Chapter-2

Overview of the study area

2.1 Introduction

The study area for the present study, i.e., Dhanpuri opencast mine, is situated in the eastern part of the Sohagpur coalfield between coordinates of latitudes 23°08'30''−23°10'30''N and longitudes 81°32'20''−81°37'10''E in Shahdol District, Madhya Pradesh (Fig. 2.1). It is a Central Indian coal basin situated in the state of Madhya Pradesh, India (Mondal et al. 2021). It is a part of Son Valley basin of Gondwana system of India along with other coalfields such as Sonhat, Jhilimili, Chimiri, Singraulli, Johilla, and Umaria-Korar coalfield. It is considered to be one of the most extensive coal deposits in the country (Pareek 1987).

The sohagpur coalfield is spread over 3000 Km^2 with a thick sedimentary deposit of about 1000 m, containing 4064 MT of coal reserve resting over basement rock (Jasper et al. 2017; Mondal et al. 2020). These Gondwana sediments mainly consisted of rocks corresponding to Talchir, Barakar, Barren Measures, Raniganj Formation, Pali, and Parsora as given in table 2.1 with WNW-ESE to E-W trend and dipping 5^0 towards north (Milici et al. 2003; Pareek 1987). The basement rock below the Gondwana sediments consisted of Precambrian granite rock, which is deep-seated and does not show any outcrop in the coal-bearing area (Dhanam et al. 2013). The basement rock is unconformably overlain by the Talchir Formation (Upper Carboniferous-Lower Permian), having an average thickness of about 124.64 m and consisting of fine to medium-grained grayish sandstone (moderately sorted) with grey shale and siltstone. The occurrence of the Talchir Formation in the area is considered to be due to the non-marine and glaciomarine deposition during the Early Permian Age, and hence marine fossils can be found in this formation (Pareek 1987; Veevers and Tewari 1995). This formation is devoid of any economic coal bed. Above the Talchir sediments, about 421.48 m of strata is characterized by the Barakar Formation (Early Permian), considered the major storehouse of coal in the Gondwana basin (Rao 1983). The formation consisted of rolling topography and is divided into two subgroups: [i] Upper (Super) Barakar Formation and [ii] Lower (Supra) Barakar Formation (Milici et al. 2003). The Upper Barakar Formation consisted of extensive coal seams (Thickness: 8–10 m) sandwiched between thick hard sandstone layers. The presence of low sulfur coal, impure sandstone, and lack of tidal indicators has shown that the depositional environment was highly influenced by rainfall rather than the sea level change (Chandra and Chandra 1987; Tiwari and Tripathi 1988). The geology of the Upper Barakar Formation consisted of relatively impure, feldspathic to arkosic, medium to coarse-grained sandstone, and laminations of sandstone/shale along with thick coal seams (Pareek 1987). This felspathic and shaly content can relate with REEs concentrations in the study area. The deposition of the Lower Barakar Formation occurred during the sea-level fluctuations, which can be inferred from paleo-channels in the cross-bedded sandstone and tidally affected laminates (Mukhopadhyay et al. 2001). The Lower Barakar Formation consisted of relatively pure, fine-grained calcareous sandstones and was devoid of economic coal seams (Milici et al. 2003). The Barren Measures (Middle

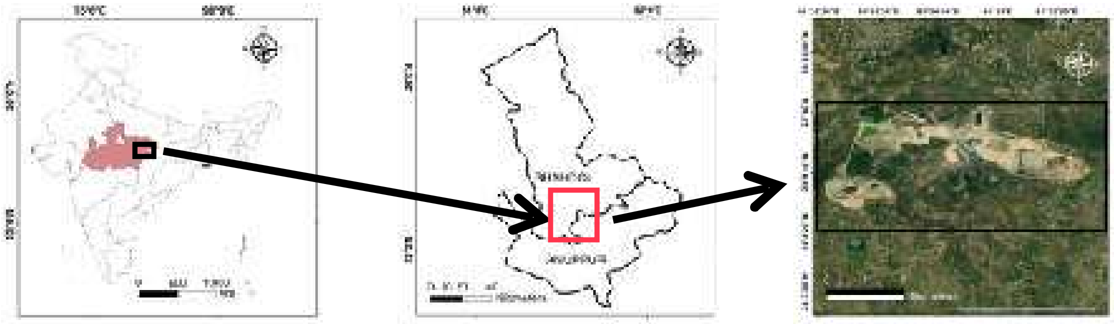

Fig. 2.1: Location of Dhanpuri opencast mine of Sohagpur Coalfield, Madhya Pradesh, India

Age	Formation (max. recorded thickness)	Lithology
Early Eocene To Late Cretaceous	Deccan Trap (100m)	Dolerite dykes and basic flows
Late Cretaceous	Lameta (25m)	Calcareous sandstone & sandy limestone
Early Jurassic To Late Triassic	Parsora (100m)	Mature well sorted arenite interbedded with lavender coloured clay beds (Not found in the area)
Early Triassic To Late Permian	Pali (+250m)	Immature sandstone with varying amount of clay matrix. Decrease in feldspar content towards top (Not found in the area)
Late Permian	Raniganj (+550m)	Fine to medium grained feldspathic, cross-bedded immature and poorly sorted sandstone alternating with gray claystone, shale and coal.
Local disconformity (scoured contact, Coal & caliche development), may be conformable in the deeper parts of the basin		
Late Permian	Barren Measures (250m)	Medium to coarse grained arkosic, immature and poorly sorted sandstone interbedded with siltstone, shale and variegated claystone.
Local disconformity (palaeosol), may be conformable in the deeper parts of the basin		
Early Permian	Barakar (265m)	Medium to coarse grained arkosic, immature and poorly sorted sandstone alternating with siltstone, shale, variegated claystone and coal.
		Medium to fine grained arkosic, immature and poorly sorted sandstone alternating with siltstone, shale and grey claystone.
Early Permian	Talchir (+120m)	Medium to coarse grained pebbly sandstone with argillaceous matrix; angular pebbles of quartz, rock fragments, claystone and shale
-UNCONFORMITY-		
Precambrian	Surguja crystalline complex	Granite

Table 2.1: Stratigraphical sequence of the Sohagpur Coalfield, Madhya Pradesh (modified after Rao 1983; Pareek 1987; Dhanam et al. 2013; Gautam et al. 2016, Agnihotri et al. 2016).

