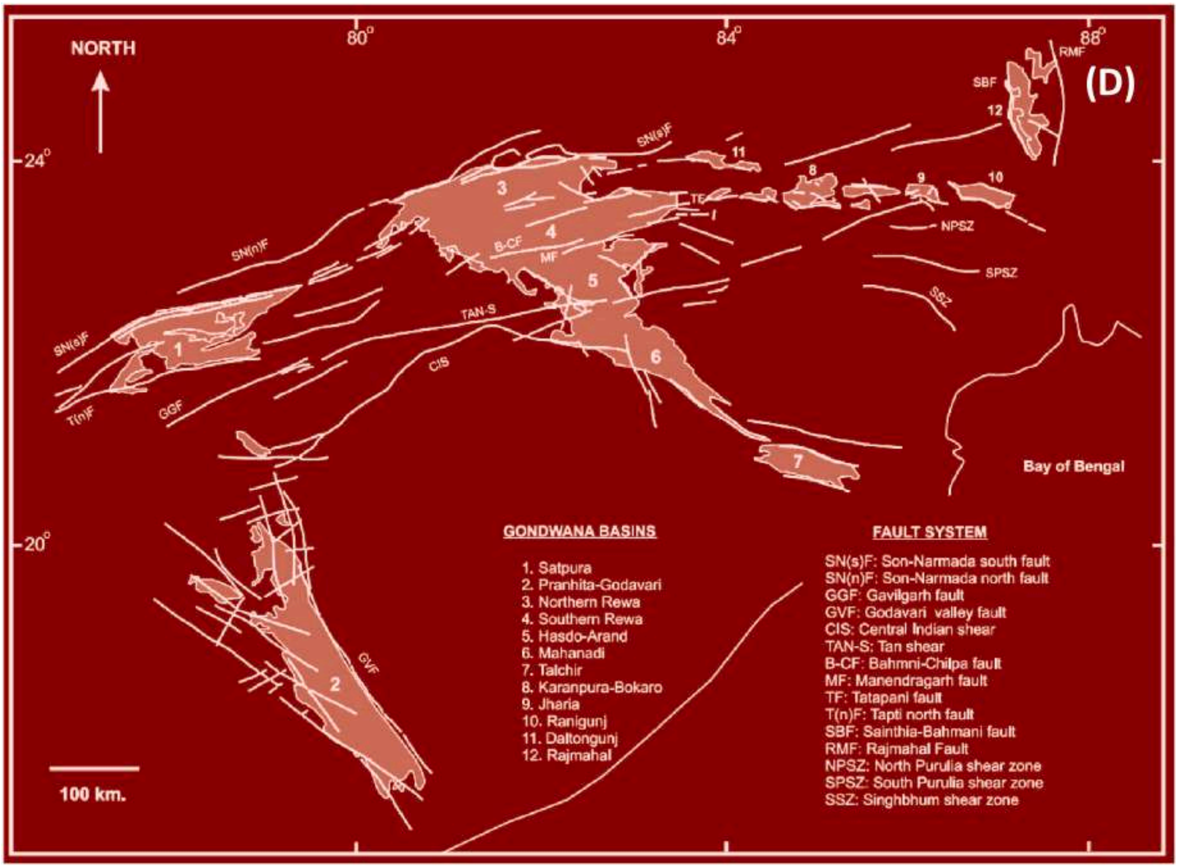

Fig. 1. (*continued*).

Bokaro Basin, formed along pre-existing zones of weakness within the Precambrian basement (Misra and Mukherjee, 2015). This is supported by the locations of these basins within suture zones between various Precambrian cratonic blocks of Peninsular India and their absence from the stable cratonic interiors (Roychowdhury, 2015). As per this view, the basins developed by a single ∼ E-W extension. While individual basin experienced different kinematics due to the varying orientations of their basal discontinuities, they still maintain overall compatibility with the regional east-west tectonic movement (Chakraborty et al. 2003a, 2003b; Acharyya, 2019).

Traditionally, the Gondwana basins have been viewed as extensional rift basins, primarily due to the presence of gravity faults that caused downward movements and the deposition of thick layers of sediments on the hanging wall block. However, strike-slip regimes also lead to subsidence (Chakraborty et al., 2003b).

The Bokaro Basin, along with other basins such as the Satpura, Jharia, Ranigunj, Talchir and Daltongunj, represents a rhombic basin formed by strike-slip along pre-existing lineaments with releasing steps or bends (Chakraborty et al., 2003b; Acharyya, 2019; Mengjia et al., 2024). The Bokaro Basin is developed presumably in a strike-slip setting with sinistral slip along its bounding faults, contributing to its complex fault patterns that align with natural and experimentally produced strike-slip basins (Chaterji and Ghosh, 1970; Chakraborty et al., 2003b). This complex structural configuration is attributed to stress perturbations and rotations of the principal stress axes within the stepover regions of the strike-slip zones (Chakraborty et al., 2003b).

Regardless of whether the origin of these basins is attributed to strike-slip movement or extensional movement, both theories agree on certain common points: the Gondwana basins are confined to deep crustal shear zones. They began as sag basins at the end of the Carboniferous or the beginning of the Permian Period, with Talchir sediments initially spreading beyond the current basin boundaries. These basins later evolved into rift basins during the latter part of the Early Permian, leading to their present-day architecture. Therefore, the current configuration of the Gondwana basins is thought to result from the reactivation of shear zones in the basement under a new stress regime (Roychowdhury, 2015).

2.2. Faults

The structural framework of the Bokaro Basin, along with other Gondwana basins, is characterized by faults. Faults within the Gondwana basins are categorized into three main types based on their occurrence: boundary faults, intrabasinal faults and basin marginal transverse faults (Dutt, 2019).

2.2.1. Boundary faults

The boundary fault defines one side of the basin, creating a "half-graben" structure where the sedimentary layers dip gently toward the fault zone. The boundary faults generally dip steeply, often exceeding 75°, with no evidence of flattening at depth, suggesting they differ from typical normal faults. The basement near the boundary faults is significantly sheared. This fault often runs along the entire length of the basin, occasionally branching out into smaller faults. In the Bokaro Basin, the boundary fault dips steeply into the basin, marking significant displacement and influencing the shape and structure of the coal seams (Chaterji and Ghosh, 1970).

2.2.2. Intra-basinal faults

These faults occur within the basin and affect the sedimentary layers, including coal seams. They are typically normal gravity faults but may include reverse faults in some areas. These faults can cause variations in the thickness of the coal seams and, in some cases, lead to the complete termination of coal seams against fault planes (Chaterji and Ghosh, 1970).

2.2.3. Basin-marginal cross-faults

A number of cross-faults are observed to affect the basin margins; the contacts of normal deposition are affected to a much greater degree while the faulted margins are affected less frequently. These faults (henceforth referred to as marginal cross-faults) always affect both the Gondwana and the basement rocks and are usually strike-slip in nature (Chaterji and Ghosh, 1970).

2.3. Tectonic framework of Bokaro basin

The Bokaro Basin is one of the several east-west trending and isolated paleo depressions situated at the eastern side of the Indian Gondwana Basin Belt (Fig. 1 A) (Jha and Sinha, 2022). These valleys contain tectonic lineaments that have preserved the oldest rocks constituting the Archean basement complex, exposed all along its peripheral parts. Overlying these basement rocks are coal deposits from the Permo-Carboniferous-Late Permian Lower Gondwana Group (Navale and Saxena, 1989). The Lugu Hill massif, which rises to ~978.40 m and serves as a major divide between East (Fig. 1C) and West Bokaro (Fig. 1B) within the Bokaro Basin (Saxena et al., 2020).

2.3.1. East Bokaro sub-basin

This sub-basin is intersected by numerous faults (Fig. 1C), leading to the development of trough and horst structures (Pophare et al., 2008). Structurally, this region can be viewed as an east-west oriented synclinal half-basin that narrows towards the east. The western section of East Bokaro forms a classic graben, with its northern and southern edges marked by prominent boundary faults. In contrast, the eastern portion presents a half-graben tectonic setting, where the Gondwana strata rest unconformably on the Precambrian basement along the northern boundary, while the southern edge is defined by a major fault. Different parts of the East Bokaro field subsided to varying extents depending on the faulting patterns (Raja Rao, 1987).

The Gondwana strata on the northern limb dip southward, while those on the southern limb dip northward. However, a complex fault system has caused significant regional variations, tilting different blocks at various angles. In the Bokaro-Kargali area, where sampling was conducted, the strata exhibit gentle dips, with inclinations as low as 5° to the south (Raja Rao, 1987).

The most notable fault, the Govindpur-Pichhri Fault, runs through the central axis of the coalfield with E-W orientation, reaching as far as Gobindpur village, situated at the northern boundary of the sub-basin, where it trends NW-SE (Dutt, 2019). This fault has the highest throw towards the southern side and can be observed in the Bokaro colliery (Dutt, 1963). Whether the Govindpur-Pichhri Fault is a single fault or is a coalescence of several smaller faults can be a matter of study in future research. Additionally, several major faults to the east of this main fault extend NNW-SSE (e.g., the Dhori-Pichhari fault). The western part of the East Bokaro Basin is impacted by numerous intra-basinal faults, oriented NW-SE and N-S, which disrupted the sedimentary layers (Raja Rao, 1987) Near these faults, the strata exhibit significant deformation. The East Bokaro Basin experienced more extensive faulting than the nearby basins.

