Palynological investigation of coal-bearing deposits of the Thar Coal Field Sindh, Pakistan

Pardeep Kumar

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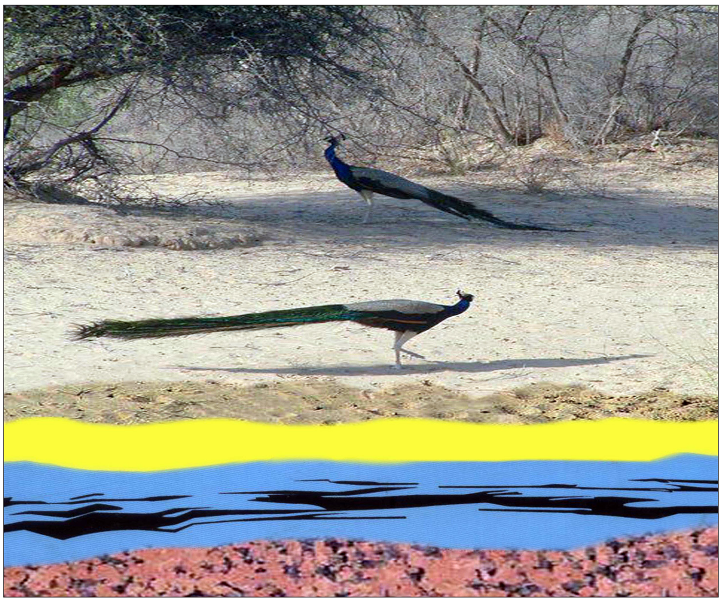

Department of Geology
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Contents

Cover Picture: General stratigraphic succession showing the coal seams under the desert sands of the Thar Coal field Pakistan ,Sindh

Palynologisk studie av kolbärande sediment från Thar-kolfältet i Sindh, Pakistan

PARDEEP KUMAR

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Sammanfattning: Palynologiska och sedimentologiska studier av prover från en borrkärna från Thar-kolfältet (nedre Indus Bassängen), Pakistan har genomförts. De kenozoiska sedimenten ligger på det granitiska urberget (som utgör den Indiska skölden) och utgörs främst av kolavlagringarna vilka är mellanlagrade av sandsten och siltsten.. Thar är namnet på det stora ökenområde som breder ut sig i gränsområdet mellan Indien och Pakistan och som överlagrar rika kolfyndigheter på båda sidor om gränsen. Genom att jämföra borrkärneloggen och resultaten av palynofaciesanalysen från denna studie så kan successionen indelas i tre paleoekologiska enheter; 1. våtmarksmiljö; 2. träskmiljö med kolbildning; 3. fluvial flodslättsavlagring. Den nedre delen av borrkärnan med de kolbärande intervallen avsattes under anoxiska till måttligt anoxiska förhållanden medan den övre delen deponerades under helt oxiska förhållanden.De palynologiska associationerna består enbart av icke-marina palynomorfer, dvs. pollen sporer samt alger och svampsporer. Totalt identifierades 60 arter. Dessa utgörs främst av pollen och domineras av pollen från blomväxter (angiospermer). De kolbärande sedimenten är intressanta då de uppvisar en hög mångfald av pollen och sporer, men i sedimenten i övergången mellan flodslättsavlagringen och kolavlagringarna är bevaringsgraden dålig. Där utgörs den palynologiskaassociationen av en stor andel amorft organiskt material (AOM). Detta sammanfaller med ett intervall som visar på kraftigt reducerade (anoxiska) förhållanden och här innehåller sedimenten även pyrit. I den basala delen av borrkärnan dominerar palm pollen representerat av pollen tillhörande släktet *Spinizoncolpites* och *Proxapertites*. Förekomst av dessa arter indikerar att sedimenten avsattes i en kustnära träskmiljö. Dessa resultat överensstämmer med andra studier från området och tyder på ett varmt och fuktigt klimat med en tropisk regnskog. Förekomsten av svampsporer och hyfer i proverna stöder dessa iakttagelser.

Nyckelord: Pakistan, palynofacies, kol, pollen, Paleocen, Eocen, kolväten

Ämnesinriktning: Berggrundsgeologi

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Abstract: A palynological and sedimentological study of samples from the Thar Coal Field (Lower Indus Basin), south eastern border of Sindh, Pakistan was performed. Thar is the name of the large desert extending into India and Pakistan and overlying rich coal deposits on both sides of the border. The Cenozoic coal deposits alternate with sandstones and in turn overlay the granitic basement rocks of the Indian shield.

The palynofacies is characterized by a gradual change of the relative abundance of structured components, i.e.; wood, and the amorphous organic matter (AOM), starting from the lower coal seam and increasing up-core. By matching the drill core log and the recorded palynofacies, three cycles were identified; fluvial, flood plain and coal swamp deposits. Based on the palynofacies analysis, the coal swamp could further be sub divided into two, by the presence of fresh lacustrine grey claystone.

The palynomorphs, identified in the studied samples are predominantly terrestrial and 60 taxa of pollen and spores were identified characterized by a dominance of angiosperm pollen. The coal- bearing sediments show a high diversity of pollen and spores. However, the transition between the flood plain and coal swamp sediments are characterized by high percentages of AOM and with poorly preserved palynomorphs. This coincides with an interval indicating highly reduced (anoxic) conditions based on the occurrence of pyrite. The family Bombacaceae (herbaceous) and Arecaceae represented by (*Spinozonocolpites* spp., and *Acanthotricolpites* spp), are the most dominant pollen groups throughout the studied samples. In the basal part of the drill core the pollen species are predominant with *Nypa* palm pollen of the genus *Spinizonocolpites* and *Proxapertites* spp. Occurrence of these species indicates that the sediments were deposited in a coastal swamp. These results agree with other studies from the area on palynomorph assemblages indicating a warm and exceptionally humid climate in a coastal zone and with a tropical rainforest in the area of the depositional environment (Sahni 2006). The presence of fruiting bodies and epiphyllous fungi in the samples supports episodes of warm tropical-subtropical climate under high precipitation during deposition of the Thar sediments. The lower coal bearing interval and the middle transition (flood plain and coal swamp) were deposited under anoxic to moderate anoxic conditions whereas the upper part was deposited under the influence of completely oxic conditions.

Keywords: Pakistan, palynofacies, coal, Pollen, Paleocene, Eocene, hydrocarbons

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1. Introduction

The Thar coalfield is located in the eastern part of Sindh province, Pakistan, in the Thar Desert (Fig. 1). The deposits have been dated as middle Paleocene to early Eocene in age (Fassett & Durrani 1994). The Paleocene-Eocene transition was a very critical interval in the region's history, including the collision of India with the Asian continent and, globally, the climate was characterized by a thermal maximum (Sahni et al. 2006).

There have been two major episodes of coal accumulation throughout the Geological record, in the late Carboniferous-Early Permian periods and during the Tertiary (Thomas 1992). The coal formed during the Late Carboniferous-Early Permian has usually high rank. In the Southern Hemisphere continents and India, the Permian was the dominant coal-accumulating period. Regarding the Tertiary coal deposits, they range from lignite (brown coal) to anthracite. The properties of coal are generally based on several factors such as the types of vegetation, depositional environment and palaeogeographic position. The Thar Coal, which is located in the southeastern part of Pakistan, was deposited in the late Paleocene on the flanks of the Indian sub-continent, which in other places hosts large coal deposits.

The coal of the Thar field was first discovered by the British Overseas Development Agency (ODA) in cooperation with the Sindh Arid Zone Development Authority (Sazda 1991). It is a giant coal field with 175,000 million tonnes resources cover 9,000 square kilometers with dimensions of 140 km (north-south) (Fassett & Durrani 1994). The coal deposits are of a particular interest due to the correspondence in their depositional age with the collision of the Indian subcontinent with Eurasia. Additionally, these coal reserves are of an economic interest because Pakistan has recently faced a situation of elevated electricity shortages. One of the major reasons for this energy shortage is the fact that, despite being a coal-rich country, the efficient utilization of coal resources has not been possible. Coal meets only less than 10% of the commercial energy needs of the country and accounts only for 1% of power generation (Private Power & Infrastructure Board, Government of Pakistan, 2008). Omitting the socio-political factors limiting the utilization of these resources, it ought to be stressed that the lack of scientific knowledge has greatly hindered the exploitation of the coal potential of Pakistan.

1.1 Aim of the study

Being a student of geology and native of the largest coal deposits of Thar Desert, situated at the southeastern border of Pakistan, it was my keen interest to study the geological aspect of these immense coal deposits. The master thesis was a great time for me to analyze the Thar Coal sediments. Samples obtained from MTS 19 borehole block X of the Thar Coal field enabled me to examine the palynofacies through this drill core, and then to imply the paleoenvironment through the studied interval. The results will possibly, have implications for understanding the past geological history of the coal deposits in adjacent areas to put the results into a broader, regional context.

2. Geological setting

The Indian sub-continent comprises a distinctive geographic entity; the countries included in the sub-continent, including Bangladesh, India, Nepal and Pakistan, are practically cut off from the rest of Asia by the world's highest mountain chain. Nearly half of the sub-continent's boundary is bordered by the Himalayas and its associated montane branches: the Sulaiman and Kirthar ranges to the Hindu Kush in the northwest are located in Pakistan (Roy 2005). In many respects, the geology of the subcontinent has more in common with the Southern Hemisphere continents than its immediate neighbouring countries. Except for the Himalayas and associated mountain ranges, the Indian sub-continent is largely composed of a shield of Precambrian rocks overlain by a series of younger (late Paleozoic, Mesozoic and Cenozoic) sedimentary basins. Pakistan is located along part of the Cenozoic convergence zone between Greater India and Eurasia. It is bounded by the subducting margin of the Arabian Plate, which extends beneath the Makran coast. Prior to Jurassic times, Greater India was part of the Gondwanan continental mass. The breakup of Gondwana (Australia, Afro-Arabia, South America and Antarctica) initiated in the Middle Jurassic after which Greater India started to drift north (Ali & Aitchison 2008).

The separation of Madagascar from India occurred at about 84 Ma (Late Cretaceous: Santonian), after which India continued its northeastward drift with an altered seafloor spreading velocity (Kazmi & Jan 1997). As India continued its drift during the Late Cretaceous, continent-to-arc collision was occurring (at 98 to 72 Ma) in the areas of the Zagros and Oman Mountain ophiolite zones (Coward et al. 1987). During the early Eocene, the counter clockwise rotation of the Indian plate relative to Africa about a pole north of Madagascar (Powell 1979) occurred simultaneously with a reduction in its velocity of migration. In the late Eocene, fig. 2 the final collision between the Indian and Eurasian continental crusts took place (Patriat & Achache 1984). The separation of the Indian landmass from Gondwana during the Late Cretaceous to early Paleogene had great influences on the fauna and flora (Sahni & Kumar 1974, Sahni et al. 2004, 2006, Sahni 2006, Rust et al. 2010). The Thar coal sediments could probably form-

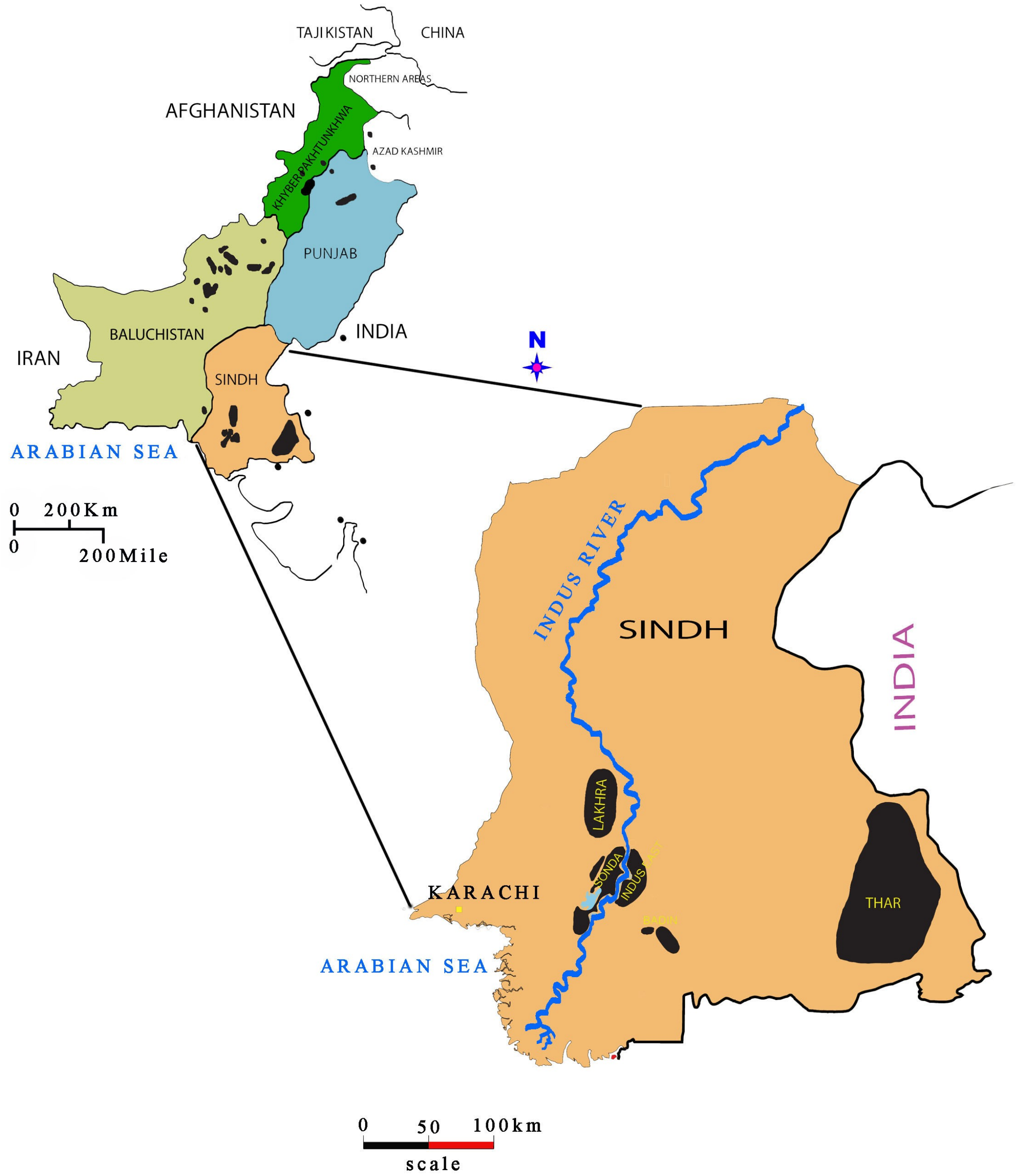
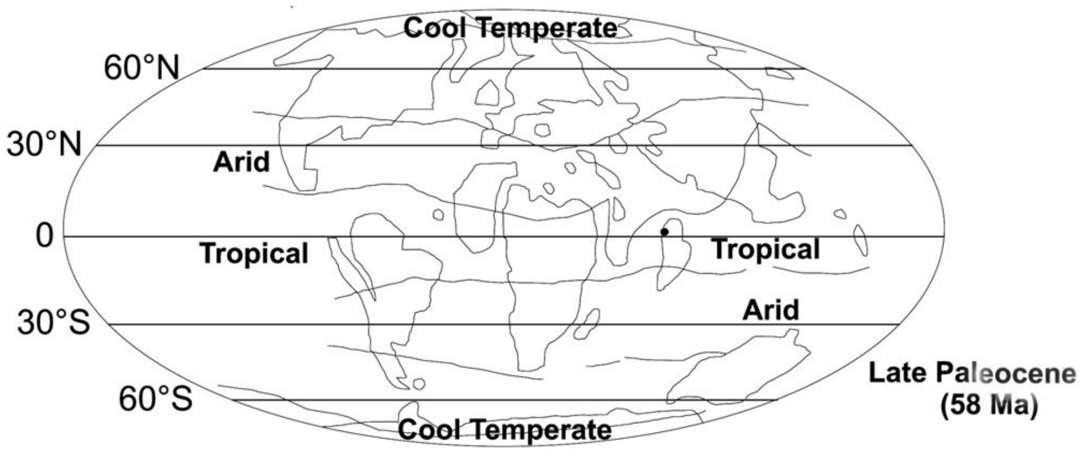