Permian) is the next overlying succession, which is separated from the Barakar through a local discontinuity. It does not have much economic value as the formation lacks any coal seams. The Barren Measure consisted of a thick layer of sedimentary deposits (average thickness: 368.78 m), having basic geology of ferruginous medium to coarse-grained sandstone with green and grey shale. It also contained angular to sub-angular grains of feldspar along with quartz and was sometimes characterized by chlorotic sandstone along with a marker bed of aluminous claystone existing all across the basin (Milici et al. 2003; Rao 1983). The deposition of sediments in Barren Measures occurred over a tectonically stable alluvial plane in a dry climate, which can be inferred from its ferruginous and oxidized strata composition, and presence of impure sandstone with inter-beddings of

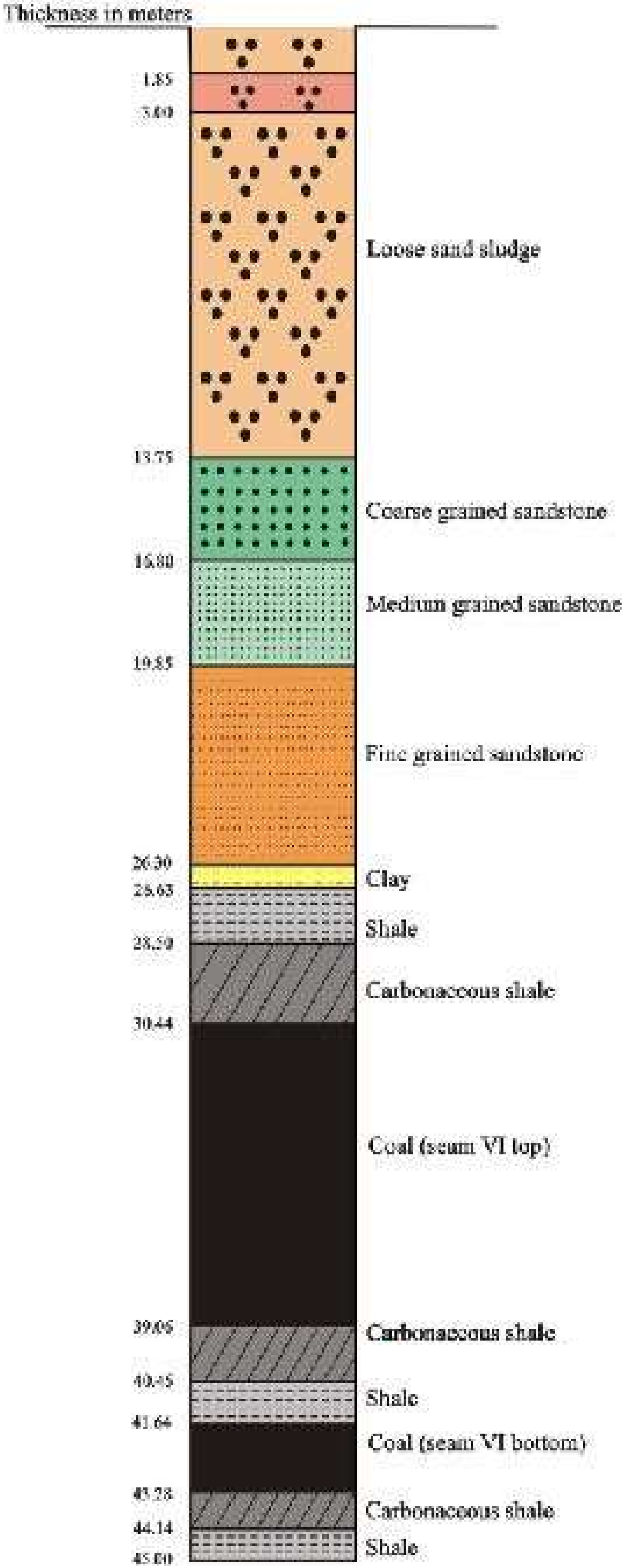

Fig. 2.2: Lithology of Dhanpuri opencast mine of Sohagpur Coalfield (Agnihotri et al. 2018)

variegated siltstone and claystone (Mukhopadhyay et al. 2001). Barren Measures is again separated from the overlying Raniganj Formation (Late Permian) through a local discontinuity, whose average thickness is about 500 m. The Raniganj Formation contained thin coal seams, which are locally distributed in the area along with impure sandstone. These sandstone beds are sandwiched between the laminate, dominated by the tidally affected zones (Mukhopadhyay et al. 2001). The tectonic instability and frequent changes in the depositional environment have been the main reason behind the regional distribution of the coal seams. The following overlying sedimentary sequence is the Pali Formation (Early Triassic-Late Permian), having an average thickness of 350 m. Its geology consisted of carbonaceous shale, coarse-grained sandstone, grey and chocolate color shale in the lower part, whereas its upper part consisted of medium to fine-grained sandstone and a few coal seams (Pareek 1987). The Parsora Formation (Early Jurassic-Late Triassic), with an average thickness of 100 m, is situated above the Pali Formation. The Pali Formation consisted of pebbly, ferruginous coarse-grained sandstone and shale. The uppermost succession in the sedimentary sequence is the thin Lameta (Late Cretaceous), consisting of calcareous sandstone and sandy limestone, whereas the overlying Deccan Trap (Early Eocene-Late Cretaceous) mostly consisted of dolerite dykes (Mondal et al. 2020; Dhanam et al. 2013).

The geological plan and the summarized details of the geological successions of the Sohagpur coalfield are given in fig. 2.3 and table 2.1, respectively (Rao 1983; Pareek 1987; Dhanam et al. 2013; Gautam et al. 2016, Agnihotri et al. 2018). The preliminary studies showed that a series of faults had intersected the coalfield (mostly trending towards E-W, NW-SE, and NE-SW), out of which the Bahmni-Chilpa fault is the most apparent discontinuity, dipping towards the North with a high fault angle of about 45^0.

