

Spore Color Index Study of the Hongsa Sediments, Lao PDR: Implications for Thermal Maturity and Paleoenvironment

THUNYAPAT SATTRABURUT¹, YUPA THASOD^{2*}, BENJAVUN RATANASTHIEN²
AND SIRASIT VONGVASSANA¹

¹*Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom 73170 THAILAND*

²*Department of Geological Sciences, Faculty of Science, Chiang Mai University, Chiang Mai, 50200 THAILAND*

*Corresponding author. Yupa Thasod (yupa161@gmail.com; yupa.t@cmu.ac.th)

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ABSTRACT. – Palynological analyses of samples from Neogene organic-rich fine-grained sediments in the Hongsa coal deposit, Lao PDR, have yielded a high count of palynomorphs, including abundant sporomorphs with varying colors. This study aims to evaluate the thermal maturity of the sediments and their paleoenvironment using the Spore Color Index (SCI). Microscopic analysis of sporomorph color variation provides a quick method to reconstruct the thermal alteration of sediments. Only monolet spores were selected to investigate spore color variation. The results show that almost 50% of the lightest colored monolet spores are pale yellow to light yellow, indicating a thermally immature zone within the early diagenetic stage of organic matter transformation. This group represents in situ materials, consistent with coal rank and vitrinite reflectance. Another group shows yellow to brown sporomorphs, suggesting the catagenetic stage, with coal ranks ranging from subbituminous to low volatile bituminous. The latter group is considered reworked sporomorphs transported to the Hongsa deposit area along with in situ palynomorphs. These reworked materials possibly originated from the Mesozoic bedrock surrounding the Hongsa basin, influenced by the basin's development related to the interaction between the Indian and Eurasian plates.

KEYWORDS: Hongsa coal mine, lignite, palynology, thermal alteration index, sedimentation, diagenesis

INTRODUCTION

The evolution of sedimentary organic matter is primarily governed by temperature, burial depth, and time—factors critical for evaluating petroleum potential (Rullkötter, 1993; Olivier and Atud, 2017). Sedimentary basin analysis plays a central role in exploration geology, providing insights into depositional environments and structural frameworks that control the distribution of hydrocarbons and mineral resources (Wangen, 2010; Allen and Allen, 2013; Miall, 2013; Buratti et al., 2024). Thermal maturity is commonly assessed using parameters such as vitrinite reflectance (Stach et al., 1982) and Tmax from Rock-Eval pyrolysis (Espitalié et al., 1985). Fossils, including spores and conodonts, are also effective indicators of thermal maturity, as their physical properties—such as color, reflectivity, and fluorescence—change progressively with increasing burial depth and temperature due to loss of hydrogen and oxygen relative to carbon (Marshall, 1990; Buratti et al., 2024).

Spores and pollen exhibit temperature-dependent color variations that make them particularly sensitive indicators of early-stage thermal maturation, often providing more refined resolution than vitrinite reflectance, especially in immature sediments (Zhao, 1984; Olivier and Atud, 2017). Additionally, reworked palynomorphs recovered alongside in situ assemblages offer valuable information on sediment provenance (Batten, 1991). Owing to their small size, abundance,

and chemically resistant sporopollenin walls, spores and pollen are highly durable and frequently preserved in the geological record. Their widespread production and persistence make them effective tools for reconstructing thermal history and paleogeographic conditions.

The use of palynomorph coloration in thermal maturity assessments has received growing attention in recent years (e.g., Moghazi et al., 2020; Spina et al., 2021; Spina et al., 2022; Nchimbi et al., 2022; Buratti et al., 2024; Hokam et al., 2024). However, no comprehensive study has yet been conducted using spore color to assess the thermal maturity of sediments in Laos.