2.3.2. West Bokaro sub-basin

The West Bokaro sub-basin is further divided into two sub-basins, which are formed by a twin synformal structure. These consist of a northern and a southern synform separated by an indistinct central antiform that runs E-W. The Archean highlands exposed around Mandu town represent the central antiform (Tiwari et al., 2016). The three structural axes converge in the coalfield's eastern section. In the northern synform, the northern limb's strata dip southward at 15–25°, while the southern limb dips northward at 5–15°, except in the Tapin and Parej blocks. For the southern synform, the southern limb dips

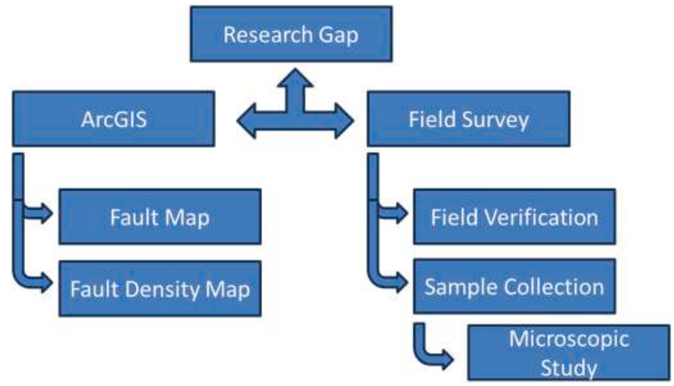

Fig. 2. Flowchart illustrating the research methodology involved in this research.

northward at 10–15° in less disturbed areas and 25–30° in the more disturbed areas. The basin is also characterized by several faults (Fig. 1 B) with displacements with a few m to over 400 m slip (Tiwari et al., 2016).

The north-east corner and southern boundary of the West Bokaro coalfield is heavily impacted by faulting (Fig. 1 B). These faults can be categorized into four main groups. The two most dominant fault sets run in E.N.E.-W.S.W. and W.N.W.-E.S.E. directions. The third and fourth sets are oriented along N.E.-S.W. and N.W.-S.E. lines. Major fault displacements vary between 61 and 304 m, while the smaller fault sets exhibit lesser shifts, typically ranging from 15 to 60 m (Banerjee, 1970). The east-west or strike faults run parallel to the boundary faults and predate the NW-SE faults, which often displaced older faults (Raja Rao, 1987).

Appendix I presents stratigraphy of the Bokaro basin.

3. Tectono-sedimentary evolution of Bokaro basin

The tectonic evolution of the Bokaro basin began with the deposition of Gondwana sediments influenced by the pre-existing topography of the Archean landscape. Depressions left by glacial activity, such as in the northwest part of the West Bokaro coalfield, were filled with Talchir sediments. In much of the southern and southeastern regions of the coalfield, Talchir sediments were absent, indicating limited early deposition. Following the Talchir period, a significant environmental shift occurred, leading to the deposition of Karharbari rocks in the northwest region. The composition of these sediments, characterized by poorly sorted feldspathic sandstones with angular fragments, suggest rapid transport from a rejuvenated source.

As subsidence continued, the Lower Barakar period saw clastic sediments and organic material deposited, primarily by streams from the western rejuvenated source. The sedimentary structures and fossil evidence indicate an east-northeast direction of current. During the Barakar to Raniganj periods, another depression formed in the southern part of the coalfield, which got gradually filled by sediment by the end of the Barren Measures period. The early Barakar period was marked by rapid deposition of coarse-grained sediments, with cross-laminated sandstone and abundant plant debris forming thick coal seams, indicating a fluviolacustrine environment. The frequent presence of coarse sandstone beneath these seams suggests transported sediments, rather than *in-situ* formation. As sedimentation progressed, the Middle and Upper Barakars showed an increase in finer sediments e.g., shale, while the Barren Measures were marked by carbonaceous shale and ironstone bands, reflecting a stable depositional environment. The Raniganj period saw renewed deposition of coarse sediments and coal, likely due to mild rejuvenation of the source area. This influx was followed by gradual filling of the basin from the west, with the Panchet period marking the final phase of deposition, centered around the Lugu Hill region. Conglomerates in the Panchet formation reflect the final stages of basin filling (Banerjee, 1970; Raja Rao, 1987).

The limited presence of Sawang group of seams on the down-thrown side of the Govindpur-Pichhari fault indicates a syn tectonic sedimentation at least during the early permian, in this area (Dutt, 2019). Overall, faulting plays a crucial role in shaping the Bokaro Basin sedimentation and basin architecture, influencing coal seam distribution, thickness, and the overall sedimentary arrangement.

4. Methodology

The methodology followed in this study is described in Fig. 2.

4.1. Data set and map preparation

The fault data of Damodar basin was downloaded as a shape file from the Bhukosh website (accessed on 10-Nov-2023), a gateway to all geoscientific data of the Geological Survey of India. ArcGIS 10.3 was used to prepare the fault map. For the preparation of the fault density map, the line density command was run on the fault data in ArcGIS (Bhatt et al., 2024).

4.2. Field verification and sampling

Geological fieldwork is essential in remote sensing studies of tectonic deformation because it validates remote data by providing ground truthing and allows for detailed observations and measurements of geological features that are not visible in remote sensing images. Fieldwork also enables the detection of subtle structures, the collection of rock samples for laboratory analysis (Fig. 1 A), and provides context for accurately interpreting tectonic processes. By integrating fieldwork with remote sensing, a more reliable and comprehensive understanding of tectonic deformation is achieved.

4.3. Sample preparation for microscopy

The coal samples are non-oriented and coal pellets were prepared for petrographic characterization by crushing the samples to sizes <18 mesh. The coal mount was prepared using cold-setting materials without pressure. Petrographic study was conducted using an advanced petrological microscope (Leica DMP2700P) equipped with reflectometry for the identification of liptinite macerals, model analysis software (LASv4.6), and an imaging system. Immersion oil, with a refractive index of 1.518 at 23 °C, was used as the medium between the coal pellet and the objective lens, following standard procedures (ISO 7404-3, 2009). Macerals were identified based on the ICCP classification (ICCP, 2001, 1998; Pickel et al., 2017).

4.4. Types of fractures in coal and their role in paleo tectonic reconstruction

Fractures are common in coal beds and can significantly influence the stability, mining and fluid flow within coal seams. A specific type of fracture found in coal is called a cleat, which typically forms in two mutually perpendicular sets, which are also perpendicular to the bedding plane. These fractures are of “opening-mode”, indicating that they form without shear displacement (Laubach et al., 1998).

Although the fracture system in coal is crucial for mining, particularly in underground operations, it has received relatively little attention in terms of understanding its structural classification and origin. Despite its importance, the relationship between coal fractures and tectonics remains poorly studied and is debated. The genesis of cleats can be linked with compaction, shrinkage and dewatering during coalification, as well as tectonics. While compaction alone can generate fractures, the uniform orientation of cleats over large areas suggests that tectonic forces have influenced their development. Studying the orientation and characteristics of these fractures allows geologists to reconstruct past stress fields and tectonic events (Laubach et al., 1998).

Table 1
Types, distribution and spatial scale of fracture systems in a coal seam (Li et al., 2016, 2018a,b,c; Lyu et al., 2020).

	Type	Distribution position in the coal seam	Spatial scale of fracture length
Visible fractures	Exogenetic fractures	Throughout the coal seam	Tens of cm up to tens of m
	Gas-expanding fractures	Vitrinite and bright coal	A few cm up to tens of cm
	Cleats	Vitrinite and bright coal	A few mm up to a few cm
Micro-fractures		Coal matrix	Few μm up to hundreds of μm

It is widely recognized that natural fractures in coal seams display multi-scale characteristics, ranging from m-scale faults to micro-scale intergranular fractures (Pant et al., 2015). The Coal geologists from China follow a system of classification of fracture in coal (Li et al., 2016; Lyu et al., 2020) (Table 1). Broadly, the fracture system in coal seams can be categorized into micro-fractures and visible fractures, including exogenetic fractures, gas-expansion fractures and cleats (Li et al., 2016, 2018a,b,c; Lyu et al., 2020).

In tectonically active areas, fracture intensity and style may vary near faults or folds, providing insights into the basin’s tectonic history. Thus, fractures in coal, including cleats, serve as important markers for understanding both coalification and tectonics (Laubach et al., 1998). Su et al. (2001) studied cleat in detail and proposed a classification related to its characteristics and origin. They stated that due to the varying development stages of face and butt cleats, multiple spatial patterns can form in coal seams (Fig. 3). The first is the reticular pattern, which is further classified into regular (I_1) and irregular reticular (I_2) sub-patterns. The second is the isolated cleat pattern, with straight (II_1) and S-shaped (II_2) sub-patterns. Lastly, the third is the random cleat pattern (III), characterized by an unpredictable arrangement (Su et al., 2001) The classification he proposed is workable for macroscopic to microscopic levels. At the macroscopic level, all types of cleats were visible; however, Type I_1 and II_1 were the most common. Su et al. (2001) also proposed the type of tectonic stress responsible for the generation of a particular sub-pattern of cleat.

4.5. Classification of coal based on the tectonic deformation

Coal structure refers to the geological fractures of a coal seam shaped by tectonic activity. Moderate deformation can enhance fracture development, while excessive stress can break the seam into fine particles, damaging the cleat system (Meng and Li, 2013). A moderately deformed coal with numerous cleats not only provides a larger surface for the gas to be adsorbed, but also provides a well-developed network through which the CBM can be produced. Hence it is vital to characterize the coal based on these structures, for the CBM prospect identification and reservoir characterization. This research proposes a coal classification framework for Indian coal, inspired by the structural classification systems currently employed in China (Lyu et al., 2020; Meng et al., 2016). Based on different tectonic stress regimes, coal structures are classified into five sub-class: integrated, blocky, cataclastic, granulated and mylonitized, with the first one being intact and the latter ones are designated as the tectonically deformed coal. Deformed coal often shows changes in composition and texture. Higher rank can be related to tectonics, which also promotes dynamic metamorphism. Table 2 details the classification.