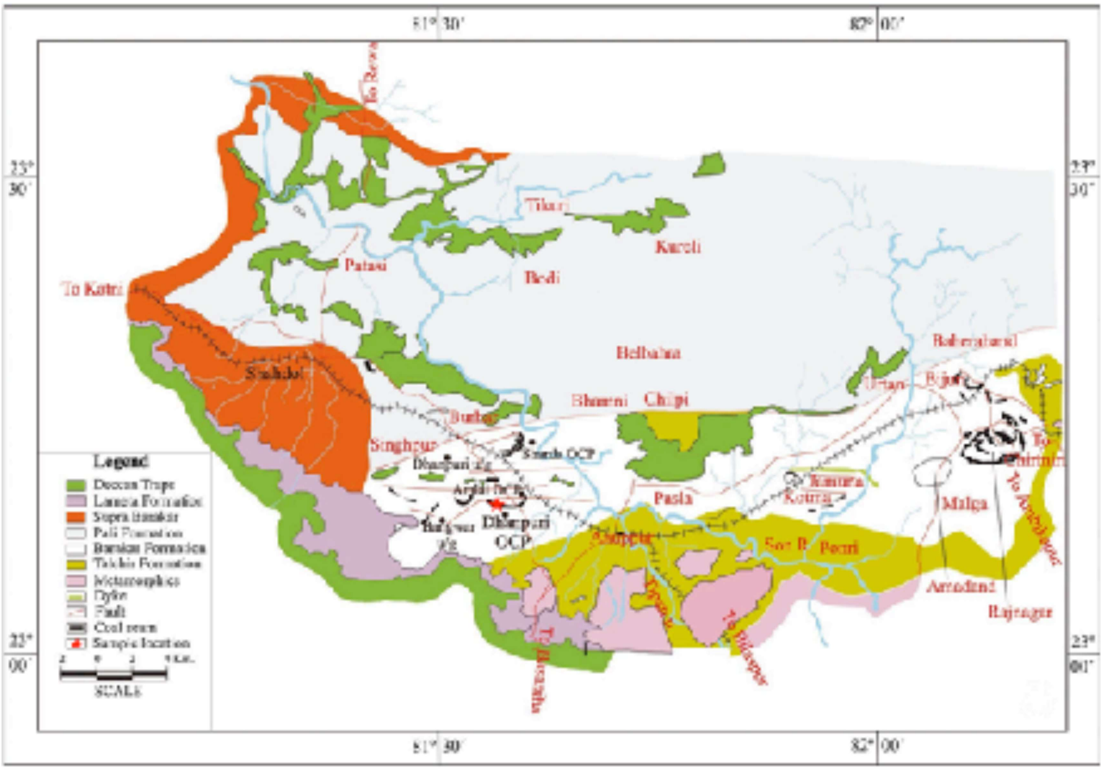

Fig. 2.3: Geological formations and location map of Sohagpur Coalfield, Madhya Pradesh, India. (Agnihotri et al. 2018)

Fig. 2.4: Photograph of Dhanpuri OCM of Sohagpur Coalfield, Madhya Pradesh, India.

The orientation of the Bahmni-Chilpa fault is along the E-W direction, and the maximum recorded throw obtained from the borehole data was around 650 m. Thus, the fault mentioned above has divided the coalfield into two parts (Milici et al. 2003) and serves as the guiding parameter toward the occurrence of coking coal in the area. The Barakar seams in the downthrown (northern) side of the fault possess the coking property, which might have resulted from the intense heat generated due to the higher depth of the seams and flow of intrusive bodies.

The coal seams in the upthrow (southern) side of the Bahmni-Chilpa fault mostly contained non-coking coal (Choudhary et al. 1984). Thus, the economic coal seams in this area are not so deep-seated as compared to the northern part of the coalfield (depth range of major seams: 150–400 m), which can be inferred from the surface exposure of Barakar along the coal block.

2.2 Physiography and Drainage

Son River and its tributaries drain the entire Shahdol district. Thus, the area falls in the Ganga Basin. The river Son flows north till the northern extent of the district, marking the western boundary of the Shahdol with the Umaria District. After that, the River Son flows due east and marks the northern boundary of Shahdol district with Satna district. The important tributaries of the Son river are the Kunak Nadi (small river) and the Chuwadi Nadi. The river son is draining the southeastern parts of the Shahdol district through its important tributaries like Tipan, Chandas and Bakan, flowing in the north-west direction with a dendritic pattern, draining the central plains of the Shahdol district.

Another important tributary of the Son River is the Banas River, flowing along the district's eastern boundary, marking the boundary of the Shahdol with the Sidhi District. The north-western part of the district is drained by the Banas River and its tributaries, namely the Jhanapar River, Kormar Nadi, the Rampa Nadi, and the Odari Nadi. Banas River confluences with the Son River at the northernmost tip of Shahdol District.

2.3 Rainfall and climate

Shahdol district experiences a temperate climate characterized by a hot summer, well-distributed rainfall during the south-west monsoon season and mild winter. The winter season commences from December and lasts till the end of February, followed by the summer from March to the middle of June. The south-west monsoon (rainy season) continues from the middle of June to September, when the south-west monsoon is active, while October and November constitute the post-monsoon (retreating monsoon season). The climate of Shahdol District, as calculated by Thornthwaite Precipitation Effectiveness Method, is a humid climate with forest-type vegetation.

May is the hottest month, with a mean daily maximum temperature of 41.4°C and a mean minimum temperature of 26.5°C. With the onset of southwest monsoon during June, there is an appreciable drop in day temperature, while at the end of September or early October, there is a slight increase in day temperature, but nights become progressively cooler. January is generally the coolest month, with the mean daily maximum temperature at 25.6°C and the mean daily minimum temperature at 8.4°C. The average daily maximum temperature is about 41.4°C, and the minimum temperature is about 26.5°C. During the south-west monsoon season, the relative humidity generally exceeds 88% (August). The driest part of the year is the summer season when relative humidity is less than 38%. April is the driest month of the year. The wind velocity is higher during the pre-monsoon period compared to the post-monsoon period. The maximum wind velocity of 6.8 km/hr is observed during June, and a minimum of 2.3 km/

hr during December. The average annual wind velocity of the Shahdol district is 4.3 km/ hr. The average rainfall of the Shahdol district is 1131.4 mm.