Cenozoic coal-bearing basins are found in many areas throughout Southeast Asia, particularly in northern Thailand and northern Laos (Fig. 1). While the majority of economically significant coal deposits are Miocene and younger in age (Friederich et al., 2016), several basins—such as Ban Pa Kha, Ban Pu, and Mae Lamao—have been interpreted as Oligocene to early Miocene in age (Ratanasthien, 1991; Watanasak and Songtham, 2014). They typically occur within numerous small graben and half-graben sedimentary basins. The thermal maturity of oil shales and coals in some basins in Thailand was determined by vitrinite reflectance (Petersen et al., 2006). Vitrinite reflectance values from northern Thailand indicate thermal immaturity across several basins. The Late Oligocene to Early Miocene Ban Pa Kha and Ban Pu Subbasins yield reflectance values of 0.42–0.43 %Ro,

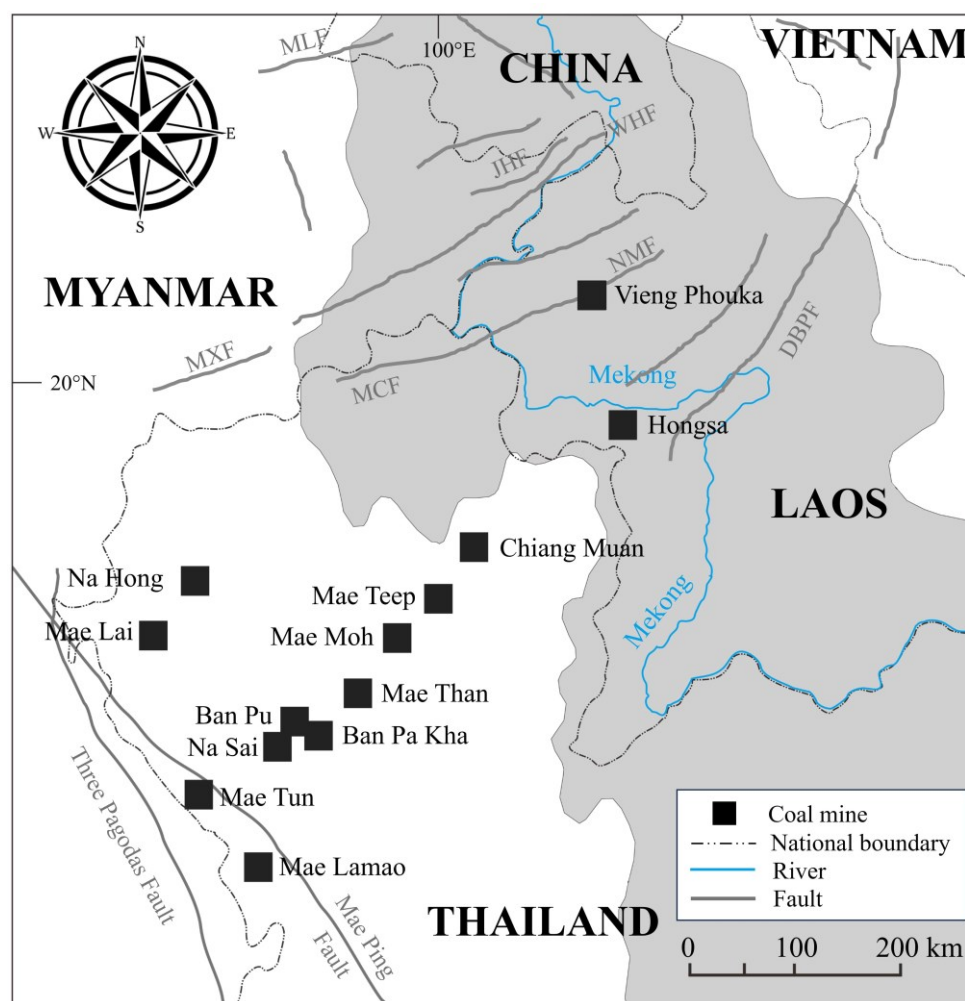


FIGURE 1. Distribution of current and historical coal mines across northern Thailand and northern Laos. The gray-shaded area delineates the extent of the Mekong Basin (modified from Gupta, 2009; Friederich et al., 2016). Major regional fault zones are also illustrated, including those situated within the Mekong Basin: the Dien Bien Phu Fault (DBPF), Mae Chan Fault (MCF), Nam Ma Fault (NMF), Mengxing Fault (MXF), Wan Ha Fault (WHF), Jinghong Fault (JHF), and Menglian Fault (MLF).

while the Middle Miocene Na Sai Subbasin and other parts of the Li Basin show slightly higher values around 0.47 %Ro (Friederich et al., 2016), suggesting overall low thermal maturity throughout these Cenozoic deposits.