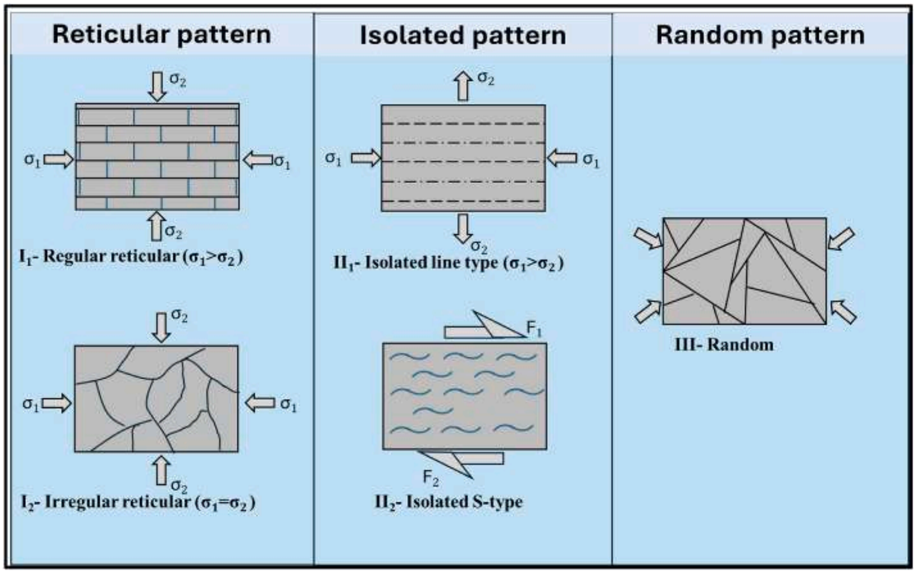

Fig. 3. The cleat network patterns include I_1, regular reticular; I_2, irregular reticular; II_1, isolated straight; II_2, isolated S-shaped; and III, random pattern. Here σ_1 and σ_2 indicate the maximum and the minimum principal stresses, respectively, and F denotes the shear force. After (Su et al., 2001).

Table 2
Proposed structural classification of Indian Gondwana coals.

Class	Intact coal	Tectonically deformed coal			
Sub-class	Integrated	Blocky	Cataclastic	Granulated	Mylonitized
Macro lithotype	Clearly visible	Clearly visible	Visible	Not clear	Unidentifiable
Structure	Banded (layered and blocky)	Bedding (Horizontal and stripe)	Traceable stipe and angular nubby	Broken pieces and barely angular	Compressed in blocks or solid particles, Foliation with crumpled slip surface
Granule size (mm)			>2 to 10	1 to 2	<1
Broken state	Intact, hard, and blocky	Easily strips out into small pieces, medium hard	Angular and partially oriented	Broken tablets, oriented and displacement	Pulverized solid block, powder
Cracks & permeability	Permeable	Highly permeable	Highly permeable	Low permeability	Very low permeability
Cracks and fracture	Developed fracture	Developed fracture	Well-developed cleats	Less developed cleats and cracks	No cleat, cracks filled by powered coal

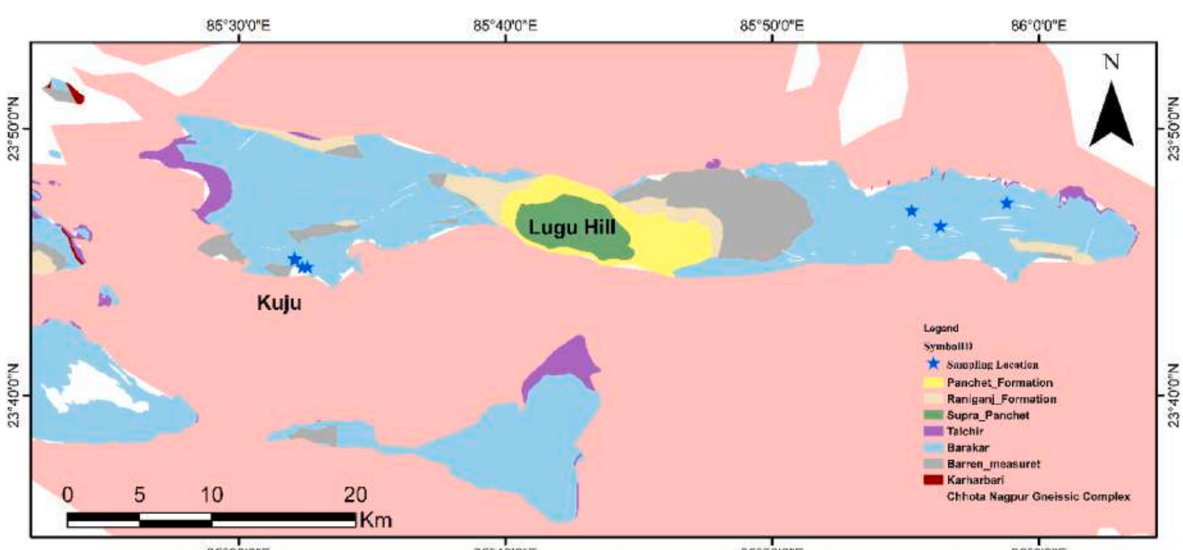

Fig. 4. Litho-stratigraphic map of the Bokaro Basin.

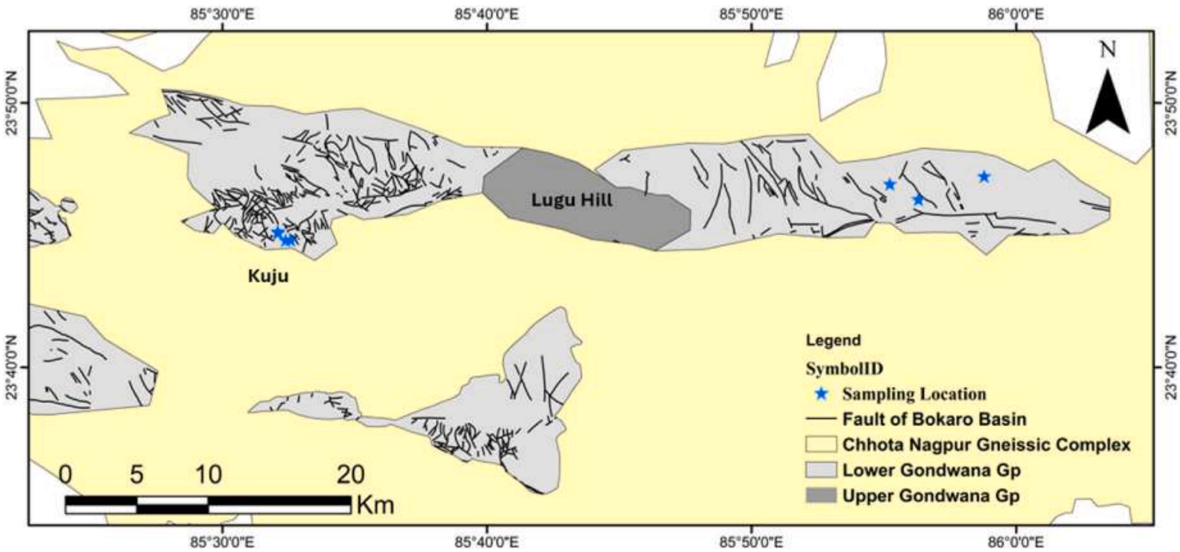

Fig. 5. Fault distribution map of the Bokaro Basin and surrounding region.

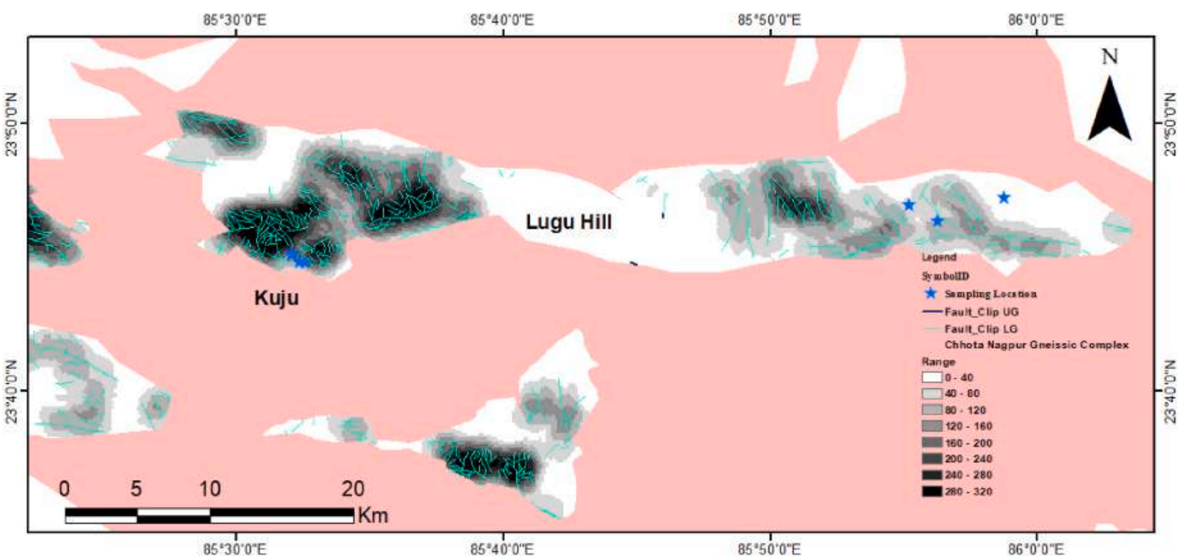

Fig. 6. Fault density map of the Bokaro Basin and surrounding region.