Fig. 1. Map of the study area and the coal deposits of Pakistan (modified from Scheinfurth & Hussain, 1988)

ed during early Eocene, after the movement of Indian Plate when a very wet climate dominated in western and north-eastern areas (fig. 2). This resulted in lush vegetation and coastal peats that later converted to lignite and coal deposits (Sahni 2006). The origin of the Thar Desert is still discussed and there are several hypotheses. A fluvial prehistory has been suggested to the east of the Indus basin. The Thar Desert which is linked with the establishment of a monsoon system by the mid-Pleistocene (Roy 2005).

2.1 General geology of Thar area

The northeast trending, longitudinal stabilized sand dunes that cover the Thar Desert of Pakistan to an average depth of about 80 m are the primary reason why the bedrock geology of this desert region is so poorly understood. The only exposed bedrock in the Thar Desert of Pakistan occurs at Nagarparker. There, the striking red-granite basement rocks tower above the surrounding dunes. The Thar coalfield (incorporating Cenozoic strata) lies upon a structural platform of older (Mesozoic and Precambrian) basements rocks in the eastern part of the desert fig. 3 (Fassett & Durrani, 1994).



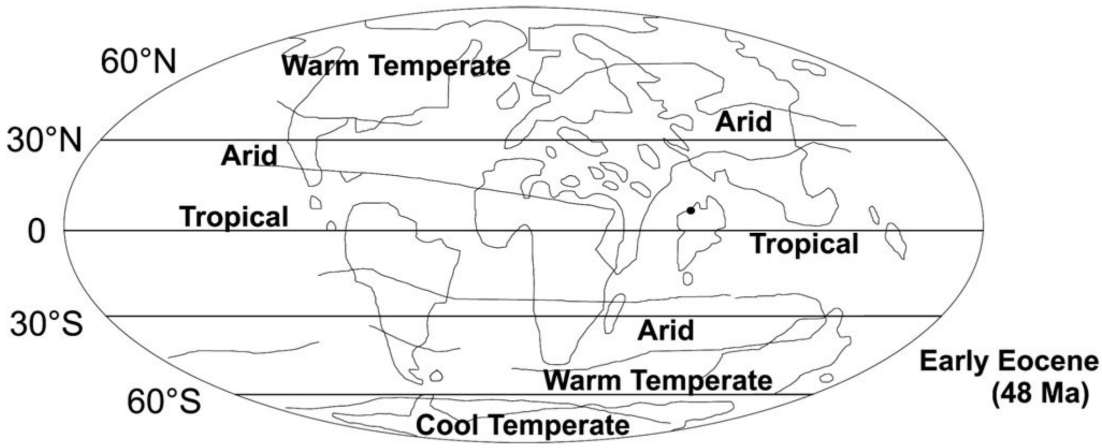


Fig. 2. Palaeogeographic map of Greater India during the late Paleocene and Early Eocene (after Parish et al. 1982)

The Thar coalfield of Sindh province is the largest coalfield in Pakistan having an area of about 9000 sq. km. Its coal resources, of all categories, based on the exploratory drilling of many holes, are estimated at 175,000 million tones (Ghaznavi 2002). Recently, the Thar Coal and Energy Board (TCEB) have approved the Under Ground Coal Gasification (UCG) Pilot Project of a 2x50 MW IGCC power plant in Thar Coal Block V. Coal will be burned underground and converted to gas. The gas produced is then used to generate clean electricity; diesel and some additional chemicals can also be obtained as byproducts of UGC. The project is being implemented and managed under the auspices of Dr Samar Mubarakmand, a renowned nuclear scientist. The Technical design of the UCG wells and prefabricated camp design have been completed.

3. Coal deposits of Pakistan

3.1 Coal deposits in lower Indus Basin (Sindh)

As shown in Fig. 1, the lower Indus Basin hosts quite a few coal deposits. These deposits extend westward from the Thar coalfield, through Tando Muhammad Khan, Badin to the Lakhra-Sonda-Thatta area. The western part lies in the folded belt zone, while most of the eastern part covers the platform slope. Shelf platform and carbonate deposits ranging in age from Triassic to Holocene overlie the basement slope (Ahmad et al. 1986; Schweinfurth & Husain 1988; Kazmi et al. 1990; San Filipo et al. 1990).

Four major coalfields in the Indus Basin have been explored. These are named as the Sonda Meting-Jhampir, Lakhra and Thar coalfields. These coal deposits occur in the Bara Formation (middle Paleocene) and in the Sonhari Member of the (early Eocene) Laki Formation. There are two different stratigraphic levels, namely the lower zone and upper zone where coal deposits of Sindh are developed. The

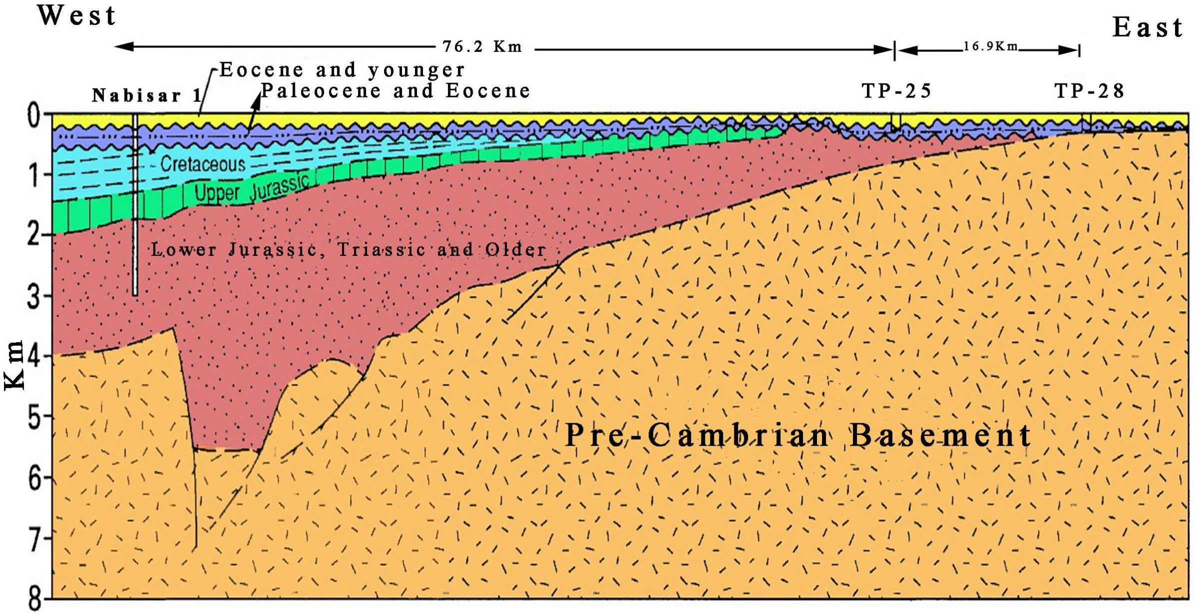


Fig. 3. General large-scale stratigraphic relationship of Southern sindh region (after Jaleel et al. 1991)

lower zone is associated with the Bara Formation (lower Ranikot Formation) of middle Paleocene age and the upper zone is associated with the Sonhari Member of the Laki Formation of early Eocene age. Owing to alterations in the facies and the depositional environments, the lignitic to sub-bituminous coal beds are at some places represented by carbonaceous shale.

3.2 Coal deposits in Baluchistan

In general, the coalfields of Baluchistan are located in the northern part of the province (Fig. 1) and contain sub-bituminous, lenticular coal beds up to 2, 3 m thick at different intervals in the Ghazij Formation of Eocene age. This units ranges from less than 1000 m to more than 2500 m in thickness. Paleocene rocks are apparently found to have no coal beds in Baluchistan (Shah 1990).

With reference to the coal deposits in Baluchistan, the geological studies in general and palynological studies in particular are fairly inadequate. Consequently, the exploration for coal has been on a very limited scale if any. It is important to mention that together with its coal, Baluchistan is very rich in other hydrocarbon resources (oil and gas). Despite these huge reserves, the area has not been exploited on large scale due to many socio-political factors beyond the scope of this thesis.

3.3 Coal deposits in Punjab and Khyber-pakhtunkhawa

In Punjab, the foremost thrust of coal exploration has usually been restricted to the Salt Range coal field. It has been revealed that Paleocene sediments in the Salt Range coalfield were deposited unconformably over Precambrian to Cretaceous strata (Gee 1990). Coal deposits in the Salt Range occur in the Paleocene Patala Formation (Warrick & Shakoor 1988, Warrick et al. 1990, Wardlaw et al. 1990). The earlier studies recorded the average thickness of the coal beds as 0.43 m and the thicknesses range from 0.1 to 2.3 m. In the Makarwal coalfield in Khyber-pakhtunkhawa, the coal-bearing strata occur in the Hangu Formation of Paleocene age. These sediments are found to be overlain by younger Cenozoic rocks, the total thickness of which reaches 5,000 m with coal thickness ranging from <1 to 2 m (Danilchik & Shah 1987).

4 Coal formation

Peat is the precursor of coal and is a sedimentary deposit formed from plant remains and inorganic substances (Cohen et al. 1987). Coal is an organic rock originated from chemical and physical transformations of plant biopolymers because of biodegradation during early diagenesis, and by the influence of the main drivers (pressure and temperature) acting over a long period following burial of the peat (Stach et al. 1982). Therefore, coal is the outcome of both biological and geological process acting on plant remains over time, in a certain environment of deposition (Thomas 2002).

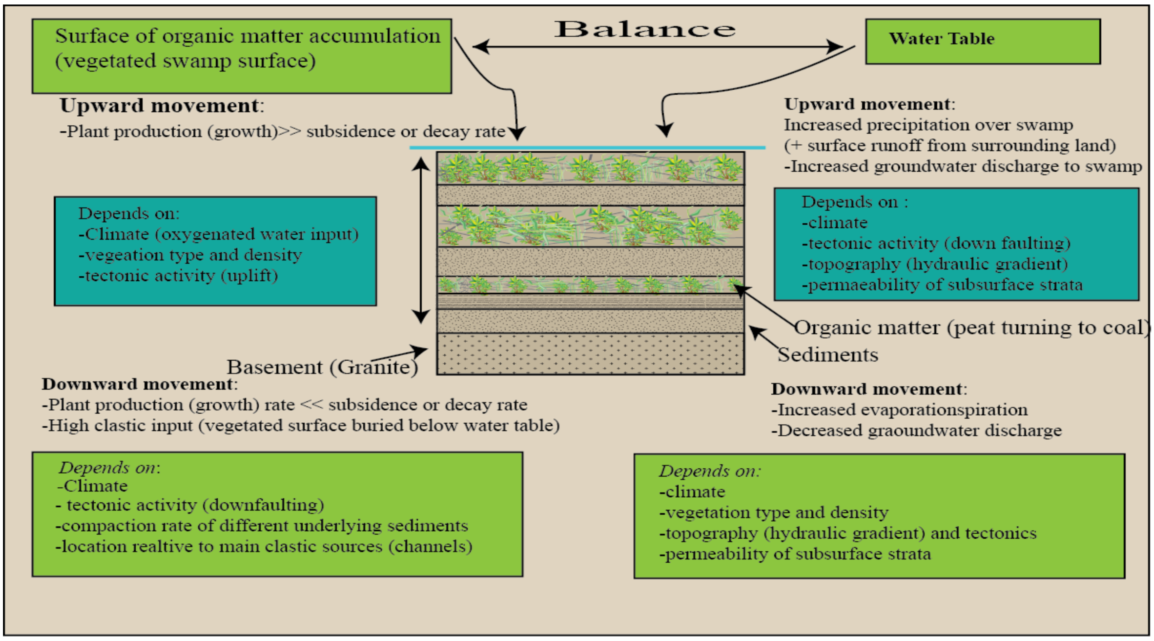


Fig. 4. Coal forming process (modified from Bordy & Prevec 2008).