As per rainfall statistics, the frequency of occurrence of normal drought in the area is 25%, and that of mild drought is also 25%, while the occurrence of severe droughts in the area is only 5%, i.e., on an average, there is a possibility of occurrence of a normal or mild drought once in every seven years, while that of severe drought once in every 20 years. The area does not experience any severe drought.

2.4 Soils

The soils in the area are generally of clayey loam types, with sandy loam soil in some areas. Loam is a mixture of sand, silt and clay in a balanced proportion. In the northern and central parts of the District, the undulating plateau with mounds is covered with slightly deep soil, well-drained, moderate to fine loamy soils on gentle slopes marked by moderate erosion. The southern hilly region is covered by very shallow loamy soils, somewhat excessively drained. The soils developed on moderately steep slopes are marked by severe erosion. The soils have been classified as per pedological taxonomy (Ibáñez and Ruiz-Ramos 2006) are as follows:

1. Ustocherpts
2. Ustorthents
3. Rhodustalfs
4. Haplustalfs
5. Haplusterts

2.5 Geological Setting

The Sohagpur coalfield comprises over 1000-m thick sedimentary strata unconformable overlying the basement Precambrian rocks. The sedimentary rock formations include the

Gondwana Supergroup and trend WNW-ESE to E-W dipping up to 5° to the North. Several faults traverse in the area. A major en-echelon ENE-WSW-trending fault with down-throw towards the North runs through the middle part of the coalfield, along its southern boundary, and is named the Bamhani-Chilpa Fault. The rocks of the Talchir Formation (Upper Carboniferous-Lower Permian) form low-lying plains, include needle shale, siltstone and boulder beds, and contain marine fossils.

The overlying Barakar Formation (Lower Permian) of the study area has a rolling topography and comprises sub-arkosic felspathic ill-sorted garnetiferrous sandstones with bands of shale, carbonaceous shale and coal seams. The formation is 450 m thick and subdivided into three members, of which the middle one is the thickest. The lower member contains a grayish-white felspathic garnetiferous sandstone, siltstone and shale, and is devoid of any coal seams. The middle member includes cross-bedded felspathic sandstones with garnet and thick workable coal seams in the lower portion. Ferruginous sandstones, shale, and siltstones characterize the upper unit.

The overlying Pali Formation (Triassic) is over 350 m thick. The Lower Pali comprises coarse-grained sandstones, grey and chocolate shale, an argillaceous facies in the western part and an arenaceous facies in the eastern part of the coalfield. Carbonaceous shale has been recorded in the Baheraband area in the eastern part of the coalfield. The Middle Pali Formation is coal-bearing and includes medium to fine-grained sandstones, shale, and carbonaceous shale.

The Parsora Formation (Upper Triassic) occurs in the northern part of the coalfield and comprises coarse-grained to pebbly ferruginous sandstones and shale. The succeeding Lameta Beds (Upper Cretaceous) include greenish and reddish poorly consolidated sandstones and shale with nodular limestone at the top. A marked unconformity separates the Lameta Beds from the Parsora Formation. The coalfield is profusely intruded by dykes and sills of dolerites (Deccan Trap, Upper Cretaceous-Eocene), and dolerites are also emplaced along the fault in Baheraband (23°18'30"N: 82°5'E) area.

The Sohagpur coalfield is a remnant of the Son valley basin of Gondwana deposition and can be subdivided into three major sub-basins from west to east: Rungta-Amlai, Kotma and Bijuri (Pareek 1987). The coal seams are being worked in the area south of the main fault zone, i.e., in the southern upthrown side of the Sohagpur coalfield.

2.6 Paleo-depositional condition of the area

It is generally accepted that the Talchir deposition commenced over a vast area on a mature, undulating topography. A single instance of such soil on the peneplain basement is preserved on the right bank of the Johilla River, adjacent to the spillway of the Johilla dam. Initially, matrix-supported boulder conglomerates representing moraine materials were deposited. Boulder beds exposed along the peripheral parts are, in many cases, stratigraphically younger. In most of the Sohagpur Sub-basin, the Talchir thickness ranges mostly between 70 m to 90 m. However, it shows a rapid increase toward the south, southeast, and southwest and ranges from 290 m to 430 m. The rapid thickness increase is due to tectonically induced sinking of the southern part by an NNE-SSW trending contemporaneous fault in the eastern part of the basin. The lithosequence across the basin indicates that the Talchir strata are sandier toward the West. All the basins of the Son-Mahanadi Valley overlie a vast expanse of Talchir strata. The distribution pattern, coupled with the thickness variation of the sediments, suggest that during the Early Permian, the main Talchir depocenter was far beyond the present southern Barakar boundary of the sub-basin. It was confined mainly to the southeastern side or further south of the basin. It also indicates that, although the sedimentation commenced in an embryonic basin (Mitra

1991), tectonically controlled subsidence aided by faulting took over in the later phase of Talchir deposition. It is corroborated by the continuous presence of a penecontemporaneously deformed blanket of coarser clastic in the upper part of the Talchir strata. The Barakar Formation decreases in thickness from east to west (380–220 m) with an average of 300 m. The irregular nature of isopach suggests local tectonic control in its deposition. The lower member (l00–l20m) of the Barakar Formation, occurring below the regional Coal Seam I, is mainly composed of fine-grained calcareous sandstone and inclined heterolithic facies of sand and mud, resembling tidal couplets. It is generally devoid of persistent coal seams.