Schneider and Göthel (2001) reported very low vitrinite reflectance values (0.16–0.20%Ro) for Eu-ulminite from Hongsa lignite, indicating low coalification. Sattraburut et al. (2021a) classified these coals as lignite A and B. Petrographic analysis shows vitrinite (huminites) as the dominant maceral group, primarily telovitrinite, detrovitrinite, and minor gelinite. Liptinite is the second most abundant, comprising cutinite, resinite, sporinite, and minor alginite. Inertinite (mainly sclerotinite) is rare, and mineral matter includes minor silica and clay. The maceral composition suggests deposition in a forest swamp environment.

Given the substantial presence of sporinite reported in a previous study (Sattraburut et al., 2021a), a detailed palynological investigation was subsequently undertaken to reconstruct the paleovegetation and paleoclimate of the coal-bearing formation (Sattraburut et al., 2021b). Notably, one intriguing observation from this investigation was the wide range of spore color intensities (Fig. 2), prompting the question: what accounts for this variation, and what insights can be drawn from it? To date, virtually no comprehensive studies have explored the diagenetic processes or paleoenvironmental implications of spore coloration within the Hongsa coal deposit, underscoring the novelty and significance of the present work.

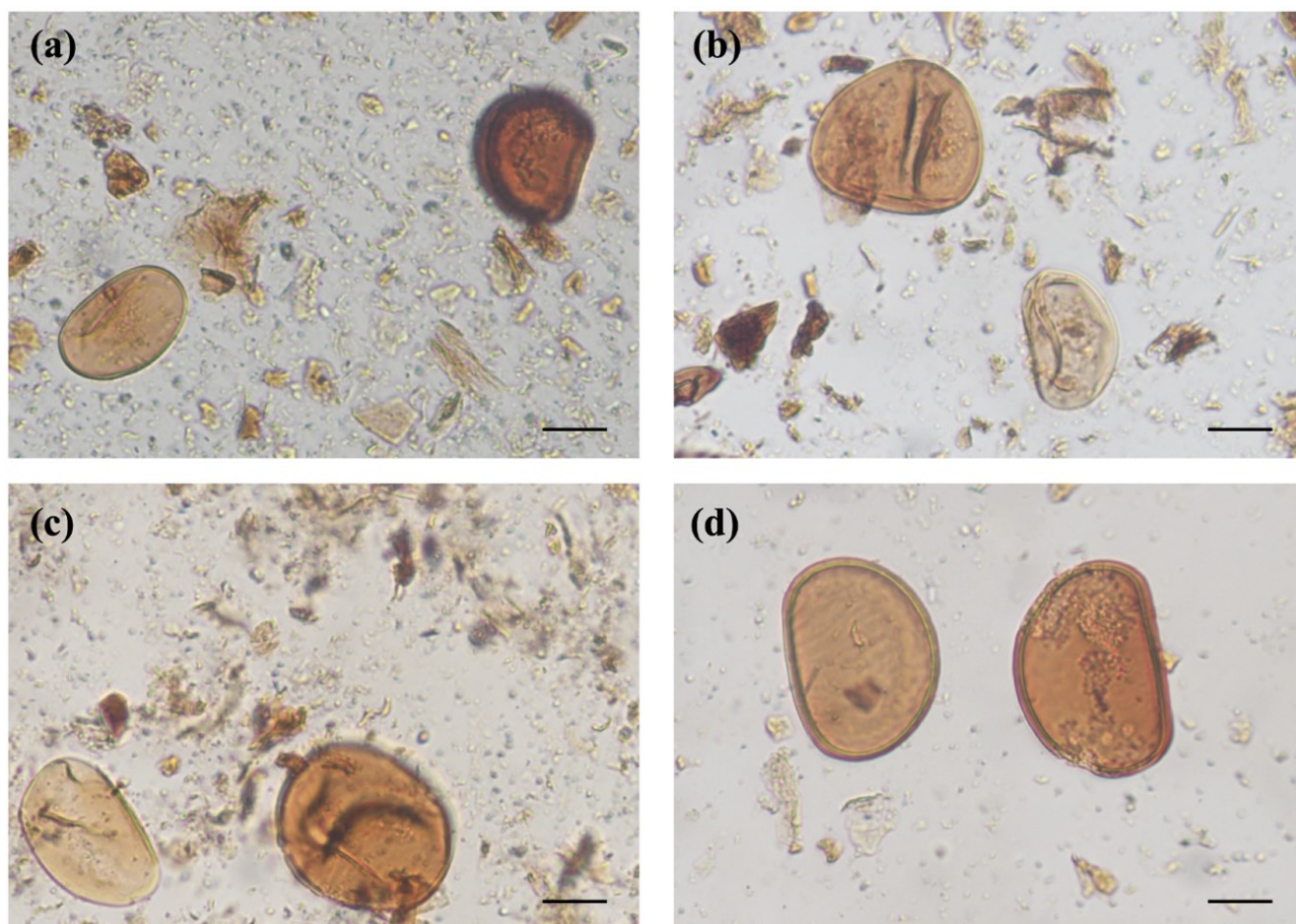


FIGURE 2. Monolete spores exhibiting varying color intensities. Scale bars represent 10 μm .

The reliability of the Spore Color Index (SCI) is well established, with numerous studies demonstrating its strong correlation with other indicators of thermal maturity, including vitrinite reflectance and the Thermal Alteration Index (TAI) (e.g., Senftle et al., 1993; Olivier and Atud, 2017; Buratti et al., 2024). Moreover, spore color analysis offers unique advantages in detecting early stages of thermal alteration, particularly in contexts where vitrinite reflectance values are exceedingly low and thus less diagnostic.

While the techniques employed in this study are considered classical, they remain robust and widely accepted in palynology and thermal maturity assessment—especially for low-rank coals and organic-rich sediments at immature diagenetic stages. Crucially, this study represents the first comprehensive application of the SCI in Lao PDR, specifically within the Hongsa coal deposit. The use of classical methods is intentional, reflecting their accessibility, cost-