There are many important factors (ex. depositional environment, diagenesis, and tectonic dynamics) that affect coal properties. However, there are other factors that have an influence such as the vegetation type and composition, the paleoclimate, and the bacterial action (decomposition) fig. 4. Hence, the study of the coal-bearing succession is important to analyze which properties control the coal formation. To be regarded of economic interest, a coal needs at least one of the following conditions involved during its formation.

(1) Subsidence needs to be great enough to accumulate thickness of coal.

(2) The swamp needs to be protected from a clastic supply so the organic matter is not diluted by sediment.

(3) The swamps needs to have sufficient plant growth to accumulate peat and a chemistry that prevents rapid decay of the peat.

5. Material and Methods

For this palynological study, samples were taken from various intervals of the MTS 19 Block X drill core recovered from the Thar coalfield, Pakistan. Thirty-two samples were selected from the drill core material, including different lithologies such as sandstones, mudstones and coal; eleven of these were processed for palynology at Global Geolab Ltd., Alberta, Canada, using standard commercial palynological techniques. Other samples were processed in the microfossil lab at Lund University according to Vidal's (1988) standard palynological processing technique, whereby around 10–50 g of rock is first treated with dilute hydrochloric acid (HCl) to remove the calcium carbonate and accessory minerals, then subsequently macerated by leaving the sample in hydrofluoric acid (HF) of 40–60% concentration overnight. The organic residue was then sieved using a 12 µm mesh and the coarse fractions mounted in epoxy resin on glass slides.

Lycopodium spore tablets were added to facilitate the calculation of absolute palynomorph abundances. Pollen and spores were identified (Plates 1 – 4; Tables 1-3) based on 50 counts to assess the variation in abundance. However, some samples were poor in palynomorphs and less pollen and spores were counted in these (samples 8, 9, 10). Further, a palynofacies study was performed to aid paleoenvironmental interpretation. The samples contents were grouped in the following categories: spores, pollen, fungi, wood, cuticles and amorphous organic matter. Samples were studied using light microscopy. The analysis included identification of these palynomorphs groups, the number of organic particles / slide range was 500 particles.

5.1 Palynofacies analyses

The variable accumulation of organic matter deposited in sediments, termed organic facies, palynofacies or terrestrial biofacies, is determined by different factors of palynology, taphonomy and geochemistry. The organic facies are defined by the properties of the complete organic matter assemblage and are commonly constrained to specific lithological units. Their descriptive terminology is similar to that of other stratigraphic facies (table.1), especially marine invertebrate biofacies. Combaz (1964) was the first to introduce the term palynofacies for all organic material easily identifiable in palynological slides. Nowadays,there are various definitions and classifications of palynofacies in the literature. The term is now used to encompass associations of all acid-resistant organic remains (spores, pollen, algae, acritarchs, chitinozoans, foraminiferal linings and also fragments of various plant tissues).

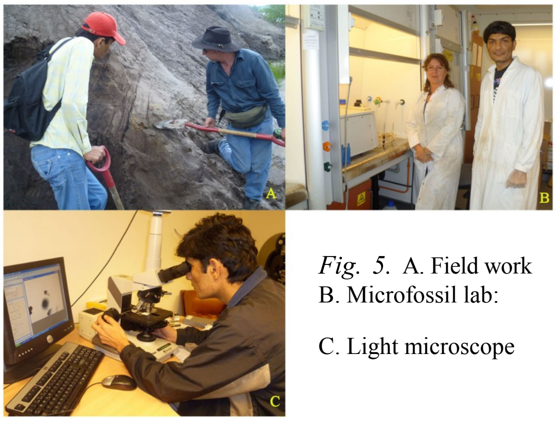


Fig. 5. A. Field work B. Microfossil lab:

C. Light microscope

A palynofacies is a distinctive assemblage of specific HCl and HF-insoluble organic matter (palynoclasts) whose composition reflects a specific sedimentary environment (Powell et al. 1990). Habib (1982) and Tyson (1995) indicated that palynofacies represent a specific sub-component of true organic facies, i.e., they are palynologically defined organic facies.

Table. 1. Description of organic particles in sediments modified from (Oboh Ikuenobe et al. 1997).

Palynodebris	**Characteristics**	**Size (µm)**
Amorphous organic matter	Structureless, irregularly shaped, yellowish-amber to brown masses: usually gel-like	Variable
Marine palynomorphs	Dinoflagellates, acritarchs and chitnous inner linings of foraminiferal tests	30–90
Algae	Aquatic algal remains mainly Pediastrum	20–70
Resins	Unstructured amber-colored exudates, mainly from stem tissues	Variable
Black debris	Opaque particles with sharp angular outlines: lath-shaped, or in some cases more equidimensional	20–>200
Yellow-brown fragments	Structureless particles of yellow to light brown color: attributable to highly degraded herbaceous material (leaf mesophyll?)	5–80
Black-brown fragments	Unstructured dark brown to nearly black particles: attributable to highly degraded woody material	Variable
Cuticle fragments	Platy epidermal-patterned fragments of waxy cuticle coating leaves, stems and roots: pale yellow to light brown in color	30–>200
Plant tissues	All other herbaceous material including parenchyma	Variable
Wood	Light to dark brown particles with sharp angular edges and/or discernible cellular structure: mainly lath-shaped	30–>200
Sporomorphs	Land plant spores and pollen dispersed by water into continental and marine environments	10–80
Fungi	Fungal remains such as spores and hyphae	5–>100

5.1.1 Palynomaceral / Kerogens/Organic particles

Woody kerogen /organic particles occur in two types, (b) inertinite and (c) vitrinite (fig. 5). The studies of these palynomacerals help to evaluate different aspects of coal formation. The size of these kerogen particles are directly linked to the source and accumulate in different sediments. In addition, the reflectance of color help to determine the maximum temperature subjected to a sample (Burmham and Sweeny, 1989). The origins of these kerogen types are different. vitrinite is derived from woody tissues of stems, roots and leaves. On the other hand inertinites are black opaque fragments derived from the oxidation of any component of higher plants. The occurrences of inertinite kerogen are found frequently in terrestrial- deposited sediments.

5.1.2 Amorphous Organic Matter

This is organic matter that does not have a definite structural characters. The origin of AOM is from different sources of organic matter, such as degraded plants, animal debris and structured kerogen. AOM generally occurs abundantly in fine sediments such as claystone and mudstone deposited under anoxic conditions. Amorphous organic matter occurs in different colors, pale to brown, grey or yellow and it can be distinguished on its textural basis (Thompson & Dembicki 1986).

5.2 Sedimentology

Lithological classification was performed based on grain size and color of the sediments. Hydrochloric (HCl) acid was used to detect traces of carbonates.

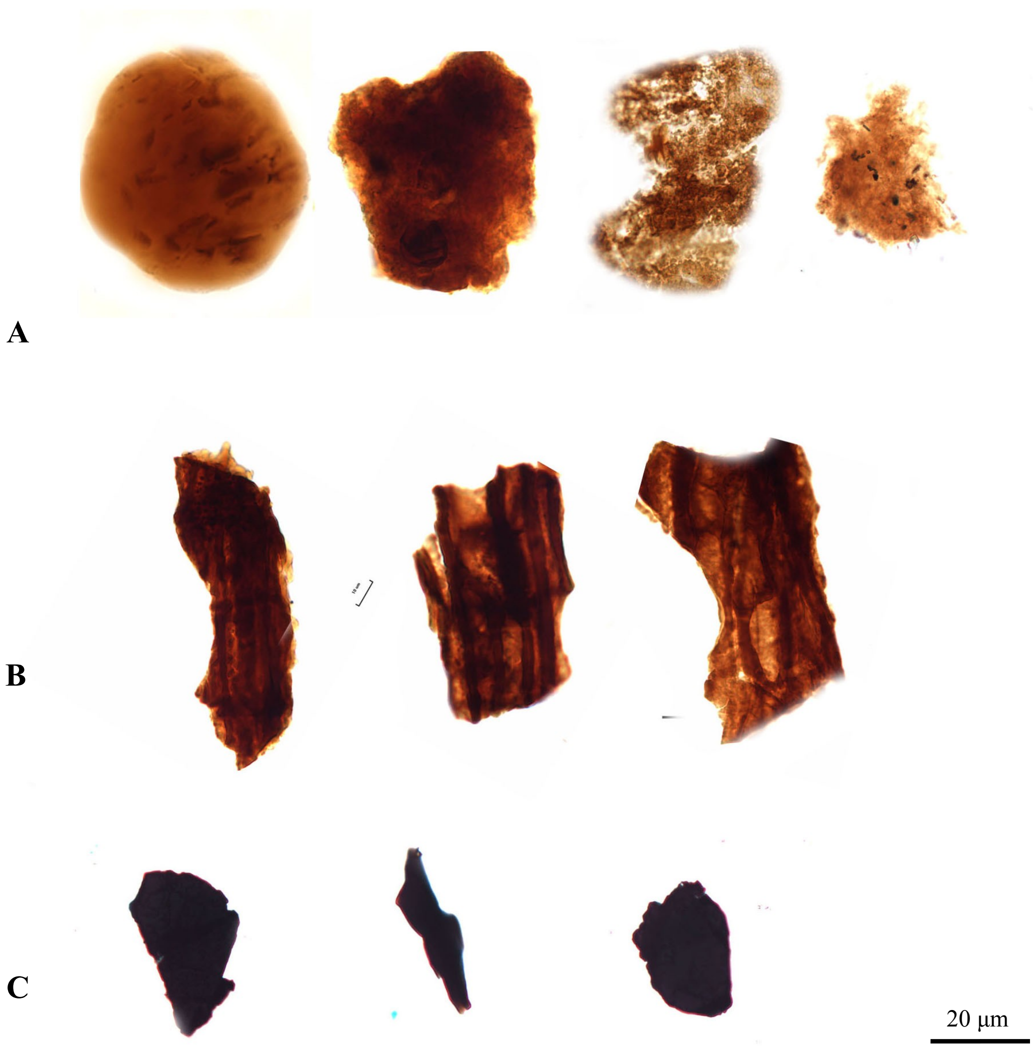


Fig. 5. Photomicrograph of kerogens under light microscope (a) different types of amorphous matter, (b) brown wood-translucent (vitrinite), c) black wood opaque (inertinite).

6. Results

6.1 Palynofacies with macroscopic description

The samples were studied for their qualitative and quantitative composition and grouped into palynofacies categories. These samples show highly diverse palynomorph suites, the components of which are grouped into seven main categories: pollen, spores, algae, cuticles, wood, fungi and amorphous organic matter. Lycopodium spores were also counted in order to calculate the number of organic matter particles in every gram of sediment. The main categories of palynomorphs show variable distribution through the studied succession. The results are shown below.

Sample#MTS-1 at depth 256.20 m. The lithology is dark clay rich-coal containing wood (36.1%), amorphous organic matter (16%), cuticle (27.1%), fungi (14.2%) and pollen (4.8%) followed by some minor spores, and algae.

Sample#MTS-2 at depth 248.30 m. This is a dark clay-rich coal. This sample is dominated by wood (31.6%), amorphous organic matter (27.3%), fungi (17.1%), cuticle (13.7%) and pollen (5.9%) followed by algae, and spores. Pollen assemblages are dominated by Spinozoncolpites and different tricolpate forms.

Sample#MTS-3 at depth 239.78 m. This is a pale grey massive claystone. The palynological assemblage is dominated by amorphous organic matter (32.8%), wood (13.9%), fungi (15.7%) pollen (16.4%), cuticle (13.9%), spores (2.7%), and algae (4.5%). Pollen species are highly diverse and occur in high percentages from all studied samples (spinozoncolpites, triporate, polyporate, tricoplorate).

Sample#MTS-5 at depth 228.7 m. The lithology is a pale gray claystone. It contains isolated visible wood fragments and is dominated by cuticle (42.7%), amorphous organic matter (10.2%) wood (17.7%), pollen (10.2%), and fungi (14.5%), together with minors of spores and algae. Epiphyllous fungal fragments are very well-preserved.

Sample#MTS-7 at depth 221.25 m is a medium grey claystone with isolated woody coal fragments. It is dominated by well-preserved cuticle sheets (42.5%), wood (23.8%), fungi (16.2%) and amorphous organic matter (13.8%), with minor amounts of pollen algae.

Sample#MTS-8 at depth 205.50 m is a medium to dark grey claystone with abundant thin small roots and weak lamination. It is dominated by well-preserved cuticle (47.6%), AOM (22.1%), wood (16.2%), fungi (12.1%) and some minor pollen grains.

Sample#MTS-9 at depth 202.70 m is a medium to dark grey claystone with abundant thin small roots and weak lamination. It is dominated by amorphous organic matter (47.3%), wood (22.7%) with minor constituents of pollen, fungi and cuticle.

Sample# MTS-10 at depth 191 m is a medium grey sandstone with coalified wood. It is highly dominated by amorphous organic matter (48.9%), wood (27.7%), and some other minor constituents in the following order: cuticle, fungi and pollen.

Sample# MTS-11 at depth 177.50 m is a pale to light grey siltstone, with rare weak flat lamination. The recorded palynoassemblages are rather poor and dominated by wood (35%), amorphous organic matter (24.4%), and cuticle (22%), with minor constituents of fungi, and algae.

Sample# MTS-12 at depth 149.25 m macroscopically represents iron-rich concretions in massive grey to brown siltstone. The recorded palynological elements are dominated by amorphous organic matter (38.1 %.), wood (26.8%) and cuticle (19.6%), fungi (13.4%) and minor constituents of pollen. Generally this sample had poor preservation of the palynological assemblages.