The upper member of Barakar Formation consists almost entirely of coarse to medium-grained sandstone, a much lower proportion of shale and siltstone and five regional coal seams (I to V) varying in thickness from 0.5 to l2 m. All the coal seams seated over carbonaceous-rooted earth often show the development of A and B horizons of paleosol. The vertical accretion of paleopeat land has been abruptly terminated by the deposition of fluvial sands right over the mire surface by avulsed channels. The rise of paleo-mire's water table resulted in the deposition of wave-rippled and turbidite sands in the roof rocks of the coal seams. The vertical aggradation of channel sequence within the parting sandstones separating the coal seams may also indicate the base level rise during each high stand stage. It triggered the lateral movement of the trunk channel from the deeper part of the basin to its shallower part. The sharp and erosional lower contacts of the channel sequence point towards the sudden migration of the paleo-channels over the mire. The accelerated rate of base-level rise may be due to the rapid sinking of the basin. The uppermost regional Seam V grades upward to variegated green and grey paleosol of substantial thickness. It displays a gleying feature toward the top. The soil exhibits blocky peds and argillan stress cutan, which testify to changing from a coal-forming wet climate to a seasonal dry and wet climate. The facies boundary of Seam V and the paleosol, interpreted from their spatial disposition, appeared to follow the NW-SE trend in the western part of the basin (Plates VI and XI). The paleocurrent direction during the Barakar time was mostly unimodal with a broad spread of the current rose diagram. The regional direction was NNW. This trend coincides with the oblique system of paleo drainage in the basin. It can be assumed that the channel-levee system was restricted to the western highland during the culmination stage of deposition of the Barakar sequence. The remaining low-lying flood plain of the eastern part was occupied by poorly to well-drained peat land and shallow lakes. The general coarsening upward trend of the Barakar litho-sequence may indicate basin ward progradation during an overall high-stand stage.

The paleosols of the Barakar Formation associated with or without the coal seams are dark grey in color and rich in carbonized roots and leaf litter (Mukhopadhyay et al. 2011). The change of paleosol character has been marked from the top section of the youngest Barakar coal seam (Seam V). The seam degenerates upward into grey, green, and red mottled paleosol through a persistent zone of carbonaceous shale in the central and eastern part of the basin. The blanket of paleosol horizon without any underlying coal seam continues in the western part of the basin/levee complex in the western part during the development of paleopeatland in the low-lying central and eastern parts of the basin. The paleosol also indicates a change from wet to the seasonally dry and wet climate. During the short, wet period, the rain-washed clay filled the vertical cracks in the soil developed during the long dry period. This process led to the formation of stress argillan cutan bounded blocky peds. Moreover, it also attests to rise of the base level during the deposition of Seam V. During the high stand of base level, accentuated bacterial activity (due to a decrease in the acidity of the mire water) resulted in degeneration of the peat land. The succeeding base level fall led to the development of paleosoil catena above the coal seam.

The isopach map of Barakar strata in the Sohagpur Sub basin shows a general thickness variation from 200 m in the west to 320 m to the east. In the northeastern part, the Barakar thickness increases to 380 m. Moreover, the basin slope was toward the south during the earlier Talchir period, but it sloped N-NE during the Barakar strata's deposition. Moreover, unlike the Talchir strata, the Barakar sediments are coarser and sandier toward the east. The contemporaneous fault, which remained active during the Talchir period, probably became inactive during a later phase. A comparison of the isopach maps of Seam I and Seam II shows that the locale of their greater thickness remained almost identical. Moreover, persistent greater thickness for both seams north of the Bamhani-Chilpa Fault suggests that Bamhani-Chilpa Fault probably came into existence during the deposition of seam I and remained active even during the deposition of seam II. It remained active, intermittently throughout the Barakar period, as indicated by the abrupt deterioration of coal quality of the upper seams on the downthrown side of the Bamhani-Chilpa Fault, which extended across the basin from this period.

The Barren Measures is devoid of coal seams and generally comprises medium to fine-grained siderite sandstones with three to five thick beds of paleosols of regional persistence. The sandstone consists of 2D and 3D mega ripples (both current and wave) and rhythmic plane/wavy bedding, which ubiquitously display graded base and laminated tops with ripple bedding and mud clasts at different levels. It was formed in a flood basin lake due to sheet floods arising from direct precipitation. Individual flood events are marked by the rapid introduction of the coarsest debris, followed by progressively finer sediments as the flow waned. Impounded water flooded the distal sand flat, and waves reworked the sediments. Clay drapes were desiccated during falling water and could be incorporated in the next cycle. The paleosols are variegated grey, green, brown, and red colored mudstone having inter-beds of fine sandstones. These are cumulative paleosols and have been formed under a seasonal dry and wet climate during a prolonged period in slightly acidic to neutral groundwater conditions. The paleosols are generally thick and cover a large area of the basin. The third unit above coal Seam V is the thickest bed (15–30 m) and was traced throughout the basin in the subsurface. It may indicate a geological discontinuity.

The Barren Measures contain three regionally correlatable paleosols and four or five local zones (Mukhopadhyay et al. 2011). The paleosols lack distinct development of soil horizons. However, color mottling of grey, green, brown, and red hues is usual. The structure of mottled paleosols is represented by blocky peds and argillan stress cutan. Nevertheless, the occurrence of spherosiderite around rootlets and concentration of peanut-sized sideritic globules in grey and green colored zones was observed at different levels. The paleosol structure of the Barren Measures also indicates the continuation of seasonal dry and wet climates. The fine-grained sandstone beds occurring at different levels within the paleosol zones or on their floor are generally sculptured by wave ripple bedding. It testifies to the recurrence of a large but shallow lake in the Sohagpur Sub-basin during the early part of the Upper Permian period.

Unlike its lower contact with the Barakar, the contact between the Barren Measures and the overlying Raniganj strata is gradational and has been tentatively marked at about 30m below the first Raniganj coal seam. As the basal Raniganj coal bed is impersistent, the contact is arbitrary. Calcareous nature, a common characteristic of Raniganj strata, was also present in upper Barren Measures strata.

The Barren Measures are 200–350 m thick. However, the thickness increases toward the downthrown central part of the Bamhani-Chilpa fault, unlike the underlying Barakar strata. It suggests continued vigorous activity of the Bamhani-Chilpa and associated faults during the deposition of the Barren Measures. In addition, the Barren Measures are thinner westward, that is, the areas of relatively more significant sinking remained confined toward the east and across the Bamhani-Chilpa Fault were due to the contemporaneous activity of the same.