5. Results & discussions

5.1. Regional observations

GIS and remote sensing evidence: The litho-Stratigraphic map created from data downloaded from Bhukosh reveals the distribution of rock types in the district of Hazaribagh and Ramgarh (Fig. 4). The Bokaro Basin appears as a narrow, linear, and isolated sedimentary sequence, embedded within the high-grade metamorphic rocks of the Chhotanagpur Gneissic Complex. Almost a complete sequence of Lower and Upper Gondwana formations is exposed in this basin. The Talchir and Karharbari formations are exposed along the marginal parts of the basin, while the Barakar Formation occupies extensive areas in both the East and West Bokaro basins. The Barren Measures are relatively less exposed in East Bokaro, but they cover large areas on the western side of the East Bokaro Basin. The Raniganj Formation is more exposed near the depocenter along the foothills of Lugu Buru Hill and at a few locations in the marginal areas of both East and West Bokaro basins. The relatively younger Upper Gondwana group of rocks crop out near the basin's depocenter, i.e., on the Lugu Buru Hill.

To study tectonics in detail, a fault distribution map was prepared (Fig. 5) using ArcGIS. This map reveals the distribution of various faults within the Bokaro Basin and its adjoining areas (Fig. 5). The most evident observation from the map is the uneven distribution of faults, with a higher concentration along the northern and southern margins, particularly on the southern margin of the basin. The Bokaro Basin contains two to three sets of faults. Apart from the E-W trending major faults, which are mostly concentrated near the northern and southern margins, occasionally appearing in the axial region of the eastern part of the East Bokaro Basin and, in some cases, near the Mandu highlands in the western part of the West Bokaro Basin. The more prominent fault set runs NW-SE, while a less prominent one trends N-S to NNE-SSW. The analysis of direction of these faults indicates that the oblique to transverse faults within the basin might be intrabasinal faults. In contrast, a more prominent set of faults runs parallel to the basin axis along the basin's margin, and it plausibly represents the basin boundary fault. The concentration of faults in specific locations and the presence of two to three distinct fault sets are key insights derived from the map.

To gain a better understanding of the areas affected by deformation, a fault density map was prepared, highlighting regions impacted by

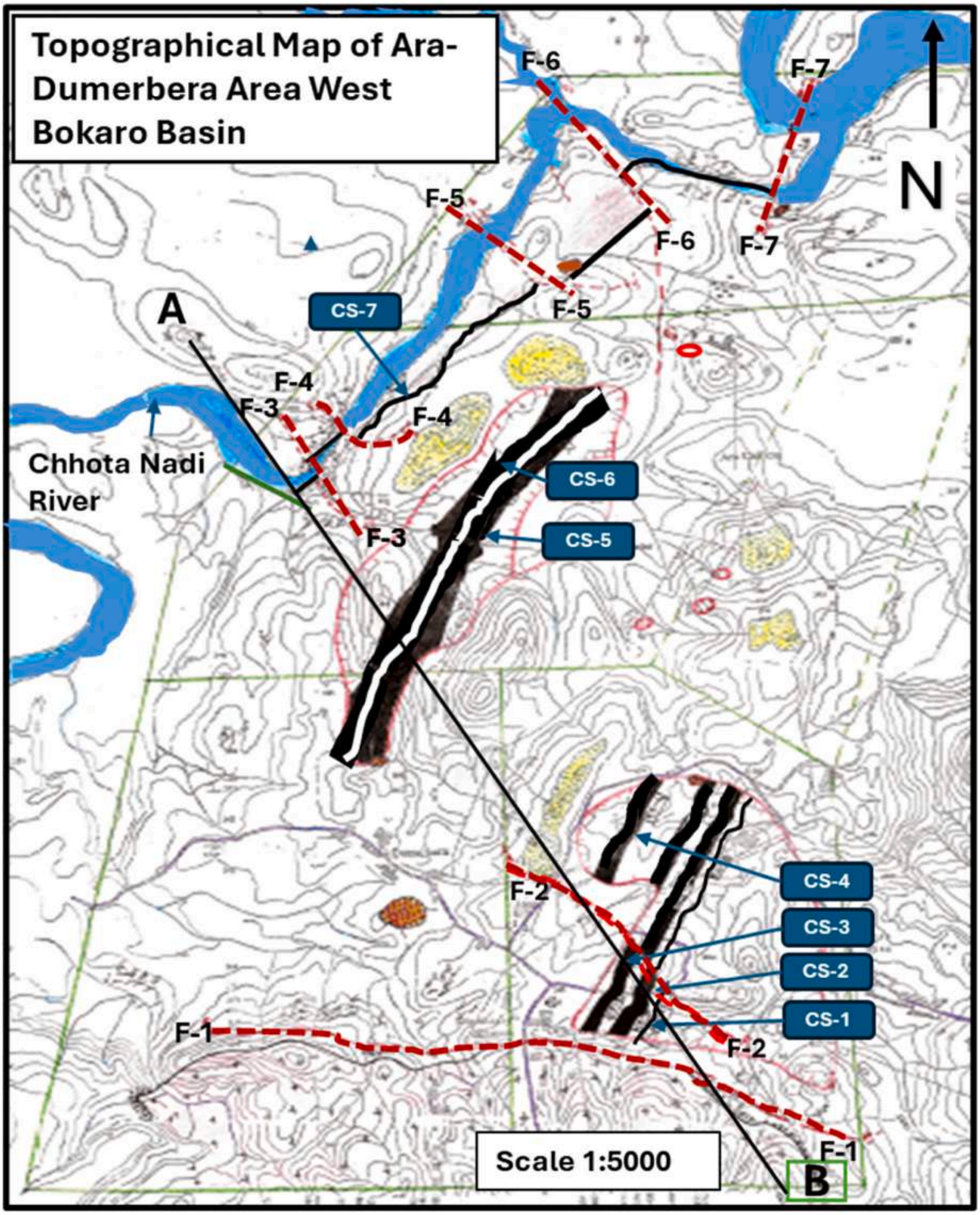

Fig. 7. Topo-map of the study area, Location: Ara-Dumerbera village, West Bokaro basin, A-B Traverse taken for the preparation of geological cross section, CS- Coal Seam (Black Colour), F- Fault (dashed red line).

fault-related deformation (Fig. 6). The map indicates that the fault density varies drastically across the basin. The West Bokaro Basin appears to be more tectonically disturbed than the East Bokaro Basin. Central and southern regions of the West Bokaro Basin are particularly affected.

5.2. Megascopic to macroscopic scale observations

Field validation and sample collection: Ground truthing through fieldwork is crucial to validate remote sensing data with the meso-scale structures documented in the field.

5.2.1. West Bokaro basin

A traverse (Line A-B in Fig. 7) was undertaken, starting from Ara village and moving north to northwest. This village is situated at the southern margin of the West Bokaro Basin, near a highly tectonically deformed area. The traverse was selected based on fault distribution and fault density maps to explore the most fault-affected regions and the

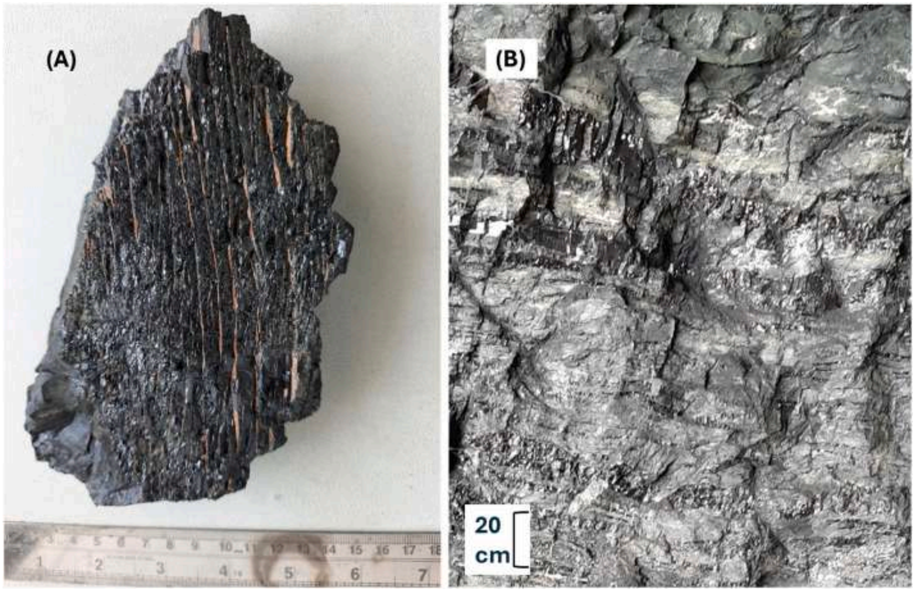

Fig. 8. (A) I_1, regular reticular cleat, the development is attributed to the compression, as per Su et al. (2001), the cracks are filled by secondary clay minerals (B) a fresh cut section of Seam 6 from the Ara-Dumerbera area of the West Bokaro basin, where coal is marked by the bright and dull bands. Development of multiple set of cleats within the bright band are particularly noticeable and may be classified as gas expanding fractures/cleats.