Sample# MTS-13 at depth 107 m is a light grey micaceous massive silty claystone. The palynological assemblages are highly dominated by cuticle (50.1%), amorphous organic matter (16.9%), wood (15%), and fungi (14.7%), with a minor component of pollen (1.7%), algae (1.7%), and Salvinia sp.

The absolute number of organic matter particles /gr of each studied sample have been calculated by adding. Lycopodium spore tablets (Table 2). These results were also correlated with the geophysical log. The basal samples (no. 3 and 4), which derive from the grey mudstones, deposited under influence of fresh water swamp vegetation yielded moderate values of organic particles per gram sediment. The samples 10, 6, 5 which are the samples from the claystones that lie between the coal beds, have high values of organic matter per/gram, reaching as high as nearly 600.000 particles per gram. Finally, the samples from the upper part of the drill core where the sediments are dominated by fluvially deposited silt and sand, yielded very low values of organic matter, only between 104 to 1553 particles per gram.

6.2 Summary of recorded palynofacies trend

A lack of organic particles and low diversity of palynomorphs characterizes the uppermost part of the Thar coal sediments. This part was deposited under a fluvial depositional setting. The abundance of the black palynomaceral inertinite and fresh water algae

Salvinia sp., indicates the sediments are transported from terrestrial sources.

The middle part is the typical transition zone between the Paleocene (Bara Formation) and sub-recent sediments. The sediments are mainly composed of sandstones and claystones. However, claystones are typically rich in a carbonaceous material with pyrite beds of a few centimeters and with visible resins and woody fragments. This indicates strongly reducing conditions, and low preservation of palynomorphs in this interval. The palynoassemblages from this middle part recorded low abundance of palynomorphs. Gymnosperm pollen species were recorded indicating moist, cool temperate environments in the nearby upland area.

The basal part of the core is the main coal bearing unit. This was deposited in a swamp environment. The recorded palynological assemblages through this interval is dominated by Nypa pollen (*Spinozoncolpites* sp.,) monocolpate, (*Proxapertites* sp.,) zonapertural, and trilete spores.

In the interval 221.25 to 199 m, the general trend of palynofacies is a low abundance of pollen and spores, indicating episodes of dry climates and oxidizing post-depositional conditions. The presence of fungal fruiting bodies, epiphyllous fungi fragments, were recorded at 205.5 m from a dirty coal. The fungal spores co-occur with moderately rich pollen assemblages also containing a few fern spores. This probably corresponds to an anoxic environment with low microfossil preservation. The predominance of AOM is possibly due to chemical oxidization and pyrite is present. Thus, the recovered cuticle sheets, and pollen were found with pyrite scars.

An interesting, restricted unit of fresh-water, lacustrine grey claystone was recorded between the coal-bearing units at 239.78 to 248.30 m. The palynofacies in this unit is characterized by a high abundance of palynomorphs mainly dominated by diverse angiosperm pollen and fern spores. Other abundant components are terrestrial black palynomacerals, the fresh-water algae *Cymatiosphaera cubotensis sp.* and a high abundance of cuticles. In addition, two pollen taxa, only found in this interval occur: *Retimonocolpites* sp., and one typical *Spinozoncolpites* sp. with typical small echinate spine exines. (Plate 2: 10). It is herein tentatively interpreted as pollen from fresh-water swamp vegetation. The interval 248.30 to 260.80 m, the frequency of fern and algal spores (Cymatiosphaera cubotensis) reduces and the lithology becomes carbonaceous shale, to very massive mudstone with iron concretions. Pollen of Arecaceae (*Spinozoncolpites* sp. and *Proxapertites* sp.) is present in these samples. These possibly indicate a back swamp depositional environment for this interval.

6.3 Relative abundance of palynomorphs

The general trend of palynomorph distribution and preservation is relatively good, improving down-core and being highly tied to the depositional environment. Palynomorphs recovered during this study represented seven major categories viz., tricolpate, monocolpate, tricolporate, and polycolpate, pollen and trilete spores, monolete spores and fungal spores. These categories were recorded throughout the studied interval. Miospores are very sparse in the youngest sediments. In the coal-bearing sediments, however, the palynomorphs are abundant.

Angiosperm pollen represent the major constituents of the palynofloras throughout these sediments. The dicots dominate in the coal-bearing sediments (Bara Formation). The pollen recovery was in some intervals poor and thus no detailed biostratigraphical interpretation could be made. Many of the identified taxa are, however, reasonably comparable with modern taxa from the sub-Indian continent and Africa (Parsad 2009). The relative abundance of fern spores increases gradually in the shaley and clayey sediments, especially between the coal-bearing intervals in claystone. The highest abundance of fern spores and pollen occurs in the basal part of the fresh-water dark grey claystone, which recorded a diverse palynomorph assemblage. Dinoflagellate cysts are reported from the Thar coal sediments at some specific depths in a previous study (Saeed 2008) but were not identified in this study. Among the pteridophytic spore families Osmundaceae (*Todisporites* spp. and Schizaeaceae *Schizaeoisporites* spp.) are most common. Among the angiosperms, pollen grains having affinity with the family Bombacaceae are frequent throughout the studied succession. Pollen showing affinities with family Arecaceae are mainly represented by *Spinozoncolpites* spp., *Proxapertites* spp, and *Acanthotricolpites* spp.

Table 2. Organic particles /gram of sediments in studied sample from the Thar drill core.

sample no	Organic particle/gram
13	1553
12	104
11	211
10	282816
6	591781
5	?
4	86667
3	10418

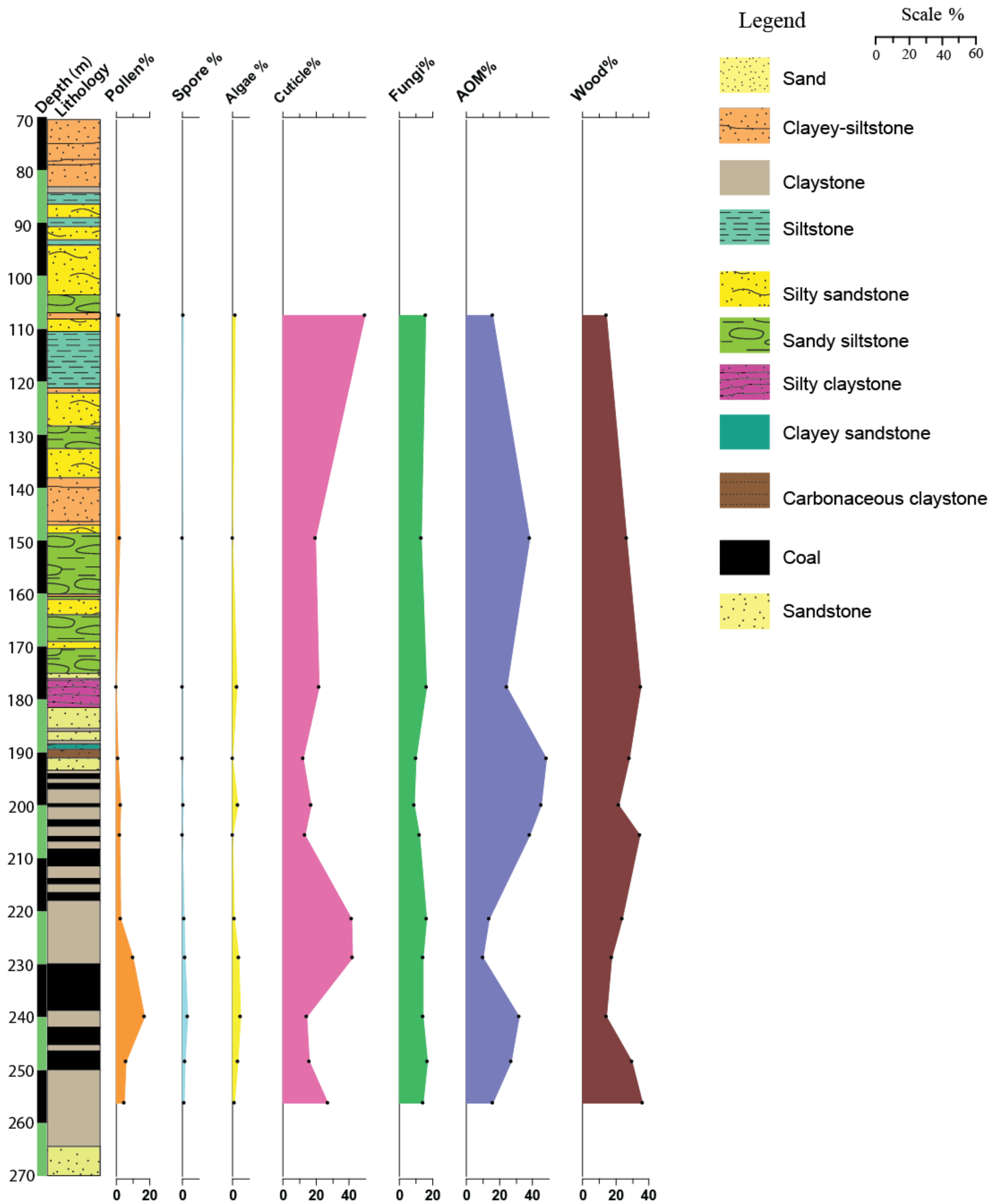


Fig. 6. Quantitative representation relative abundance of dispersed organic matter and palynomorphs in the studied samples.

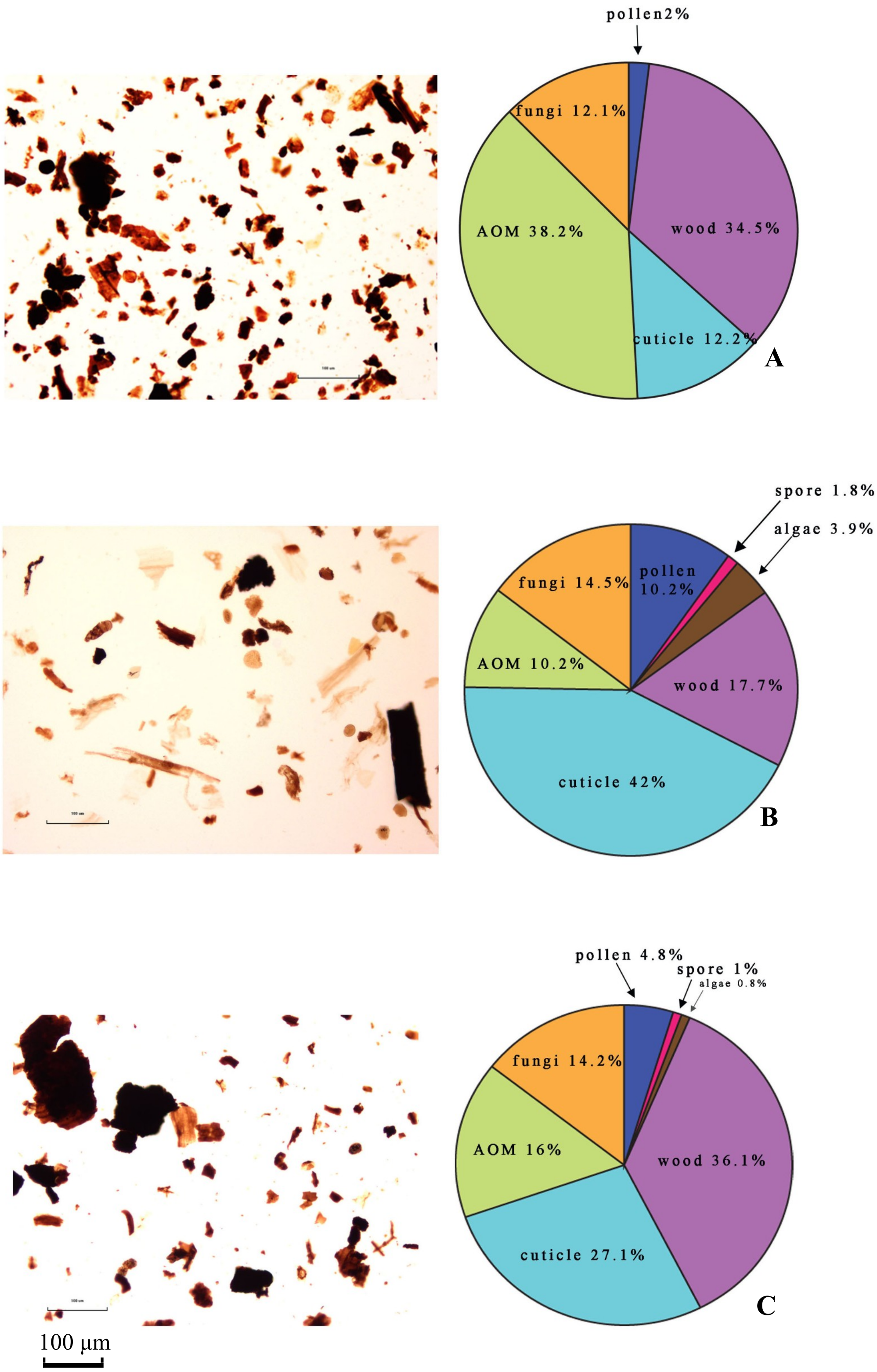


Fig. 7. Composition of representative samples of different palynofacies (A) recorded results in the pie chart a represent reducing environment, (B) Represent fresh-water vegetation, possibly indicating brackish environment, (C) Photomicrograph and pie chart represent back swamp depositional environment.

Table 3. General quantitative palynofacies data expressed as percentages for the different groups.