The lithosome changes upward. The appearance of carbonaceous mudstone/coal seam and patches of calcareous cement in the sandstone indicate the beginning of the Raniganj Formation. The lithosome generally comprises ripple-bedded, fine to medium-grained sandstone, inclined heteroliths (mud-dominated) with paleosol beds (grey, green, mottled) and lenticular coal seams. The presence of limestone in the upper part of the Raniganj Formation is a noteworthy feature. It reflects the high base level equivalent to the maximum flooding surface. The heterolithic facies is characterized by lenticular and flaser bedding, sequential bioturbation, and combined flow ripple. Reversal of paleocurrent directions and falling watermarks has been observed at different levels. The lower delta plain with distributary mouth bars and inter-distributary bay/lake could be a possible deposition scenario. The paleocurrent pattern changes to two opposite bipolar modes during the deposition of the Raniganj Formation. The vector average was NNE and SSW.

The paleosol of the Raniganj sequence occurs with or without the coal seams. The coal seams are lenticular in nature and are restricted to abandoned channels. The paleosols associated with the coal seams are always dark grey in color and display horizontal root systems. It indicates hydromorphic paleosols development in the high paleo-groundwater table. On the contrary, the paleosols associated with the mud rocks display light grey, green, or reddish-brown color mottles and the presence of lime concretions. They also exhibit stress argillan cutan bounded blocky peds and occasionally contained vertical root systems. All these features indicate a prolonged dry period in an overall scenario of a seasonal dry and wet climate during the Upper Permian. The hydromorphic paleosols were formed in the topographically low-lying abandoned channel part of the alluvial plain.

The Raniganj Formation attains a maximum thickness of 540 m. The total thickness of the Raniganj beds may be on the order of 500–650 m, with its maximum in the north-central part of the basin. The deposition of the Barren Measures and the Raniganj Formation with about 800–1000 m strata within the short span of the Upper Permian indicates accelerated subsidence of the basin floor compared to the earlier Barakar period. We can assume that the subsidence mechanism remained almost the same: fault-aided sinking.

Regional sculpturing of the paleoerosional surface over the Raniganj sequence manifests the subsequent base level fall. It possibly represents an incised valley. It even eroded the Raniganj sequence near the basin margin in the southwestern part of the basin, and the valley fill sequence was deposited over the Barren Measures/truncated Raniganj sequence. The valley-fill sequence has been classified as Pali Formation (Ghosh and Dutta 1996).

The predominance of coarse clastics and a truncated fining upward sequence suggests that the Pali strata were deposited under fluvial conditions. Associated red mudstones display pedogenic features. The red beds increase in frequency toward the upper part near the contact with the Tiki Formation. Paleosols of the Tiki Formation are calcareous and occasionally contain gypsum, anhydrite and lime pellet conglomerates. The high base and preponderance of red coloration in Tiki paleosols indicate an oxidizing and alkaline condition in a semi-arid climate having mild rainfall. The records of abundant terrestrial vertebrates and the absence of ample vegetation in the Tiki Formation also corroborate this (Das and Datta 1999).

Both eustasy and tectonics appear to have controlled the relative position of the Gondwana sea level in central India during the deposition of the Permian coal measures. Tectonic influences on relative sea level in Gondwana basins occurred concurrently with the extension and normal faulting that began in the Late Carboniferous and continued episodically until the final separation of India from Gondwanaland during the Late Jurassic and Early Cretaceous. The climatic regime under which vegetal matter grew was preserved equally crucial to the peat-forming processes. Wet climates are necessary to support the abundant plant growth required for forming thick, regionally distributed peat deposits (Cecil et al. 1993). The stratigraphic section is drawn to a scale that compares the Permian portion of the Gondwana Supergroup with hypothetical sea level and climate curves (Mukhopadhyay et al. 2001). During the Late Carboniferous and Early Permian, the sea level is thought to have risen, and the overall climate changed from dry to wet as glaciers melted and rainfall increased during the northward migration of Pangea from the Antarctic region into cool but wet temperate latitudes (Scotese 1994). Locally distributed coal beds associated with calcareous sandstones and tidally influenced sediments in the lower part of the Barakar Formation appear to be related to the high water tables and abundant soil moisture caused by sea-level rise, drowning of existing drainage, and the formation of tidally influenced estuaries. As estuaries filled and interfluves were reduced by erosion, the subdued land surface was filled and covered with littoral siliciclastic sediments during slow but continued sea-level rise and under a relatively dry climate. Langbein and Schumm (1958) showed that maximum sediment yield, giving rise to the sandstones of the Barakar Formation, occurs at approximately 12 inches of rainfall. Minimum sediment yield and maximum formation of organic debris (peat) would occur at 60 or more inches of adequate precipitation. The widespread, thick coal deposits of the Barakar Formation reflect the episodic development and spread of regional mires over a sand-dominated alluvial coastal plain during periods of relatively wet and rainy climate and during periods of tectonic and eustatic stability. Concurrently, the relatively lower volumes of siliciclastic sediments that were eroded from the hinterlands during these wet and rainy periods were transported past coastal plain mires into adjacent shallow marine environments of deposition. Aggradations of this coastal plain, accompanied by a change of climate from wet and cool alternating with warm and dry to hot and dry, is the mechanism that is inferred to have produced the fluvial-dominated Barren Measures and its regionally distributed, oxidized paleosols. The return of tidally influenced sedimentation and the deposition of local coal deposits in the overlying Raniganj Formation reflects a final episode of relative sea-level rise and the formation and filling of estuarine environments within the Damuda Group under a climatic regime similar to that prevailing during the deposition of the Barakar Formation. Veevers (1994) has speculated that the change in climate from generally cool and wet (icehouse) to hot and dry (hothouse) at the beginning of the Triassic was driven by the release of CO_2 into the atmosphere from extruded Siberian Traps. In many ways, Barren Measure red beds are similar lithologically to Triassic red beds, and perhaps as a precursor to the Triassic, Barren Measures depositional environments were more influenced by allocyclic rather than autocyclic processes.