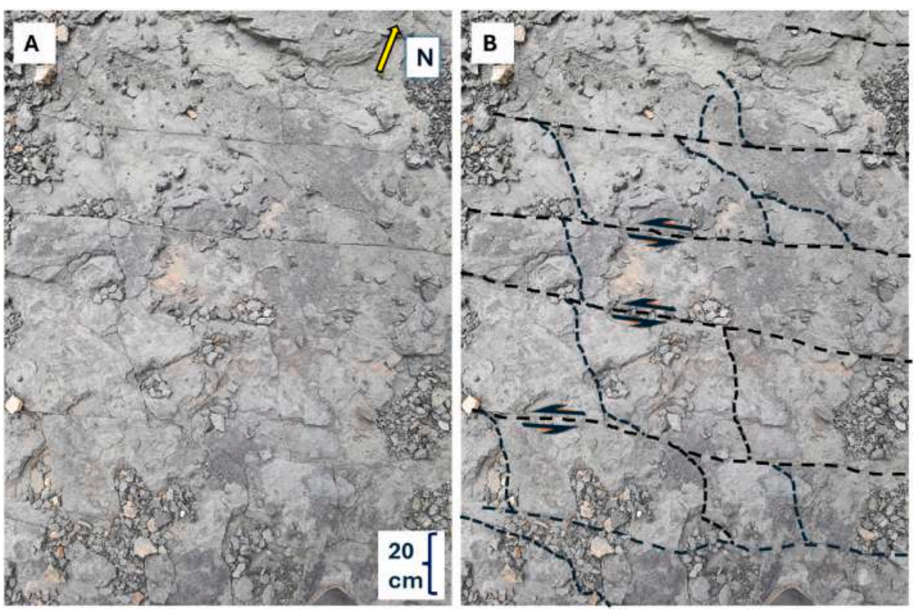

Fig. 9. Parallel fracture line on ground surface of Shale bed of Barakar formation (Horizontal exposure), sinistral strike-slip fault interpreted. A: Uninterpreted and B: interpreted images. P and Y brittle planes define the shear zone. Location: near Dumerbera village, West Bokaro.

notable presence of several coal seams of Barakar Formation. Although thick vegetation and soil cover obscures the contact between the Gondwana rocks and the Chhotanagpur Gneissic Complex (CGC), changes in outcrop rock types helped demarcate the basin margin. The Barakar Formation, well exposed due to the area's abundant coal mines, revealed at least seven coal-bearing heterolithic units of sandstones, siltstones and shales. The coal appeared banded (Fig. 8B) and contained numerous cleats (Fig. 8A), while the shale units display at least two sets of fractures (Fig. 9). The traverse concluded near the Chhota Nadi River, which flows along the junction of the Barakar and the Barren Measures formations, where few oblique-slip step faults are well exposed along the riverbanks (Fig. 10). During fieldwork, 24 coal and 4 shale samples were collected from Coal Seam-1 (CS-1), CS-3, 6 and 7 for detailed laboratory investigation. The remaining coal seam-bearing heterolithic units crop out along cliffs formed by past coal mining partly submerged into two lakes, hence close inspection or sampling was not possible. Evidence of two major faults was observed within the Barakar Formation—one located just after the contact zone between the Barakar Formation and the CGC (Fig. 7), and the other intersecting the traverse at nearly a right angle (Fig. 7). The second fault is normal fault and dips ~ S.

A geologic cross-section was created along A-B (Fig. 11) that trends NW-SE, to examine the arrangement of beds and the orientation of faults, which together define the basin architecture. The cross-section indicates a normal unconformable contact between the Barakar Formation and the CGC. The coal-bearing heterolithic units display a homoclinal structure along the southern margins of the West Bokaro Basin. In several cases, faults cut through the Barakar Formation and the Barren Measures, but these appear to be basin-margin cross-faults rather

Fig. 10. Step fault observed along the Chhota Nadi river cut in the Barren Measure Formation, in West Bokaro. The yellow dashed lines represent normal fault planes.

than the boundary faults. The presence of oblique-slip faults also suggests the influence of strike-slip tectonics on the basin's deformation.

5.2.2. East Bokaro basin

A second fieldwork was conducted in the East Bokaro Basin to examine exposures in tectonically less disturbed areas, as identified through remote sensing studies. Extensive coal mining in the region has significantly altered the natural geomorphology, making it difficult to identify faults. However, the same mining activities, especially open-cast mining, have exposed large areas for detailed inspection. Over-burden dumping near the mining pits has made it nearly impossible to detect surface evidence of faulting. At the same time, large mining pits e.g., Bokaro Open Cast Project (OCP), AKK-OCP, and Karo OCP have provided opportunities for close examination of freshly exposed deeper sections of the basin.

Field studies revealed the presence of a few intrabasinal faults and fractures. Three active coal mining sites—AKK-OCP, Bokaro OCP (Dhobi Das Patch), and Karo OCP—were visited to assess signs of deformation in the Barakar Formation. The coal in this area displays a banded structure, with abundant cleats. Coal seams here are much thicker than those in the West Bokaro Basin, and unlike West Bokaro, heterolithic

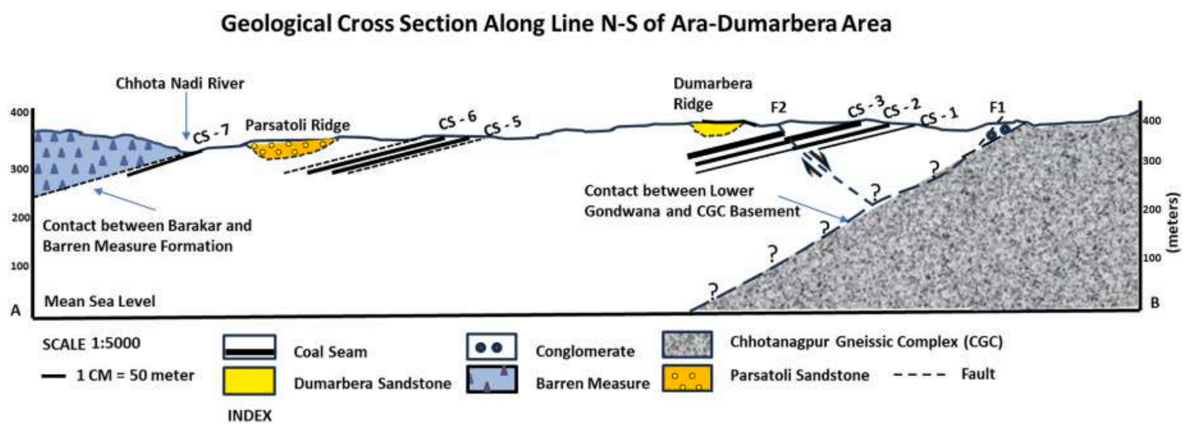

Fig. 11. Geologic cross-section prepared along the traverse A and B shown in the map (Fig. 7), the traverse starts at the southern margin of the West Bokaro basin across the CGC, Barakar Formation and Barren Measures.

Fig. 12. (A) Sub-vertical fracture swarm (NW-SE) observed in Karo Seam 6 and 7, exposed in Amlo-Khas Mahal OCP (the length of the hammer is 30 cm), East Bokaro basin, and (B) Exogenetic fractures observed in Bermo Seam exposed in Bokaro OCP (Dhobi Das patch, the height of the man in photograph is 165 cm) of East Bokaro basin.

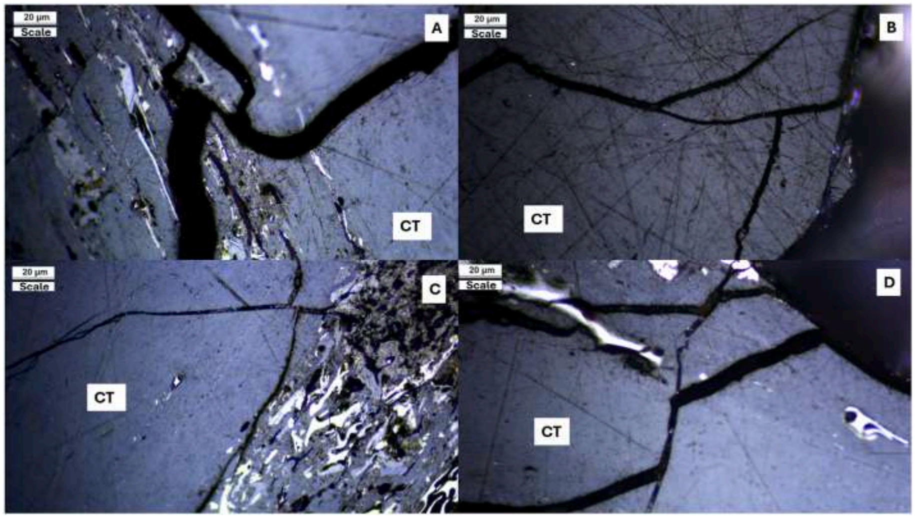

Fig. 13. (A) and (B) Irregular reticular, I_2 subcategory, (C) and (D) Random pattern cracks, III subcategory, micro photograph, Location: Near Bokaro and Kargali area, East Bokaro basin. CT-CT- Collotelinite maceral.

units are absent. In the Khas Mahal area, thick, massive sandstone, with a few fracture sets, forms the roof over the thick coal seams, while shale is relatively scarce. In Karo OCP, the shale is thin, occurs between the coal seams, and exhibits at least two sets of fractures intersecting at high angles.