effectiveness, and demonstrated reliability in regions with limited analytical infrastructure. Additionally, these methods facilitate direct comparison with existing regional and historical datasets, thereby enhancing the broader relevance and interpretability of the findings.

Accordingly, the primary objective of this study is to assess the thermal maturity of the organic-rich sediments in the Hongsa Basin using the SCI, and to interpret the diagenetic history and paleoenvironmental conditions of the study area. The approach also serves as a valuable tool for distinguishing between indigenous and reworked palynological materials.

Hongsa Coal mine in Xayabouly Province, Lao PDR was operated since 2015. Hongsa Basin developed during the Cenozoic, which is related to the tectonics of Southeast Asia (Tapponier et al., 1986; Burri, 1989; Lacassin et al., 1997; Hall and Morley, 2004; Chaodumrong and Songtham, 2014; Jain, 2014; Friederich et al., 2016). This intermontane basin is



FIGURE 3. The location of the Hongsa coal deposit in Xayabouly Province is shown as a red circle (modified from Sattraburut et al., 2021a).

composed of fine-grained clastic sediments and coal seams, which have a cumulative thickness of over 100 m, and complex fault systems can be recognized in the mine. The long period of deposition in Hongsa Basin was estimated at about 35 to 2 million years ago (Ma) (Oligocene to Pliocene) (Morley and Racey, 2011), this may be due to the lack of detailed studies conducted on this basin and there is no mammalian fossil found.

Geologic setting of the study area

The Hongsa coal deposit is located approximately 40 km northeast of the Thai–Lao border, between Huai Kon Village in Chaloem Prakiat District, Nan Province, Thailand, and Muang Ngeun in Xayabouly Province, Laos (Fig. 3). Its geographical coordinates are between latitudes $19^{\circ} 39' \text{ N}$ and $19^{\circ} 43' \text{ N}$, and longitudes $101^{\circ} 14' \text{ E}$ and $101^{\circ} 24' \text{ E}$. The basin has an approximately triangular shape, elongated in the ENE–WSW direction (Fig. 4).