As stated, the Raniganj/Pali contact is also marked by a paleosol bed, which is generally exposed in the western part of the basin. In the eastern part of the basin, the contact is marked by a major fault. Mukhopadhyay and Maity (1989) reported similar paleosol beds in the basal part of the Pali Formation in the Tatapani basin in the east, indicating its areal persistence. The Pali strata have a maximum development of 1400m in the Son-Valley Basin. In the Sohagpur Sub-basin, the thickness of the Pali Formation and younger strata can be estimated indirectly. As was stated previously, to attain the grade of coal metamorphism attained by the Barakar seams, an overburden thickness of at least 2000m of strata is required. As the thickness of the Barren Measures and Raniganj strata is around 1000m, the thickness of Triassic and Post-Triassic strata will be about 1000 m. The thickness of the Parsora beds and younger strata is about 300 m, so the thickness of Pali in the Sohagpur Sub-basin will be around 700 m. Like the Barren Measures and Raniganj beds, the Pali beds (700 m thick) were deposited in the Early Triassic, indicating a faster rate of deposition and a similar tectonic milieu.

The Parsora strata are separated from the Pali beds by another paleosol bed not exposed in the Sohagpur Sub-basin. They have a low-angular unconformable relation at places, and the Parsora beds overlap the Pali strata widely, including even the Barren Measures strata in the western part of the basin. In general, the Parsora beds are sub-horizontal and unaffected by faults. Their widespread overlap relationship with older strata like the Barren Measures suggests a period of uplift and erosion prior to their sedimentation, which is corroborated by the paleosol bed at the base of Parsora. The youngest Chandia Beds (Lower Cretaceous) have limited distribution, are confined to the northwestern end of Son-Valley Basin on the downthrown side of the Northern Boundary Fault, and are probably less than 100m thick. They comprise medium to coarse-grained arenites and kaolinite beds. Kaolinite is very important for REEs study. Its limited areal distribution and proximity to the North Boundary Fault indicate that sinking at that period was restricted adjacent to it. However, in the southern part of the basin, that is, in areas of the Sohagpur Sub-basin, it was a period of poor deposition or non-deposition.

The Lameta Beds (Upper Cretaceous) overlap the Gondwana strata from the Jabalpur Beds (equivalent to Chandia beds) in the west to Talchir strata in the east, indicating an unequal upliftment in post-Parsora and post-Chandia time. N20°E-S20°W trending faults with southerly throw probably came into existence during this period. Their development facilitated the upliftment of not only this part of the basin initially but also a major part of the basin during a later period. The basin floor tilted in the later period and facilitated the deposition of Lameta strata over a widespread area.

The Deccan Trap feeders intruded through the basement and the Gondwana strata and poured out over the Lameta beds in this part of the basin. Dutt (1999) suggested the presence of a large magma chamber below the north-central part of the basin, north of Jaisinghnagar, with radiating cone sheets. So, it can be assumed that one of the main outlets was located north of Jaisinghnagar. Chatterjee and Deshmukh (1996) calculated the possible depth of a magma chamber about 10 km from the present-day surface. Petrographic studies of the dolerite dykes suggest that it melted at the time of intrusion and had an inherent temperature of 900°C (75°C). It gives a steep paleo-temperature gradient of more than 100°C/km. However, an increase in coal maturity against the depth of Seam III indicates a paleo-temperature gradient of +50°C/km; thus, a minimum magma chamber depth of 18 km can be suggested. A huge magma chamber below the basin at that depth would result in a regular thermal halo, and as a consequence, a widespread, even, thermal metamorphism of coal seams would have occurred akin to the effects of the gradual thermal increase due to thicker overburden. However, the pattern of rank maturity of the coal seams in the Sohagpur sub-basin is localized, ruling out the possibility of a large magma chamber just below the basin. Patterns of iso-moisture and iso-vol of the Barakar seams suggests that an E-W trending magma chamber, elongated in its outline and closing toward the west, was emplaced within the basement north of the Bamhani-Chilpa Fault. The present-day pattern of thermal gradients also supports this view (Biswas 1999). The persistent high rank of the Raniganj seams also corroborates this. It can be conjectured that the ENE-WSW trending southerly dipping second-generation faults came into existence due to the emplacement of these basic bodies, which uparched the basement and the overlying Gondwana strata. It also probably led to the development of Tetka anticline (Das et al. 1997) before the deposition of the Lameta Beds. However, the basic magma finally intruded and effused over the Gondwana, overlying Lameta strata in the Late Cretaceous time. The exact relationship between the magma chamber, which was the thermal energy source for rank improvement in the Sohagpur Sub-basin, and the faults located north of Jaisingh nagar is unknown. It is assumed that in the present basin, the Bamhani-Chilpa and other major intra-basinal faults, along with associated structures, functioned as conduits for heat and increased the relative local temperature gradient. Consequently, the Barakar seams show a disproportionate increase in rank concerning the burial depth.

In the post-Deccan-Trap period, there was another faulting movement that affected sill bodies. During this fault movement, major E-W trending faults were also reactivated (Mukhopadhyay et al. 2001a).

2.7 Stratigraphy and sedimentation condition of the Sohagpur coal measures

In the western part of the Sohagpur coalfield, relatively thin (up to two meters thick), locally distributed coal beds within the lower part of the Barakar Formation and in the Raniganj Formation are associated with cyclic sandstone and sandstone-shale laminites that were deposited by the ebb and flow of tidal currents within estuarine environments (Fig. 2.2). These coal beds contain relatively more significant sulfur content than the thicker, more regionally distributed coal beds in the upper part of the Barakar Formation and were nourished by groundwater associated with high sea-level stands. Although climates were generally wet, favoring peat accumulation, tectonic instability caused repeated local fluctuations of sea level that limited the thickness and distribution of the lower Barakar and Raniganj peat deposits.

In contrast, the thick, regionally distributed sandstones and interbedded thick (8-10 meters), regionally distributed coal beds in the upper part of the Barakar Formation are interpreted to represent dry-wet climate cycles that occurred along a delta plain of relatively low topographic relief, during a period of relative tectonic stability and slow sea level rise, as Gondwana moved northward, closer to the equator (Mukhopadhyay et al. 2001a and b).

2.7.1 Talchir Formation

The basal formation of the Gondwana Supergroup in the Sohagpur coalfield is the Talchir Formation (Rao 1983). The Talchir Formation, which is about 400 meters thick, is widely distributed in the Gondwana coalfields of central India and appears to have accumulated as a glacio-marine and non-marine unit during the Early Permian (Veevers and Terwari 1995). It contains no economic coal beds.