Depth (m)	Pol-len%	Spore %	Algae %	Cuticle %	Fungi %	AOM %	Wood %
107	1.8	0.5	1.8	49.7	15.9	15.7	14.4
149.25	2.1	0	0	19.6	13.4	38.1	26.8
177.5	0	0	2.4	22	16.2	24.4	35
191	0.8	0	0	12.1	9.9	48.6	28.5
199.78	2.7	0.7	3.1	17	9.2	45.2	22.1
205.5	2	0	0	13.1	12.1	38.2	34.6
221.25	2.4	1	1.2	41.6	16.2	13.8	23.8
228.7	10.2	1.8	3.9	42	14.3	10.2	17.7
239.78	17	3.2	4.7	14.4	14.2	31.8	14.6
248.3	5.9	1.4	3.1	15.7	17.1	27.3	29.6
256.2	4.8	1	0.8	27.1	14.2	16	36.1

7. Palaeoenvironment

The paleogeography of the Indian subcontinent and the global warming of the paleogene led to warm and humid climates over a wide area of the Indian subcontinent (Sahni et al. 2006). The present study clearly reflects the existence of extensive swamp forests in relation to the depositional environment, as evidenced by the dominance of swamp-forest taxa represented by the Arecaceae family texas (*Spinozoncolpites* spp.,), *(proxapertites* spp.,) and *Acanthotricolpites* spp. These taxa inhabit wet environments and similar taxa are present in modern swamp forests in India (Parsad 2009).

The palynofacies study of Thar coal sediments is of great importance for paleoenvironmental analysis of depositional and climatic conditions. Palynologically and stratigraphically the studied sediments are quite similar with the adjacent part of India (Gujarat & Rajasthan), and lower Indus coal region, Sindh Pakistan which are coal-bearing sediments. The recovered pollen assemblage is more dominated by angiosperms throughout the succession.

In the lower coal-bearing part, well-preserved phytoclasts (cuticle) occur, whereas the lignite beds bear large amounts of biodegraded amorphous and pyritized amorphous organic matter. Both components confirm the prevalence of anoxic conditions. The composition of the miospore assemblage in the lower part of the core with *Retimonocolpites* sp. as a dominating element possibly indicate the presence of mangrove vegetation which also can be interpreted as evidence for marine influence, further the presence of the genus *Spinozonocolpites* sp. indicate tropical climate such as rain forest ecosystems during late Paleocene-early Eocene for the Thar Basin.

The palynofacies in the upper part of the succession show that the fluvial sources contains black angular debris and a lack of palynomorphs and other organic matter. There are however, traces of calcium carbonate in the otherwise silt and sand-dominated lithology. The abundance of biodegraded terrestrial and amorphous organic matter throughout the sequence shows the dominance of anoxic conditions after the burial of the organic matter. In the upper part of the succession an increasing abundance of black debris reflects a gradual change to moderately oxic burial conditions.

Generally, three main palynofacies assemblages are identified at different intervals which correspond to variations in the depositional environment and are reflected by changes in the lithology (Fig. 6 & 7).

1. Peat swamp environment (depths 256.20-199.78 m): the lithology is coal/claystone with high yields of palynomorphs with e.g., pollen and spores,of a high diversity. Plant tissues are often abundant and degraded appearing amorphous in structure, black debris and fungal material (spore and hyphae) often common.
2. Flood plain environment (depths 193-176 m): the lithology is carbonaceous claystone, clayey sandstone with moderate diversity of palynomorphs (pollen and spores), plant tissues including leaf cuticle, are generally abundant and well preserved.
3. Fluvial/fluvial channel environment (depths 173-107 m): the lithology is sandstone/siltstone with low diversity and yield of spores and pollen, variably preserved degraded plant tissues and black debris common.

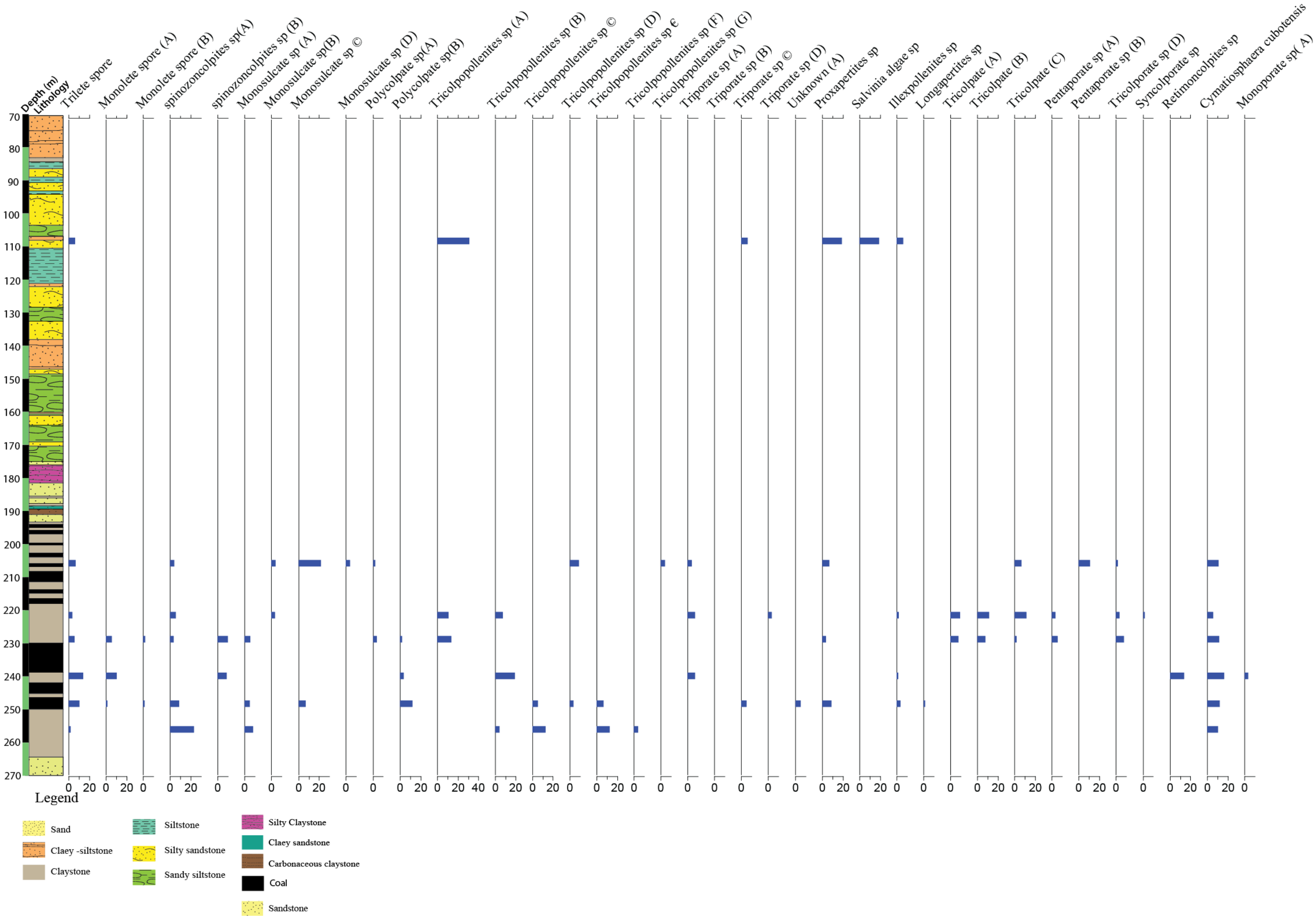


Fig. 8. Distribution and percentage abundance of pollen and spores indentified in this study.

In the large perspective, the early Cenozoic coal deposits of the Indian-subcontinent are interconnected in regard to their biotic assemblages, prominent among which are land mammals, pollen, ostracodes and foraminifera in interbedded shale, claystone and argillaceous limestone (Shani et al. 2006). The abundant fungi and fruiting bodies in the coal-bearing sediments suggest a warm climate during deposition.

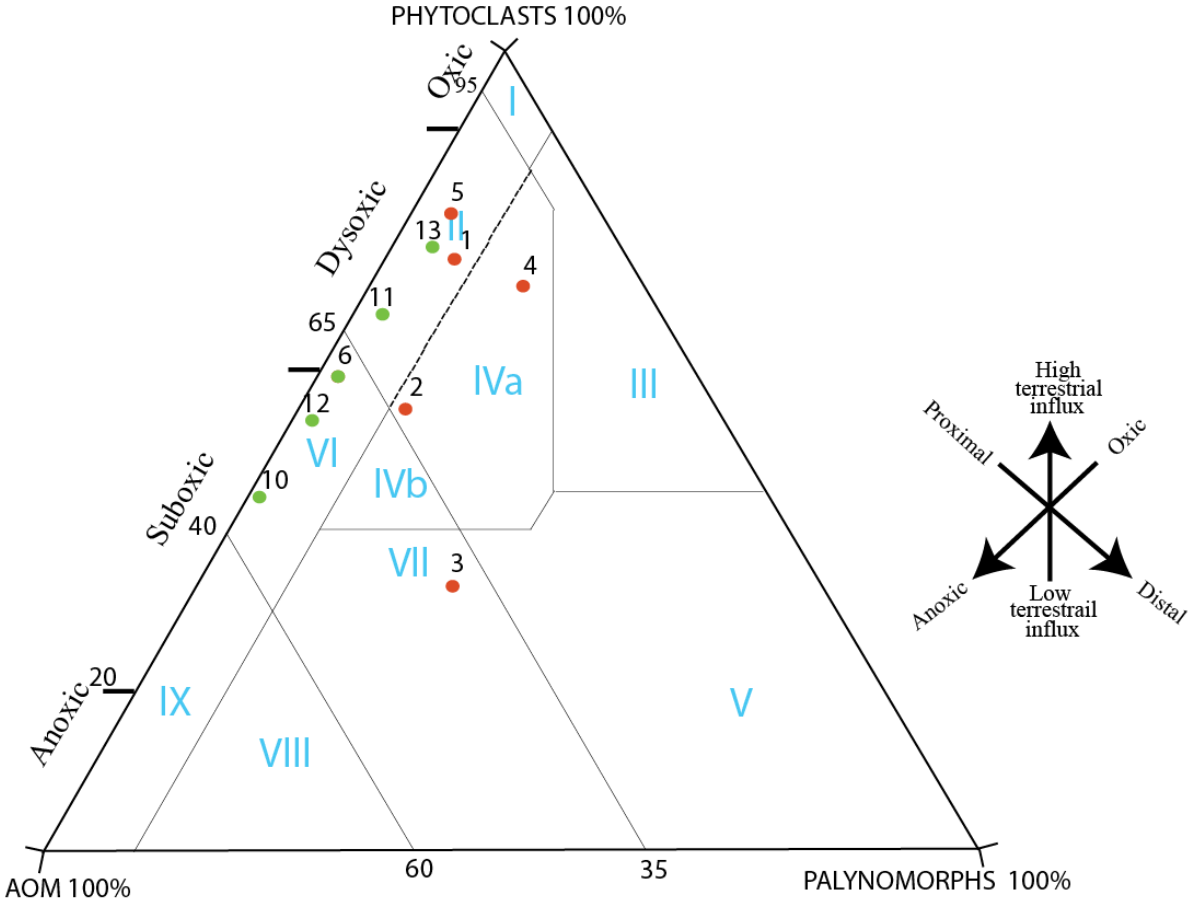


Fig. 9. AOM –Palynomorph-Phytoclast ternary diagram plot (after Tyson, 195). The palynofacies data, mainly plotted along phytoclast-AOM line in II and VI fields. Details of these fields are given in the following table.

Palynofacies Fields	Environment	Kerogen Type
I	Highly proximal shelf or basin	III (gas prone)
II	Marginal dysoxic-oxic basin	III (gas prone)
III	Heterolithic oxic shelf ("proximal shelf")	IIIor IV(gas prone)
IV	shelf to basin transition	III or II (mainly gas prone)
V	Mud-dominated oxic shelf ("distal shelf")	III>IV(gas prone)
VI	Proximal suboxic-anoxic shelf	II(oil prone)
VII	Distal dyoxic-anoxic "shelf"	II(oil prone)
VIII	Distal dyoxic-anoxic shelf	II>>I(oil prone)
IX	Distal suboxic-anoxic basin	II>> (highly oil prone)

8. Discussion

This work aimed at interpreting the depositional environment of the Thar coal deposits based on palynofacies and palynology. The studied samples were selected mostly from the coal-bearing interval. They were recovered either from the base of the coal seam or the top of the coal. They have good palynological preservation especially in the interval dominated by flood plain section sediments. However the fluvial sediments show very low preservation of palynomorphs and organic matter, with many samples found to be barren. Three palynofacies assemblages, each representing a depositional environment were identified in this study: coal swamp, floodplain and fluvial environments respectively. (1) The coal swamp is characterized by a high yield of the pollen genus *Spinozonocolpites* produced by brackish-water palms, together with fungal material. (2) The flood plain environment is characterized by a high diversity of plant tissues including very well preserved leaf cuticle sheets. (3) The fluvial environment (silty sandstone/sandy siltstone) is characterized by a low diversity and relatively high abundance of spores and pollen.

There are several hypotheses concerning the genesis of these thick coal seam deposits. During the Late Cretaceous, the entire part of the area was uplifted (Fig. 4), which led to erosion of the uppermost Cretaceous rocks; thus the Thar coal depositional area was most certainly uplifted higher than the western part, resulting in the erosion of the older Paleozoic rocks so the basement granite in eastern parts of Thar coal field were exposed (Fassett & Durrani 1994). Following this continuous erosion cycle, the area again subsided and Paleocene and Eocene age rocks were deposited on top of the Cretaceous unconformity in the west of the Thar coal area.

However, low ash and sulphur content in the Thar coal would tend to indicate that the coal formed in raised peat bogs rather than in low-lying swamp environments. From the western border of the Thar coal field area, marine planktic foraminifera dated to the late Paleocene were identified (Mohan & Usmani 1982, 1983). This relationship clearly indicates that at the time when the Thar coal was formed, the sea was to the west and shoreline was trangressing and subsequently regressing across the western edge of Thar coal field area. No dinoflagaellates cysts were encountered in the studied samples, but they have been reported to exist in coeval deposits in the same area previously (Saeed 2008). However, pollen produced by plants such as mangrove were encountered in this study indicating possible brackish-water environments. The reason as to why the dinoflagellates were not detected in this study may be due to insufficient sampling resolution. These dinoflagellate cysts described by Saeed (2008) give interesting information related to the depositional environment of the Bara Formation and refer to swampy conditions with marine incursions. The presence of *Retimonocolpites thanikaimonii* is the first one recorded from this area. This species is very common in Paleocene-Eocene successions of the Cambay Basin in India (Prasad et al. 2009) and indicates moist, evergreen rainforest ecosystems.