The Karo group of seams belongs to the Barakar Formation and is well developed in this region. These seams were studied in various mining patches of Karo-OCP and AKK-OCP. Beginning with the lowermost coal seams (CS), CS-6 and CS-7, studied at AKK-OCP, they were found to be highly fractured. In addition to cleats confined to the coal seam, at least two sets of exogenetic fractures were identified, intersecting at high angles and oriented along E-W to ESE-WNW and N-S to NNE-SSW. Several near-vertical fracture swarms (NW-SE to ESE-WNW) were also observed in these seams (Fig. 12 A). Karo CS-8 and 10 are well exposed in several patches in the Khas Mahal OCP, exhibiting well-developed cleats and exogenetic fractures. Karo CS-11, studied at Karo-OCP, located further east of the Khas Mahal area, occupies the uppermost stratigraphic position within the Karo group of seams. This

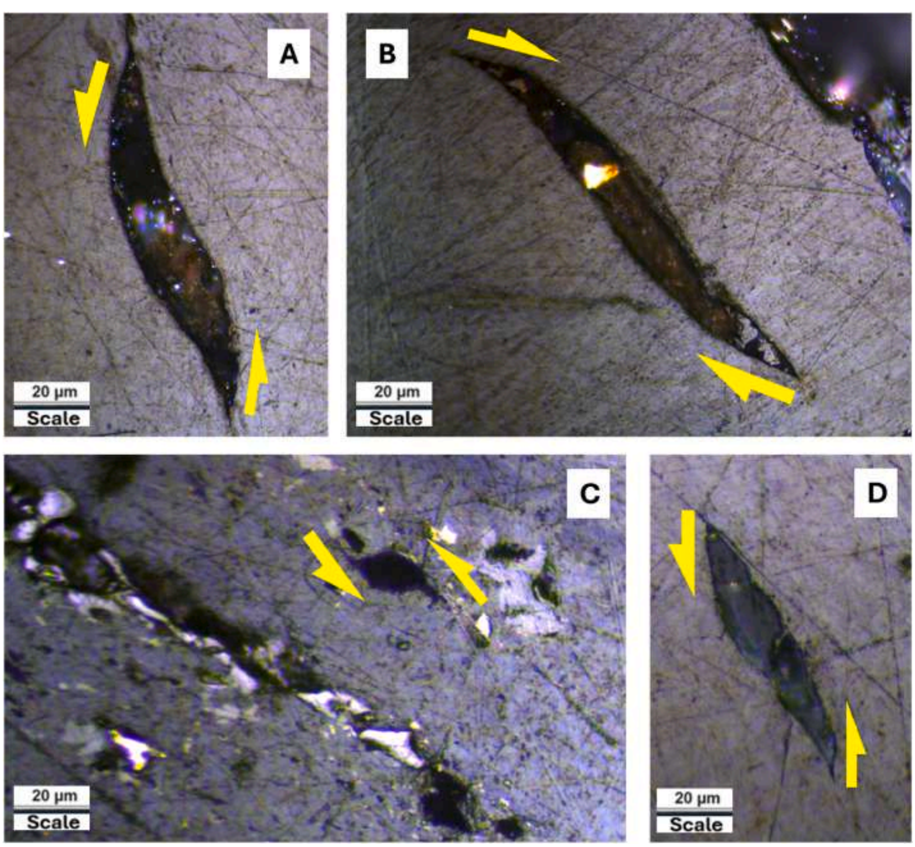

Fig. 14. Isolated sigmoidal tension gash in collotelinite, lies in II_2, isolated S-shaped subcategory, (A), (B), and (D) unfilled, (C) filled with liptinite, Location: Near Dumerbera Village, West Bokaro basin.

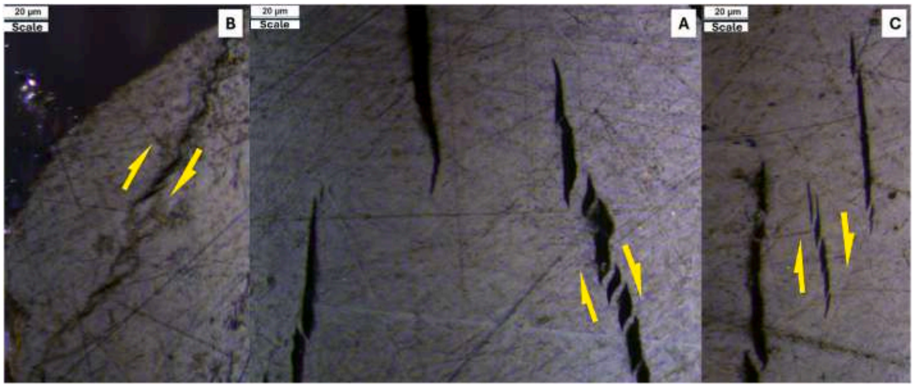

Fig. 15. Sigmoidal tension gash in collotelinite, filled with liptinite (Dutta and Mukherjee, 2019), Location: Near Dumerbera Village, West Bokaro basin.

seam is relatively thin, overlain by a massive sandstone bed and underlain by a shale bed. It is also highly fractured, with finely spaced fractured lines that cause it to easily strip out. These coals are classified (Fig. 11) blocky to cataclastic (Table 2).

The rest of the seams in the Karo group are characterized as blocky subcategory tectonically deformed coal due to their clearly visible bedding, macrolithotypes, well-developed cleats, and fractures, as well as their tendency to strip out easily. The Bermo Seam, stratigraphically positioned above the Karo group seams, is well exposed in the Dhobi Das area of Bokaro-OCP. It is also classified as blocky coal due to the well-developed fractures, visible macrolithotypes, and stripping-out nature (Table 2). In this area, large exogenetic fracture lines are present, which extend beyond the coal seams and are traceable in the adjoining massive sandstone overburden. At least two prominent fracture sets intersect at high angles in this region (Fig. 12 B).

To further explore and understand the structural aspects of the basin and their impact on coal deformation, samples were collected from each coal seam encountered during the fieldwork. A total of 36 coal samples were gathered for both macroscopic and microscopic observation.

5.3. *Microscopic observations*

For more inclusive understanding of tectonic process and complement the remote sensing and field observations, a microscopic study was conducted on the polished shale and coal pallets under reflected light microscope. A total of 64 coal and shale pallets were examined under microscope including 36 of them from East Bokaro and 28 from West Bokaro. The samples from both basins belong to the Barakar Formation. The sampling location from both the sub-basins are marked in the location map (Fig. 1 A). A range of micro-fractures and cleats were observed from the Bokaro Basin.

5.3.1. *East Bokaro*

Coal samples were collected from five different seams exposed in three open cast mines in the East Bokaro Basin, all belonging to the Barakar Formation. A total of 36 samples were taken from active mining faces in this area. Observations revealed that the East Bokaro coal samples exhibited a single type of cleat or micro-fracture, primarily confined to vitrinite macerals. Most of these cleats/micro-fractures fall into the I_2 subcategory, which, according to Su et al. (2001), indicates a compressive stress regime (Fig. 13A and B), whereas in few cases it lies into III subcategory (Fig. 13C and D).

These samples were collected from deeper sections of the basin, characterized by a lower fault density based on remote sensing analysis. However, field observations noted a high density of exogenetic fractures in the region, despite the low overall fault density. The faults present were primarily intrabasinal, more prominent and continuous.

5.3.2. *West Bokaro*

Samples were collected from old open cast mining faces belonging to four different coal-bearing heterolithic units of the Barakar Formation. These samples were gathered along a traverse from Ara village to the Chhota Nadi River. In contrast, the West Bokaro samples exhibited a wider variety of microstructures beyond just cleats and micro-fractures,

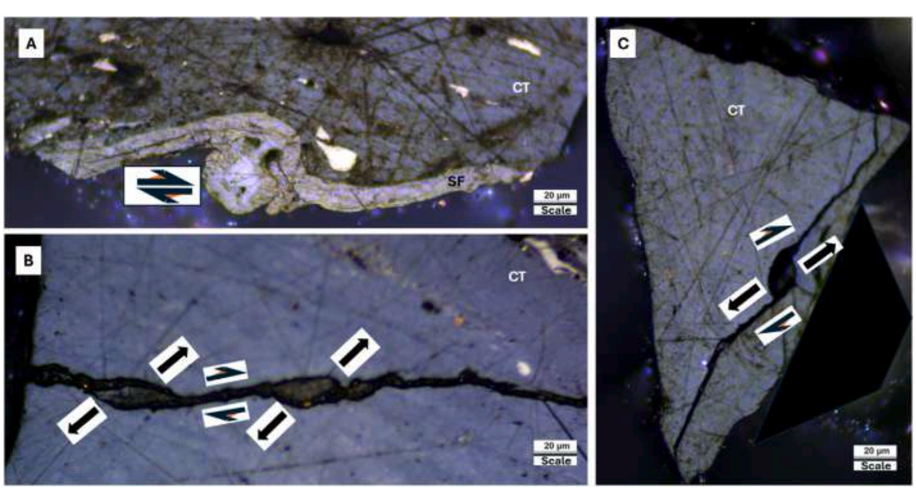

Fig. 16. (A) Delta structure and shows a top-to-right ductile shear. Since the tail and the main body appear to be constituted by the same material, it can be more accurately called as a rolling structure (Van Den Driessche and Brun, 1987) (B) Top-to-right sense of ductile shear, (C) A sigma-structure showing top to right shear sense, Location: Near Dumerbera Village, West Bokaro basin. (CT- Collotelinte, SF- Semifusinite).