2.7.2 Barakar Formation

The overlying Barakar Formation (Lower Permian) contains most of the economic coal in this coalfield (Rao 1983). In the Sohagpur coalfield, the Barakar Formation, which is 290 to 380 meters thick, is divided into a lower member consisting of fine-grained, relatively pure, calcareous and an upper member composed of relatively impure feldspathic to arkosic, medium-to coarse-grained sandstones. The lower member exhibits paleo-channels about 100 meters wide and 30 meters deep that were incised into cross-bedded calcareous sandstones and then filled with massive to cross-bedded sandstones and tidally affected laminitis. The lower part of the Barakar Formation accumulated within an estuarine setting during a period of relative sea-level instability, which is reflected by several episodes of cut and fill (Mukhopadhyay et al. 2001a). These sea-level fluctuations may be related to eustatic sea-level rise associated with the northward migration of Gondwana and the melting of Permian glaciers and to basin formation and subsidence caused by the tectonic extension that preceded the breakup of the supercontinent, Pangea (Mukhopadhyay et al. 2001a, b). Although the lower member of the Barakar Formation contains several coal beds, they are generally only locally distributed, relatively thin, and uneconomic in the Sohagpur coalfield.

However, the coal-bearing sequences in the upper member of the Barakar Formation are within thick sandstone-dominated sequences that contain few of the burrowed, rippled, and flasered cyclic sandstone/shale laminites and thin sandstones that are in the lower part of the Barakar Formation. The reduced amount of these tidal indicators, the relatively impure nature of the associated sandstones, and the regional distribution of the relatively thick, low sulfur coal beds in the upper Barakar agree with the paleobotanical evidence (Chandra and Chandra 1987; Tiwari and Tripathi 1988) that the moisture needed to nourish the thick (8-10 m) coal beds were obtained from rainfall in warm temperate climates, rather than from elevated water tables and estuarine environments associated with sea-level rise (Mukhopadhyay et al. 2001a).

Cecil (1990), in his study of paleoclimate controls on sedimentation, concluded that in warm climates, siliciclastic sedimentation is most significant under highly seasonal rainfall; that dry, nonseasonal climates were conducive to the deposition of evaporites and carbonate deposits; and that perennially wet climates supported the formation of peat deposits. Thus, alternating thick sandstone and coal beds in the upper part of the Barakar Formation may well reflect climate cycles, from warm and highly seasonal to ever wet tropical to subtropical climates, with the sediments accumulating on a generally prograding delta plain.

2.7.3 Barren Measures

A 300 meter-thick unit of unproductive strata, called the Barren Measures, occurs above the lower productive coal measures (Rao 1983). This unit generally consists of ferruginous, chloritic, arkosic sandstones interbedded with variegated siltstone and clay stone deposits. In places within the Barren Measures, a 30-meter thick variegated aluminous clay stone is a major stratigraphic marker both on the surface and in many diamond drill cores. This aluminous clay bed, and others similar to it, are expected within the Barren Measures and may represent fossil paleosols. A basal clay stone unit (3-6 meters thick) overlies the top of the regional Barakar Seam V and marks the end of Barakar sedimentation.

2.7.4 Raniganj Formation

The Barren Measures are overlain by the Raniganj Formation (Rao 1983), which is about 540 meters thick and contains several locally distributed and uneconomic coal beds (Fig.

2.2). Core data indicate that the coal beds in the Raniganj generally occur within laminate-dominated tidally affected zones that are separated by impure sandstones (Mukhopadhyay et al. 2001a). In the Sohagpur coalfield, the coal beds within the Raniganj Formation are generally too thin and discontinuous for large-scale surface mining.

Paleo-botanical evidence (Chandra and Chandra 1987; Tiwari and Tripathi 1988) indicates that climatic conditions during Raniganj deposition were generally wet, warm and perhaps the most favourable during the Permian for the development of regionally extensive thick peat deposits in the Sohagpur coalfield. Nevertheless, tectonic instability and rapidly fluctuating depositional environments precluded the accumulation of thick, regionally distributed coal beds in the Sohagpur coalfield during the Raniganj time. The Raniganj Formation is overlain by the Pali Formation (Triassic and Permian).

2.8 Brief description of the Dhanpuri opencast mine

Dhanpuri opencast mine comes under the Sohagpur coalfield. South Eastern Coalfield Limited (SECL) is a government mining company working in this area for coal mining. SECL is a subsidiary company of Coal India Limited (CIL). The production capacity from Dhanpuri opencast mine is nearly about 5 million tons per annum (MTPA). The mineable reserves range from 21-41 MTPA. The coal type is non-coking coal. The maximum depth in mine is nearly about 83 meters. Major Heavy earth moving machinery is used in mining such as Dragline, Shovel, Dumper and surface miner. The mine is operating start from 1987-88 onwards.

2.9 Justification for the selection of the Sohagpur coalfield as a study area

Sohagpur coalfield is the biggest coalfield in the Madhya Pradesh. The group covers an area of about 5,345 square kilometres with estimated reserves of 8743.69 million tonnes (SECL, 2021). The area of interest for present study is the Sohagpur coalfield, which is considered to be an important sedimentary basin of Central India. The coalfield is considered to contain vast reserves of bituminous/sub-bituminous coal of barakar formation. Despite famous for biggest coalfield, it is least studied coalfield in India, majorly from GSI and CIL works. Few geologists had done their work on the potential for coking coal and CBM resources within the Sohagpur coalfield, Madhya Pradesh, India from 1995 (Milici et al. 2003; Mondal et al. 2021). Furthermore, the previous studies were majorly related to analysis of the basin of deposition with particular emphasis on the regional stratigraphy and depositional environments of the coal-bearing strata, the geologic structure of the basin, and the geochemistry of the coal in order to understand the geologic controls within the basin (Mondal et al. 2021). There is no available data regarding the critical elements in coal and coal by-products of the study area. The coal of the study area is majorly used for thermal power plant, hence, as a case study it is choosen for other than thermal use of Indian coal and coal by-products.