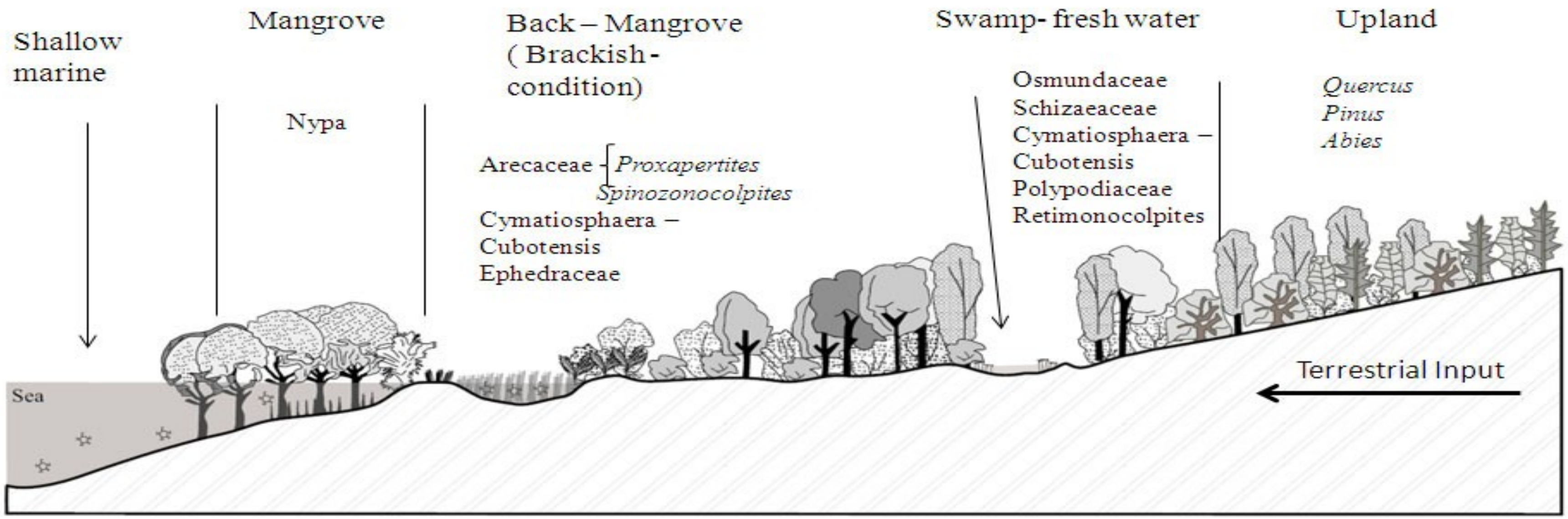
The greenhouse conditions during the Cretaceous ended after asteroid impact and volcanism (Thomas et al 2006). However, the angiosperm flora noted flourished during the Late Cretaceous to Early Paleogene globally.

The Earth experienced global warming, beginning with PETM event. This was followed by early Eocene climatic EECO episodes (Koch et al.1992; Mehrotra et al. 2005; Sahni 2006; Parsad et al. 2006; Kent & Muttoni 2008). The palynoflora of this study is very similar to that of coeval assemblages from Africa, Australia, and Madagascar (Peters & Salami 2004).

8.1 Comparison with other coal deposits of Early Paleogene

Generally, coal deposits are scattered across the whole country of Pakistan. It is well established that coal deposits of northern and western Pakistan possess high calorific value as compared to the lower Indus Basin that contributes 75% of the total coal deposits of Pakistan (Mumtaz 1986). Nevertheless, utilization of coal deposits of Sindh for commercial purposes is significantly high due to the ease of exploration and lesser amount of sulphur and ash, making it relatively friendly for the environment. Though most coal deposits of Pakistan, except the Sindh coal measures, are relatively thin and lens-shaped at places their thicknesses range from few centimeters to meters. Prior to the Thar coal-field discovery, Pakistan's coal reserves were around 9 billion tons (Kazmi 1990). With the Thar coal deposits, Pakistan has acquired the 11th place in countries having the largest lignite coal deposits around the globe.

Coal resembling the Thar coals is found in the nearby west-central part of India (Gujarat and Rajasthan where a lignite-field called Panandhro is located at distance of 160 km from the south-west corner of the Thar field. Panandhro is the third largest known lignite -deposit of India with 95-100 million metric tons. However, the coal deposits are somewhat atypical. Panandhro coal occurs in five beds from 10 cm to 10.5 m thick. Moreover, it is early Eocene in age (Misra 1992). Currently the Thar coalfield has recorded the thickest coal seam which reaches 29 meters (Block VIII) i.e. this single seam exceeds the thickest coal beds of Panadhoro lignite field (personal communication with Mr. Atta M. Rind, Scinetist, Thar Coal Project 2012). On the other hand, 85 km northeast of Thar coal field lies the Barmer Basin in Rajasthan with deposits of coal bearing sediments with



Profile of different depositional environment and palynoflora taxa (modified from Mehmet Serkan Akkiraz 2007)

Interbed several seams that alternate with fossiliferous carbonaceous clays recorded as late Paleocene to early Eocene. Lignite beds thick as thick five meters are present are present; in general these coal-beds are lens-shaped, not exceeding 1–2 meters in thickness (Mukherjee et al. 1992).

In summary it can be said that the lower Indus coal basin possesses most similarities with the coalfields of west-central India. However, when comparing the general features of the coal deposits, such as thickness patterns of coal bearing strata, chemical properties of coal and total resources, there do not appear to be any direct equivalents to the Thar coal anywhere in South Asia.

8.2 Coal reserves and the sources of energy of Pakistan

Despite the enormous potential of its energy resources, Pakistan remains energy deficient and has to rely heavily on the import of hydrocarbon products to fulfill its needs. Moreover, very large parts of the rural areas do not have the electrification facilities because either they are too remote or too expensive to connect to the national grid. Additionally, Pakistan has a wide spectrum of high-potential renewable energy resources. However, the energy sector plays a vital role in increasing all-round development and growth of the economy of a nation. In modern world, the reserves of crude oil are going to decline gradually and rise in price and, people are looking for alternatives for these hydrocarbons. Pakistan has discovered huge coal reserves and the Thar coal is the largest coal deposit in Pakistan. The coal in Thar is generally characterized as lignite, which is the lowest grade coal to utilize for power generation. Most other parts of the world utilize black coal to produce the electricity.

9. Conclusions

- The studied palynoflora of the Thar coal field is dominated by angiosperm pollen with affinity to the families Arecaceae and Bombacaceae. Based on the palynological assemblages, a warm and exceptionally humid climate is inferred. The area probably existed in the coastal zone, and was covered by a tropical rainforest in the area of the deposition.

- The studied sequence was palynologically divided into three different palynofacies zones which correspond to seperate depositional environments. The lowermost zone is a peat swamp palynofacies, which is characterized by shale, claystone and coal. The major palynological constitutes are Nypa mangroves *Spinozonocolpites* species, and *Proxapertites* species.

- Based on the studies of dispersed organic matter, summarized below (Tyson ternary Diagram) it is inferred that the lower and middle parts of sequence were deposited under suboxic to dysoxic conditions, whereas the upper part was fluvial sediments (silty and sandy) deposited under completely oxic conditions. This also accords with the amount of organic particles per gram sediment where t-

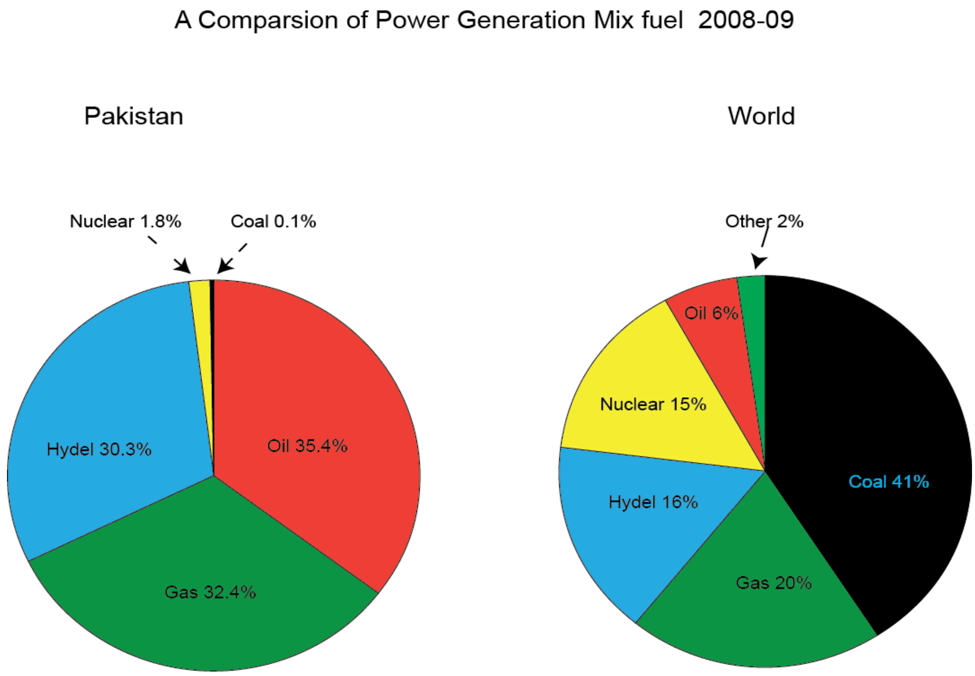


Fig. 11. Comparison of power generation in Pakistan with world power generation (modified after energy year book 2009).

he samples from the lower part of the drillcore show much higher values.

- The presence of fruiting bodies and epiphyllous fungi in the samples supports episodes of warm tropical-subtropical climate under high precipitation during deposition of the Thar sediments.

- The present results agree with the global scenario for this time interval with the global warming during the Palaeocene-Eocene Thermal Maximum (PETM). This event generated dramatic changes in terrestrial and marine ecosystems as results to which many organisms evolved, radiated, migrated and went extinct.

10. Acknowledgments

It is a pleasant duty to acknowledge the persons who made it possible for me to finish this thesis. First and foremost I would like thank my supervisor Professor Vivi Vajda for all her support that enabled me to achieve my goal. I would have been lost without her. The immense support from the Department of Geology provided me the opportunity to conduct the research in a smooth way. I would like to mention the name of Antoine Bercovici (for help in utilizing computer software and for his patience in answering all my questions), Steve McLoughlin for commenting on the manuscript and Git (for her assistance in sample preparation) in this context.

For providing the samples from Pakistan, I would like to thank Mr. Ghulam Mustafa Bajeer (of Sindh Coal Authority) and my old friends Kelash Rathore and Atta Muhammad Rind for their efforts. The pleasant memories Lund University would always be with me as an asset of my life. I am deeply indebted to the support provided by the University administration in every aspect of life. I am highly thankful to my friends in Lund who made my stay memorable. Finally I would like to thank my family members back in Pakistan for their moral and financial support, necessary for achieving such a milestone.

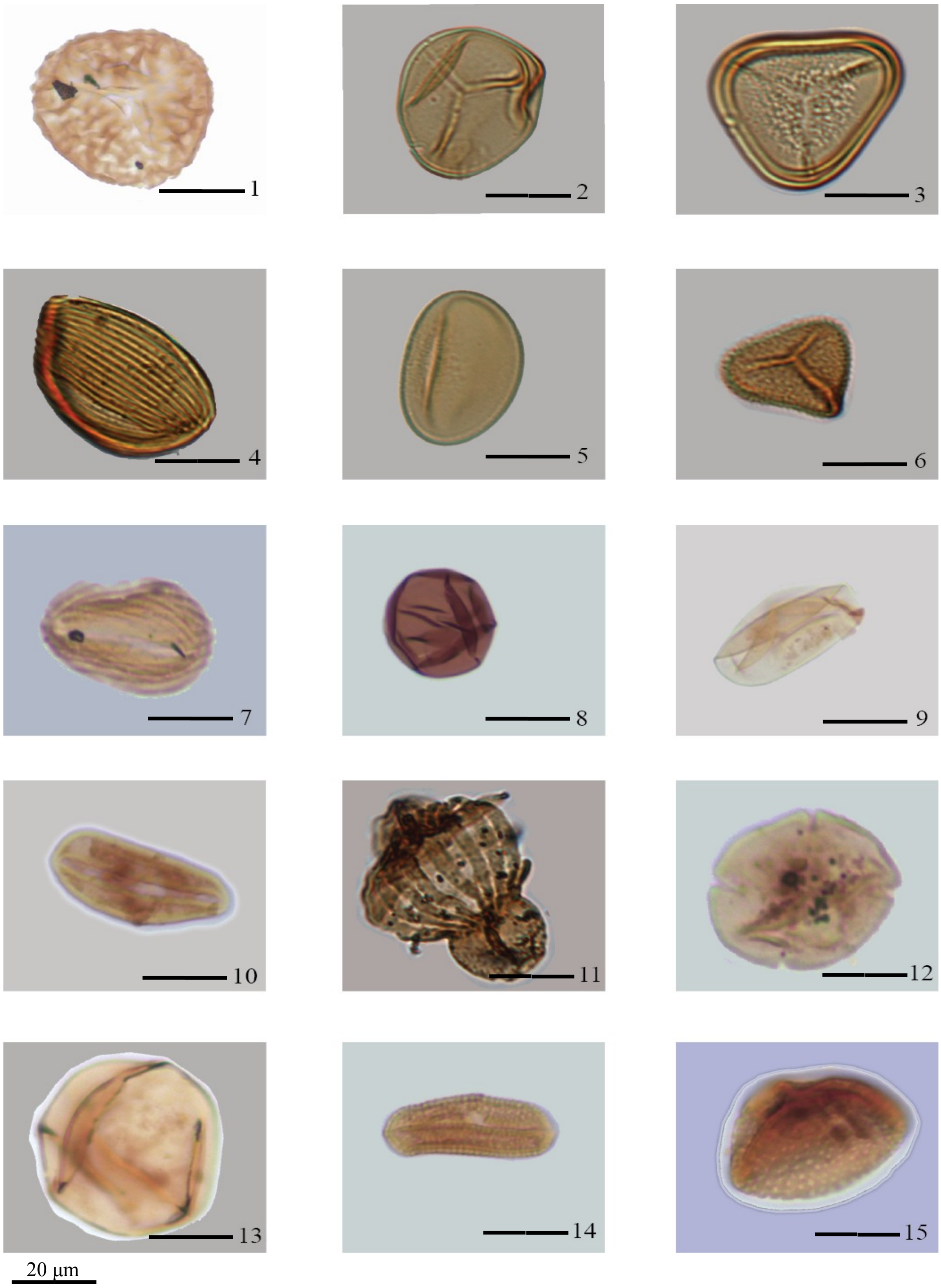


Plate 1. **(1)** Camarazonosporites MTS-3:1**; (2, 3)** *Dandotiaspora tenolata* MTS ; 3 & 4*;* **(4, 7)** *Schizaeoisporites eocenicus* MTS-2:2 EFR:O38; **(5)** Monolete spore MTS-3:1 EFR:T41; **(6)** *Trilete spore* MTS-3:1 EFR– M27; **(8)** Algal spore *Cymatiosphaera cubotensis* MTS-3:1 EFR –U33-4; **(9)** *Calamospora* MTS-4:1; **(10)** *Palmaeopollenites* MTS-6:1; **(11)** *Ephedripites* sp. MTS-11:1 EFR–N38 -4; **(12)** MTS 4:1; **(13)** *Lakiapollis ovatus* MTS-2:1; **(14)** *Illexpollenites* sp. MTS-2:1 EFR – Y35-1; **(15)** Sp. Indet.