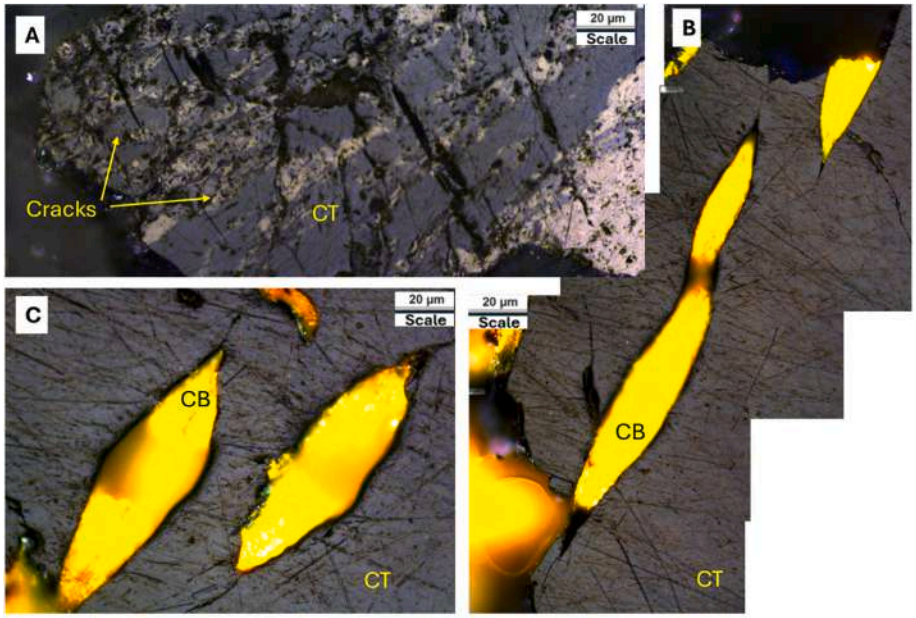

Fig. 17. (A) Isolated straight sub pattern cleat in collotelinete, (B) and (C) Partially isolated elliptical shape with pointed ends, cracks in collotelinte, filled with carbonates, Location: Near Dumerbera Village, West Bokaro basin.

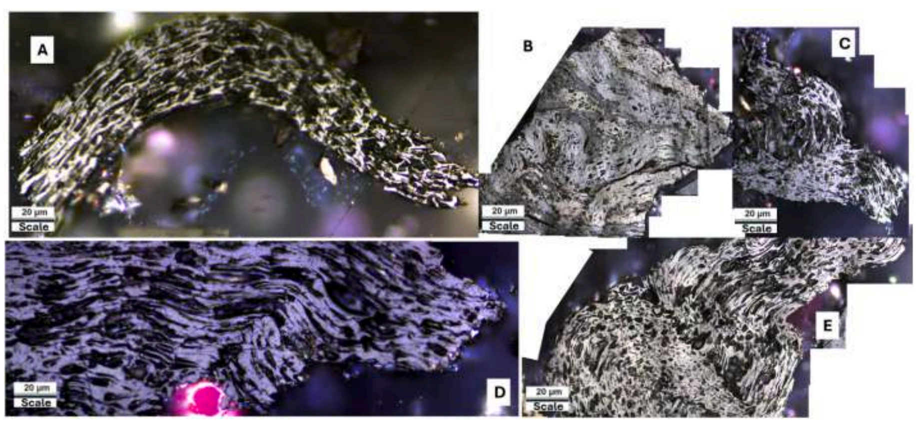

Fig. 18. Folded fusinite macerals in coal samples, Location: Near Dumerbera Village, West Bokaro basin.

with subcategories II_1 and II_2 being relatively abundant.

Compressional/Extensional Microstructures: Micro-faults were observed in macrinite sub-maceral (Fig. 19 E), with fractures predominantly found in collotelinite and occasionally in other sub-maceral types (Figs. 14–16 B, C, 17). Micro-folds, the most common microstructure, are primarily associated with fusinite and semifusinite sub-macerals (Fig. 18 A, B, C, D, and E), and only rarely seen in collotelinite or collodetrinite (Fig. 21A and B). In some instances, the grain arrangement of broken macrinite resembled boudins, surrounded by a matrix of other macerals and minerals (Fig. 20A and B). Micro-breccia was frequently observed, where angular fragments of collotelinite were bound together with unidentified fine maceral and mineral debris, pyrites and carbonate micronodules (Fig. 19A and B).

Shear microstructures: Sigmoidal tension gash was notably present in some West Bokaro samples, indicating brittle shear. These gashes are occasionally empty (Fig. 14A and B and D), and often filled with either mineral matter, particularly carbonates, or with resinite sub-macerals (Figs. 14 C, 15 A, B, and C). In a rare instance delta structure showing a top-to-right ductile shear came into notice from the semifusinite (Fig. 16 A), whereas the same ductile shear occurs in collotelinte grain (Fig. 16B and C). The samples were acquired from the coal seams located near Dumerbera Village, West Bokaro basin.

Based on Su et al.'s (2001) classification, the sigmoid veins come under the II_2 subcategory (isolated S-shaped cracks), and their formation is attributed to the shear stress regime experienced by the coal. The presence of this pattern in coal samples collected from the basin margin areas of West Bokaro basin suggests that shear forces activated after the deposition of Barakar Formation.

6. Structural classifications of coal of Bokaro basin

Based on the proposed classification (Table 2), the coals studied fall into the category of tectonically deformed coals, with subcategories ranging from blocky to cataclastic, and occasionally granulated. Tectonic deformation is more pronounced in the coals from the East Bokaro Basin, possibly due to the deep-seated nature of the coal seams and the major intrabasinal faults that intersect the basin. In contrast, the coals from the West Bokaro Basin, located near the southern margin and closer to the surface, are less deformed, despite their proximity to several basin margin and intrabasin faults. Additionally, the samples from the lowermost seam, just above the basement rock, show the most intense deformation, ranging between cataclastic and granulated, as observed in

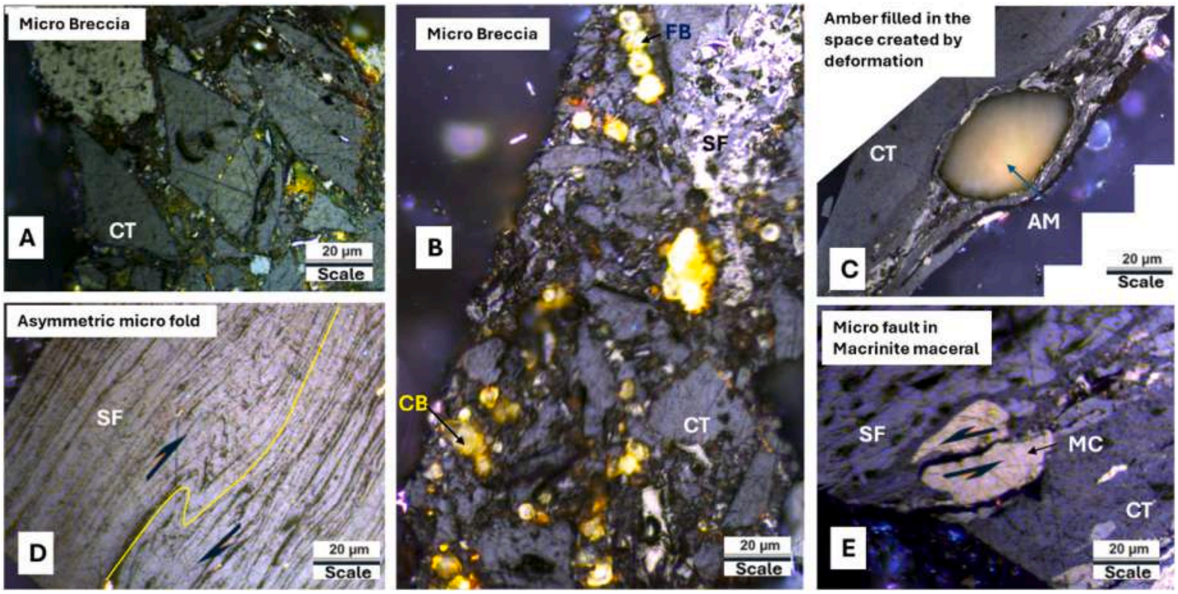

Fig. 19. (A) and (B) Micro coal breccia, (C) Amber filled by space created after deformation, (D) Asymmetric micro-fold, Micro fault in mactrinite maceral (MC) Location: Near Dumerbera Village, West Bokaro basin. (CT- Collogerlinte, SF- Semifusinite, FB- Framboidal Pyrite, Am- Amber, CB- Carbonate).

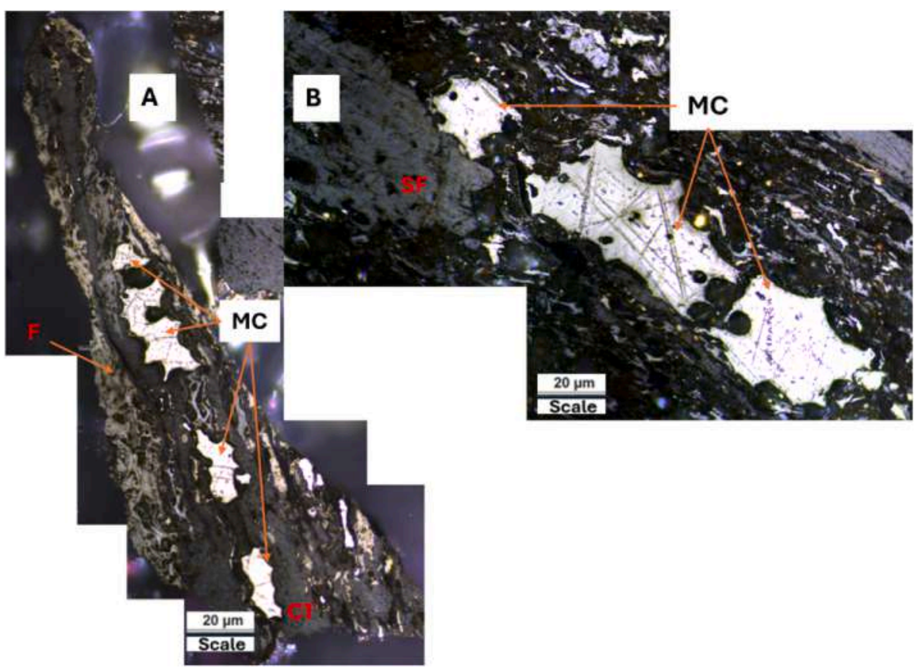

Fig. 20. Boudinage like structure Location: Near Dumerbera Village, West Bokaro basin. (MC- Macrinite, SF- Semifusinite, F- Fusinite, CT- Collotelinite).

the field.