The General Department of Geology and Mines of Vietnam (1988) described the geology of the Hongsa Basin as follows: the basement rock comprises Mesozoic sedimentary rocks, primarily terrestrial red sedimentary rocks, overlain unconformably by Neogene sediments. These Neogene sediments, characterized by non-marine depositions during the Himalayan Orogeny, mainly consist of light-gray silty clay. However, they also contain clay with some siltstone hard bands and coal-bearing sequences. The uppermost layer consists of Quaternary sediments, which include alluvial clay, silt, sand, and gravel from the Mekong River and its tributaries, covered by recent soil and lateritic sand (Fig. 5). The Cenozoic stratigraphy of the Hongsa coal deposit is shown in Fig. 6.

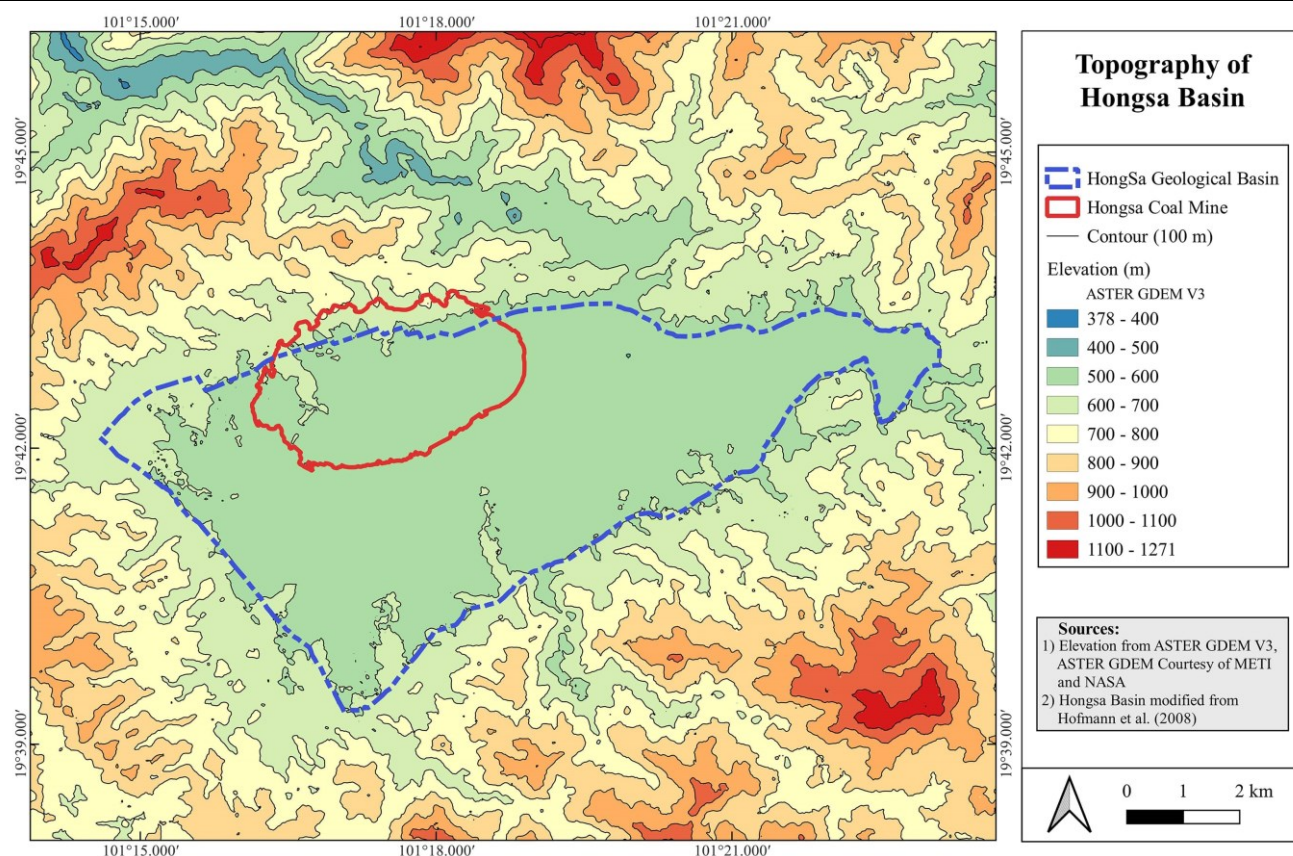


FIGURE 4. Topography of the Hongsa Basin.