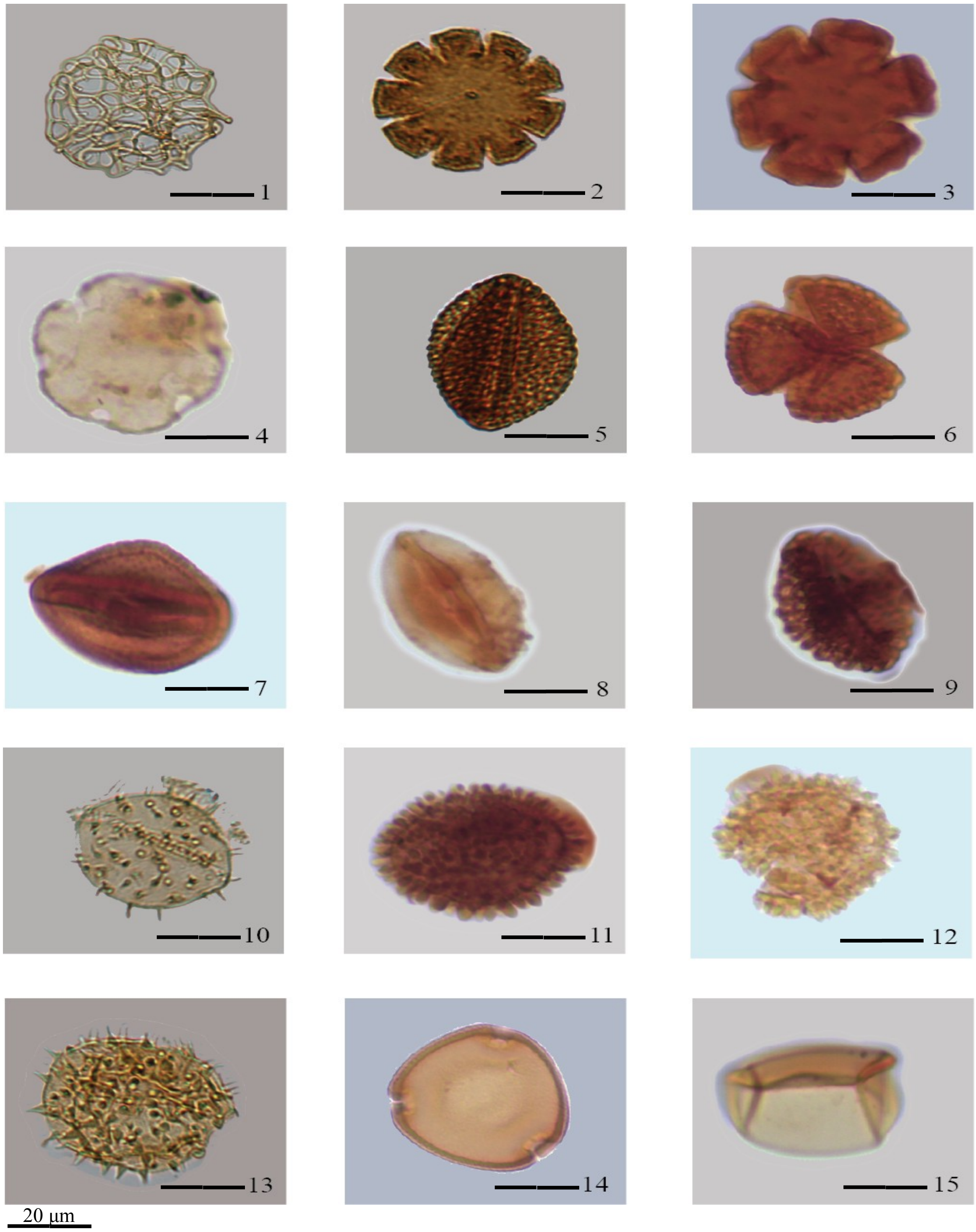


Plate 2. **(1)** *Retimoncolpites thanikaimonii* MTS-3:1, EFR– M42-4; **(2)** *Polycolpites ornatus* MTS-2:2; EFR–T 31-2; **(3)** *Polycolpites sindhi* MTS-2:1; **(4)** *Prectenolophonidites pimitiva* MTS-4:1; **(5)** *Euphorbicites communis* MTS-2:2 EFR –Q31-1; **(6)** *Margocolpites concinnus* MTS-2:2 EFR –X35-2; **(7)** Monosulcate pollen MTS-4:1; **(8)** *Palmaeopollenites* MT-S6:1; **(9)** *Clavaperiporites* MTS-2:2 EFR –S45; MTS- 6:2; **(10)** *Spinozonocolpites* sp. MTS-3:1, EFR– P29-4; **(11 , 12)** *Spinozoncolpites adamenteus* MTS 4:1, MTS 5:2; **(13)** *Spinozoncolpites echinatus* MTS- 2:1 EFR—S33; **(14)** *Carpinipites taiwanensis* sp. MTS-4:1; **(15)** *Longaperties marginatus,* MTS-3:1

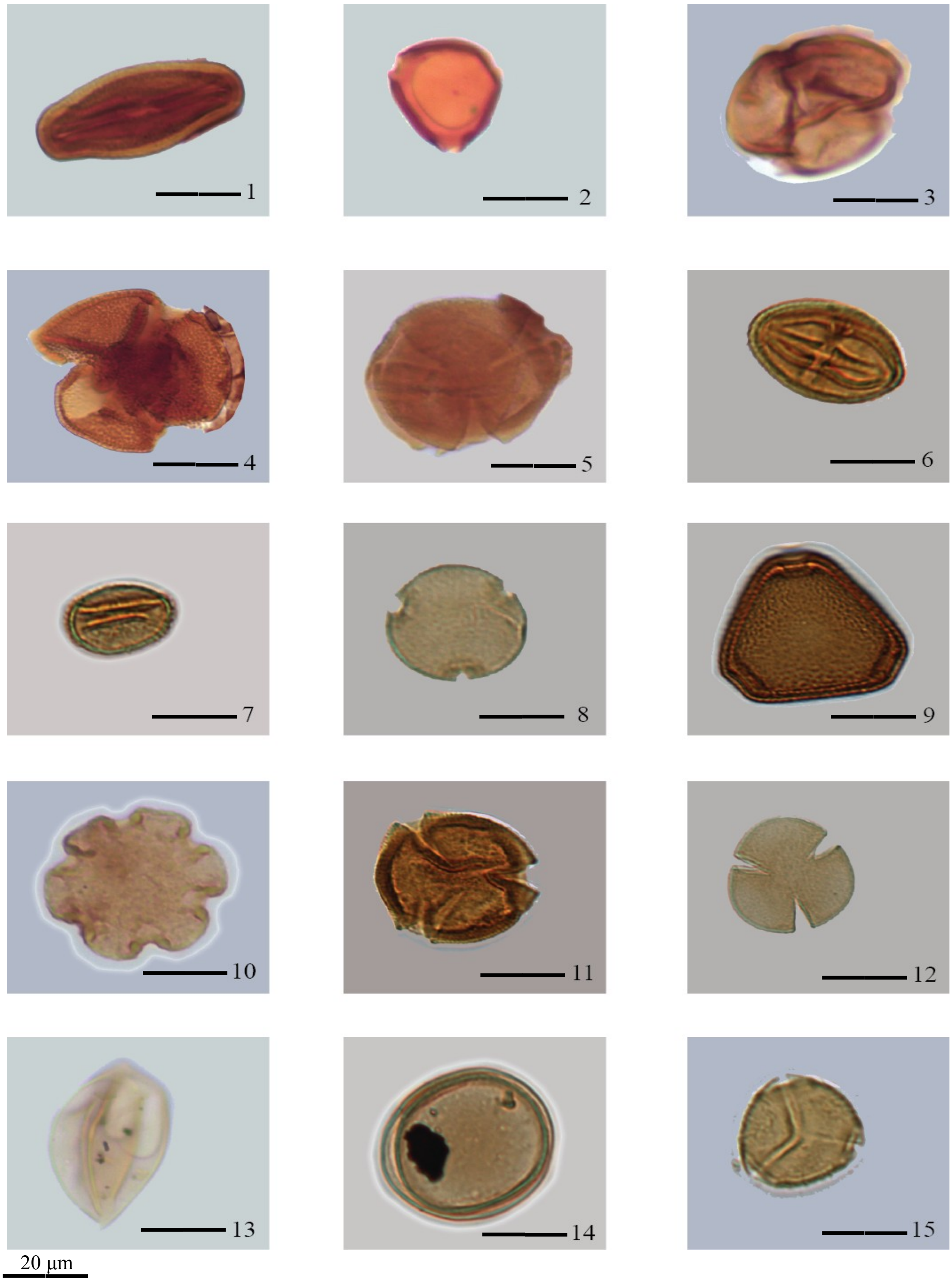


Plate 3. **(1)** *Tricolpites* sp. MTS-4:1; **(2)** *Bombacacidites* sp. MTS-5:2 ; **(3)** *Ericipites* sp. MTS-5:2; **(4)** *Margocolpites* sp. MTS-5:2; **(5)** *Palaeoaraliaceaepites distinctus* **(6)** *Tetracolporopollenites brevis* MTS – 2:2 EFR --O22; **(7)** *Rhiopites bradleyi* MTS-4:2 EFR –S31-3; **(8)** *Tilia* sp. MTS-3:1 EFR –O19; **(9)** *Symplocoipollenites tharensis* MTS- 4:2, EFR –X41-2 ; **(10)** *Jandufouria seamrogiformisi* MTS-2:2 **(11)** *Tricolporites* sp. MTS-4:2 EFR –V31-4; **(12)** *Tilia* sp. MTS-3:1 EFR –N21-2; **(13)** *Graminidite media* MTS-3:1; **(14)** *Proxapertites operculatus* MTS-13:1 EFR – S41; **(15)** *Cupaniedites* MTS-2:2 EFR –P13