7. Tectonic forces responsible for Bokaro basin evolution

Chakraborty et al. (2003b) proposed that the Karanpura and Bokaro basins, along with the smaller Auranga and Hutar outliers, together form a sigmoidal master basin. The Karanpura basin constitutes the broad central part of this structure, while the Hutar-Auranga and Bokaro basins make up the narrow extremities of the “S" shape. The Bokaro basin, situated in the northern part, is an E-W elongated basin. The southern wing, comprised of the Auranga and Hutar outliers, is similarly faulted along its southern boundary (Chakraborty et al., 2003b) Building on this framework and a reconnaissance study using remote sensing, the southern part of the West Bokaro basin was chosen for detailed analysis. For comparison, the central region of the East Bokaro basin, where remote sensing indicated a lower fault density, was also selected for study.

During fieldwork conducted around the southern margins of the West Bokaro Basin, a homoclinal contact between the Gondwana sedimentary sequence and the CGC was documented, while several NW-SE trending faults were specifically identified along the Chhota Nadi river section. These faults are predominantly normal faults and also have a prominent strike-slip component (Fig. 10). Fracture lines within the shale beds, which run parallel to the faults, display signs of top-to-left slip (Fig. 9). From these observations, it can be inferred that the basin margin faults along the southern edge of the West Bokaro Basin are

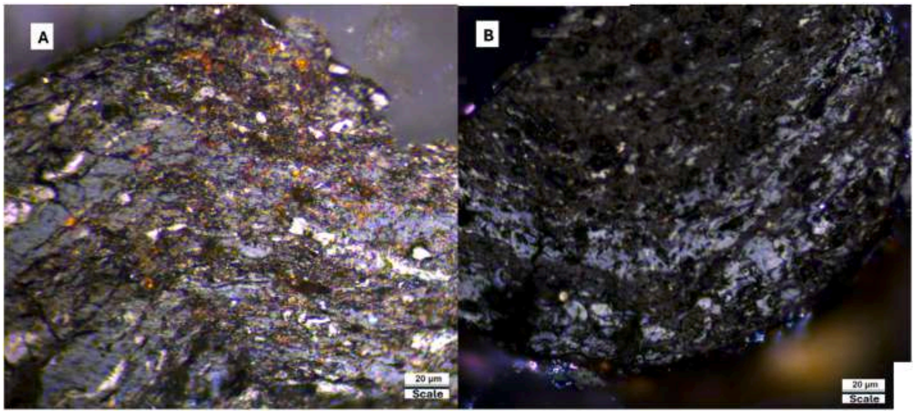

Fig. 21. Fold appeared in partially crushed, amalgamated coal macerals, Location: (A) East Bokaro Basin and (B) West Bokaro Basin.

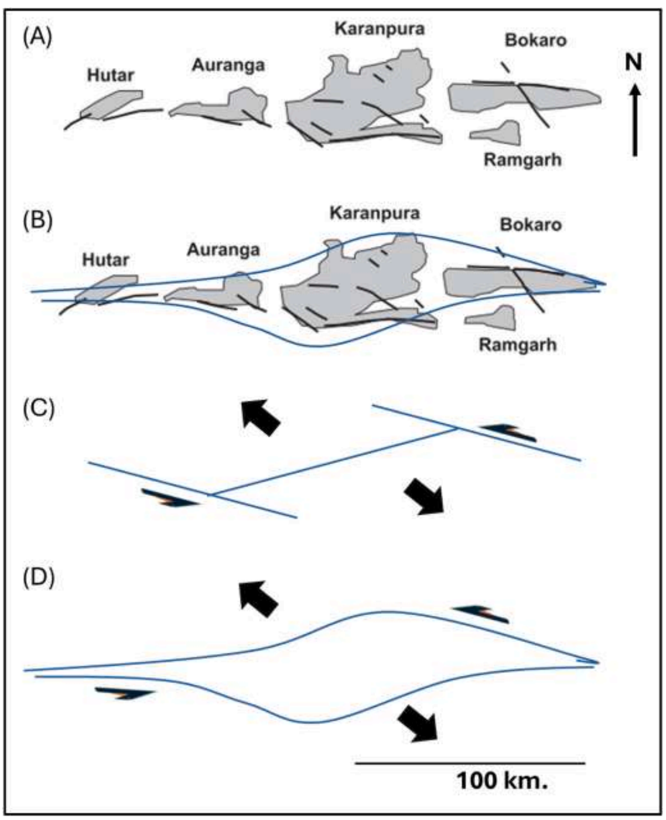

Fig. 22. Model for the development of Bokaro Basin (A) Disposition of Damodar valley basin including Hutar, Auranga, Karanpura, Ramgarh and Bokaro basins (Chakraborty et al., 2003b), (B) The sigmoid shape of the group of basins has the Karanpura Basin at its center, forming the swollen part of the "S," while the Bokaro Basin represents the easternmost wing of the "S." (C) and (D) represent the early and late stage of the basin development where, area in the inner part of sigmoid represents a pull apart basin.

characterized by dextral (right-lateral) strike-slip.

It is particularly intriguing that the coal samples from the Bokaro Basin exhibit microstructures associated with compressional forces as evident by folded fusinite grains, micro-brecciated coal, macrinite boudinage, asymmetric microfold in semifusinite, irregular reticular cracks in collotelinite macerals, and folds in the amalgamated macerals grains. Additionally, extensional forces as deciphered through micro faults in macrinite macerals and isolated straight cracks (II_1 type) and shear forces as indicated by sigmoidal tension gashes, played a crucial role in the tectonic evolution of Bokaro basin. This suggests that the Bokaro Basin, particularly along its southern margin, has undergone several phases of tectonic deformation, highlighting a complex tectonic history. Also, the presence of numerous tension gashes in collotelinite macerals of coals from Barakar formation suggests that the pulling apart of the basin continued even after the disposition of these strata. Such evidence provides valuable insight into the structural evolution of the basin.

Based on the above observation, an inference can be drawn in the form of a model for the evolution of the master basin including Hutar, Auranga, Karanpura and Bokaro. Where Bokaro basin lies at the easternmost wing of this sigmoid (s-shaped) master basin (Fig. 22). A 50 km extension leading to pull apart would imply compression in the surrounding rock materials. A field check can be done as a future work to validate the proposed model.

8. Conclusions

1. Fault distribution is highly nonhomogeneous and mostly distributed along the basin margin. This might indicate that the distribution of rift activity and the creation of space for sediment deposition were nonuniform.
2. Two distinct sets of micro-deformation features were primarily observed: extensional features such as sigmoidal tension gashes, and compressional features such as micro faults, microfolds, boudins and coal micro-breccia. Intense folding is primarily observed in the fusinite sub-macerals, while micro faulting and boudins are limited to macrinite macerals. Micro-brecciation and sigmoidal tension gashes are exclusively found in collotelinite, where micro fractures are also most prevalent. The sigmoidal tension gashes are often empty but, in some cases, are filled with resins or carbonates. Fusinite exhibits more ductile deformation compared to other macerals, while collotelinite tends to show more brittle deformation. These features indicate multi stages of deformation developed in compression, extension, and strike slip domain.
3. The coals in the Bokaro Basin are tectonically deformed, ranging from blocky to cataclastic, and occasionally granulated. Deformation is stronger in the East Bokaro Basin due to deeper coal seams and major faults, while the West Bokaro Basin coals, closer to the surface, are less affected. The most intense deformation is observed in the lowermost seam, near the basement rock, with macroscopic features indicating cataclastic to granulated forms. This may show the multiple episodes of deformation, where the tectonic activity took place during or just after the deposition. Strata were affected by late-stage tectonic activity as well.
4. The extensional stress was the primary reason for the development of the basin, but signs of shear stress were also visible in the southern marginal faults of the West Bokaro Basin. The Bokaro Basin is located at the easternmost extremity of an S-shaped master basin that

includes Auranga, Hutar and Karanpura. Through this research, it is confirmed that a pull-apart mechanism also contributed to the basin's tectonic evolution, rather than it being purely extensional. The presence of sigmoidal tension gash in the coal samples from the Early Permian Barakar Formation confirms that the shearing forces were active in the study area at least during or after the coalification. The conclusion confirms that the Bokaro Basin's evolution was driven by extensional stress, with shear stress indicating a pull-apart mechanism. Sigmoidal tension gashes in Barakar Formation coals support active shearing during or after coalification.

5. The Bokaro Basin coals, particularly those from the East Bokaro Basin, have undergone intense deformation, exhibiting structures ranging from blocky to cataclastic and occasionally granulated varieties. The development of these multi-directional, complex fracture networks enhances permeability and provides conduits for gas flow, essential for CBM production. Additionally, the deformation patterns in surrounding basins can be studied using the same methodology, which can improve understanding of the complex evolutionary history of India's Gondwana basins.

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CRediT authorship contribution statement

Manish Kumar Srivastava: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Kaushal Kishor:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Alok K. Singh:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology. **Soumyajit Mukherjee:** Writing – review & editing, Visualization, Validation, Investigation. **Shivranjan Kumar Bharti:** Resources, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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