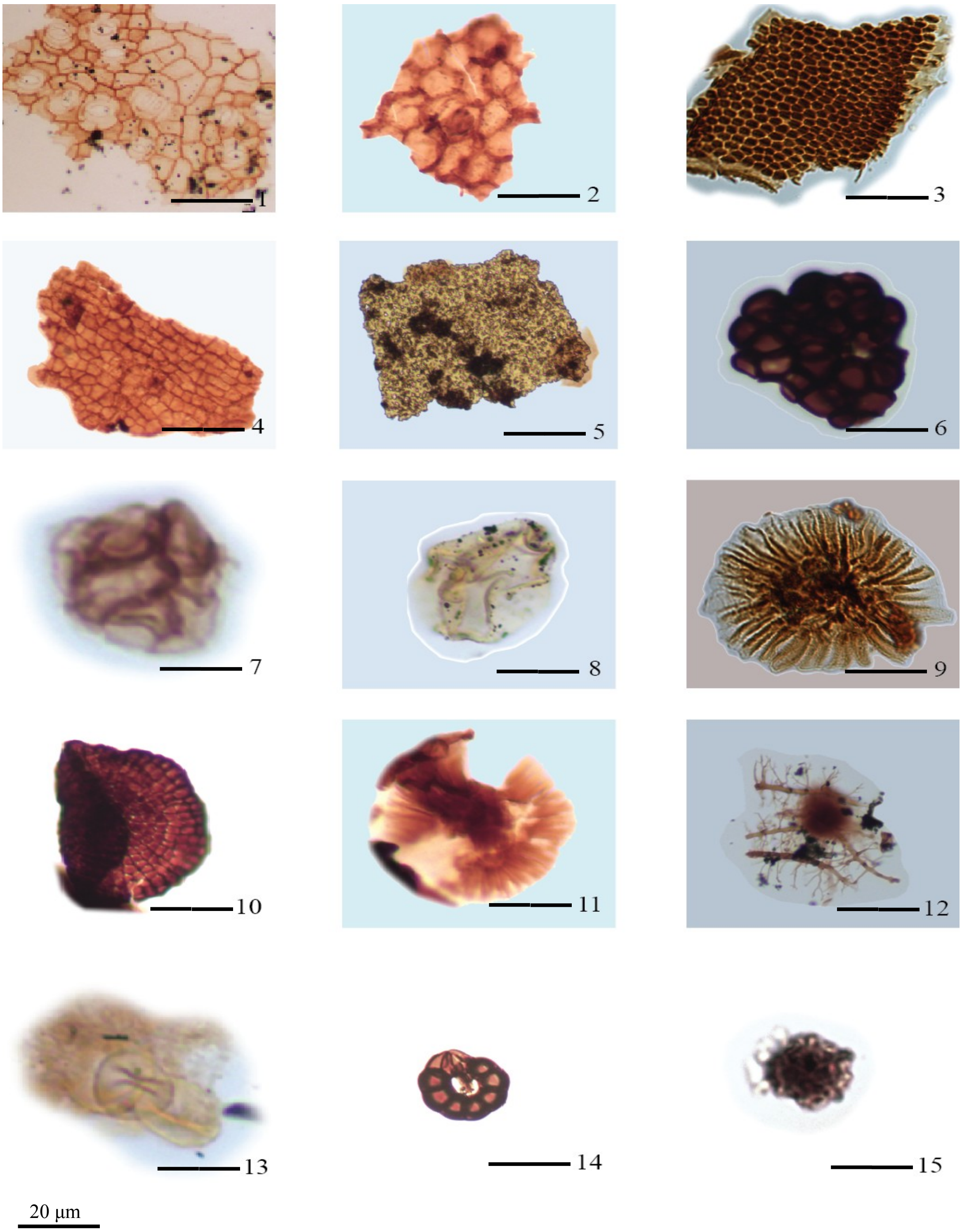


Plate. 4. **(1)** Plant cuticle with stomata MTS-13:1, EFR -Y49; **(2 , 3 , 4, 5)** Cuticle sheets; **(6)** fungal fruting body **(7)** *Salvinia* sp. **(8)** Sp indet. **(9)** fungi **(10, 11)** Epiphyllous fungi; **(12)** plant debris MTS-13:1, **(13, 14)** sp indet. , **(15)** Sp indet. MTS 7 EFR-W44;

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13. Appendix

Geophysical log

Longatidue: 70° 06‘ 00” N, 24° 36‘ 00” N

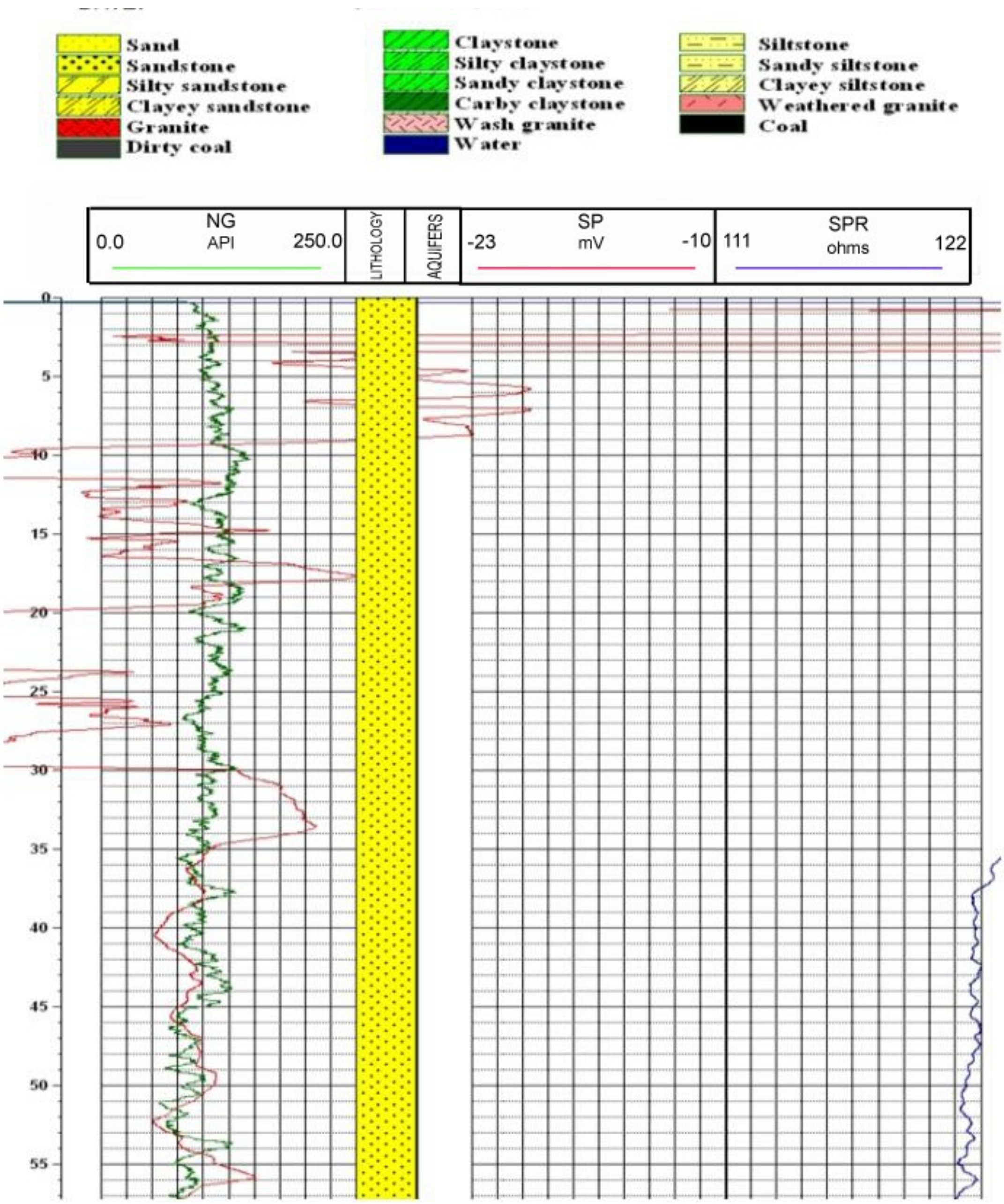
Latitude : 24° 30‘ 00” N, 24° 36‘ 00” N

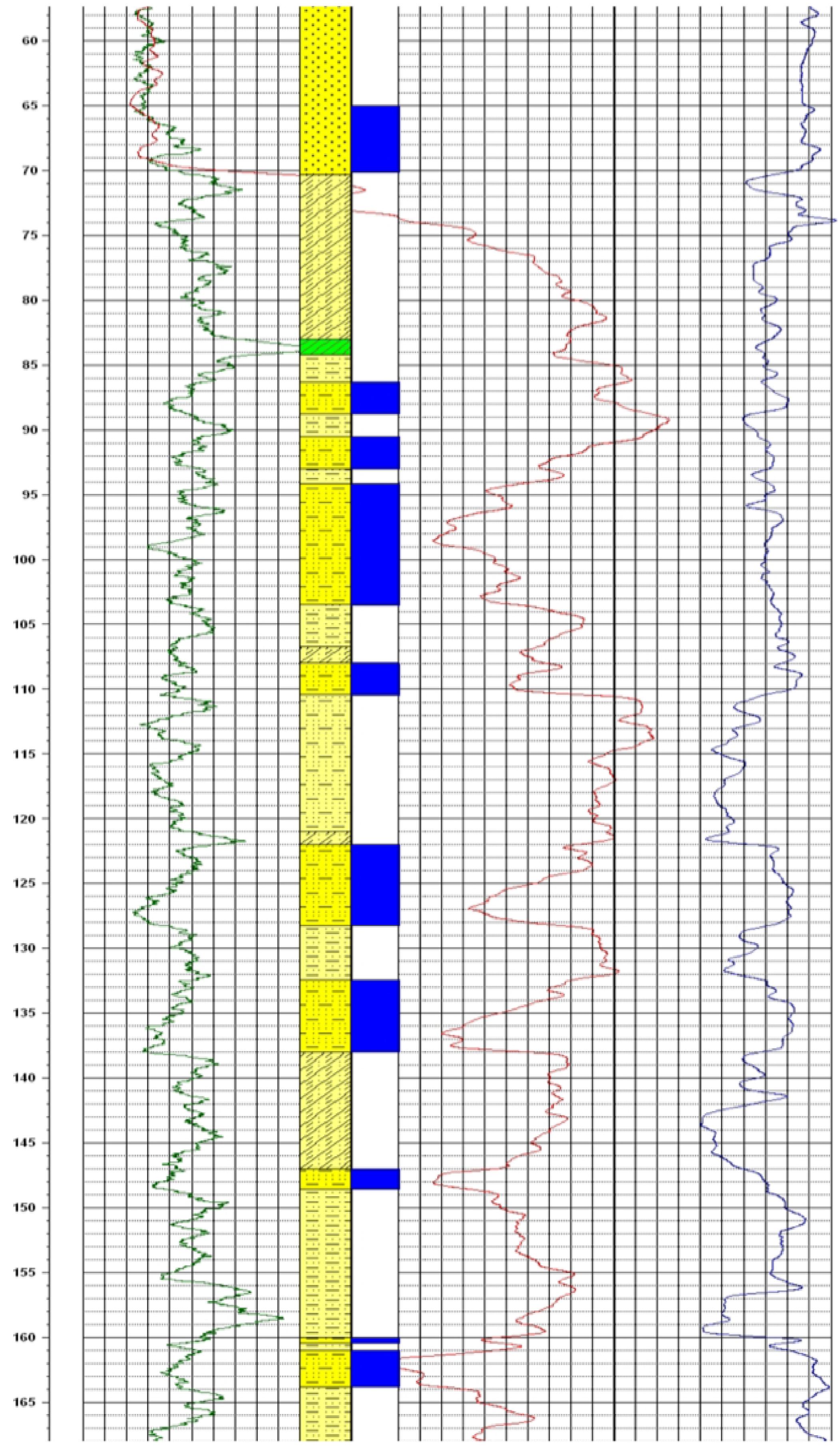
Mithrio Soomra Thar Coal field

Block X Borehole # 19

Total depth 274.62 m

From Sindh Coal authority 2012, Minerals and mines development department.





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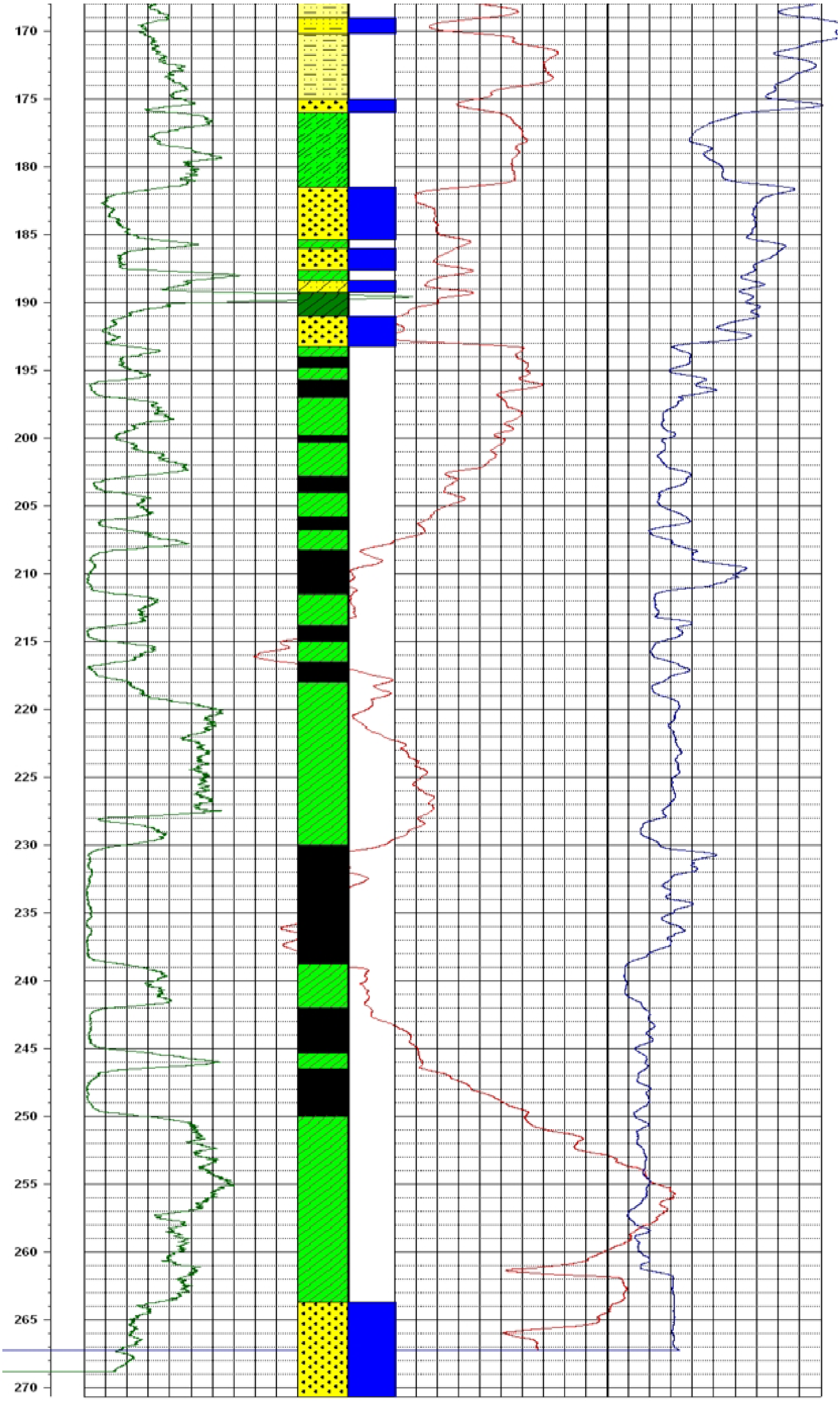
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