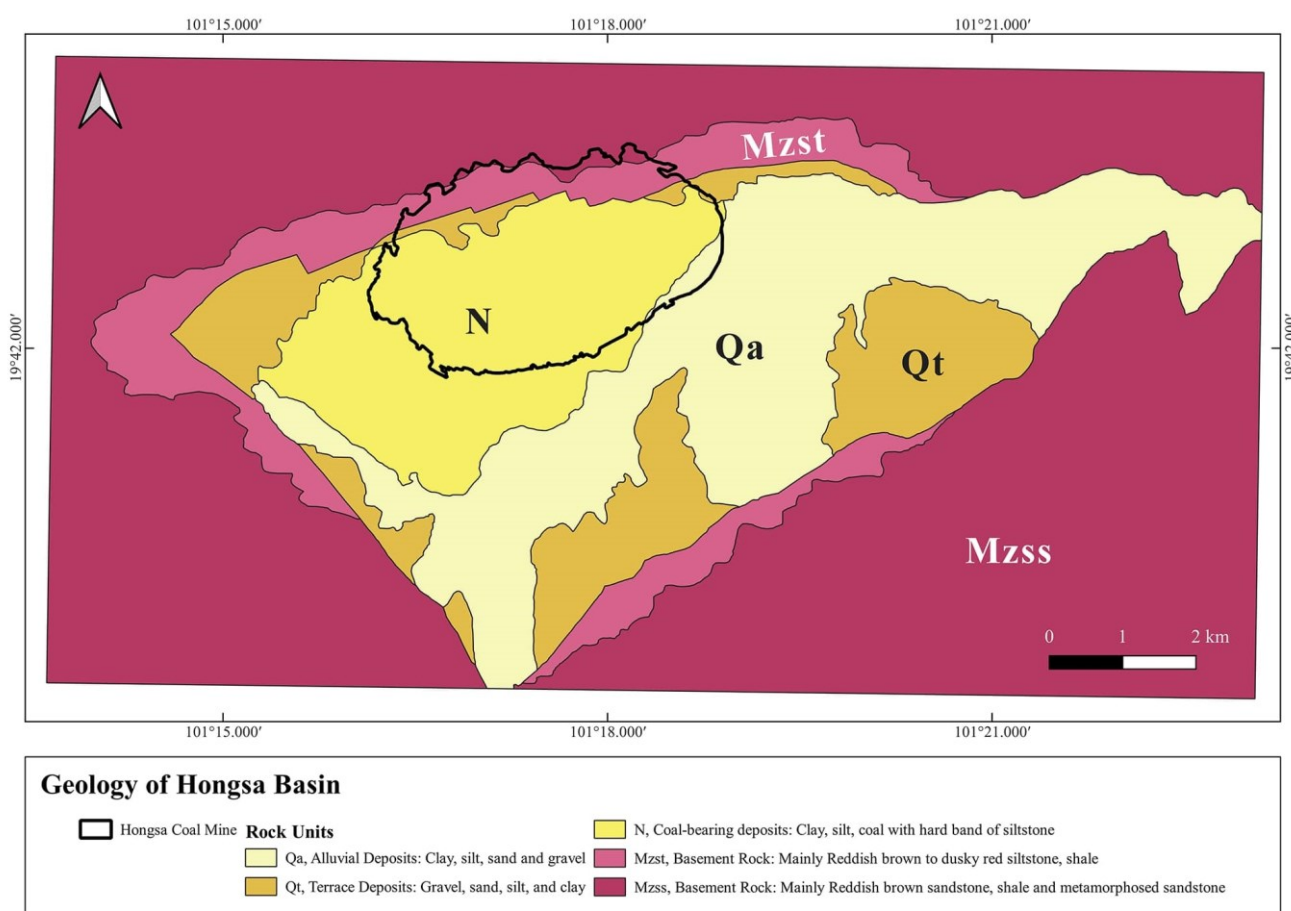


FIGURE 5. Geologic map of the Hongsa Basin (modified from Hofmann et al., 2008). Note: Quaternary alluvial deposits (Qa), Quaternary terrace deposits (Qt), Neogene (N), Mesozoic siltstone (Mzst), Mesozoic sandstone (Mzss).

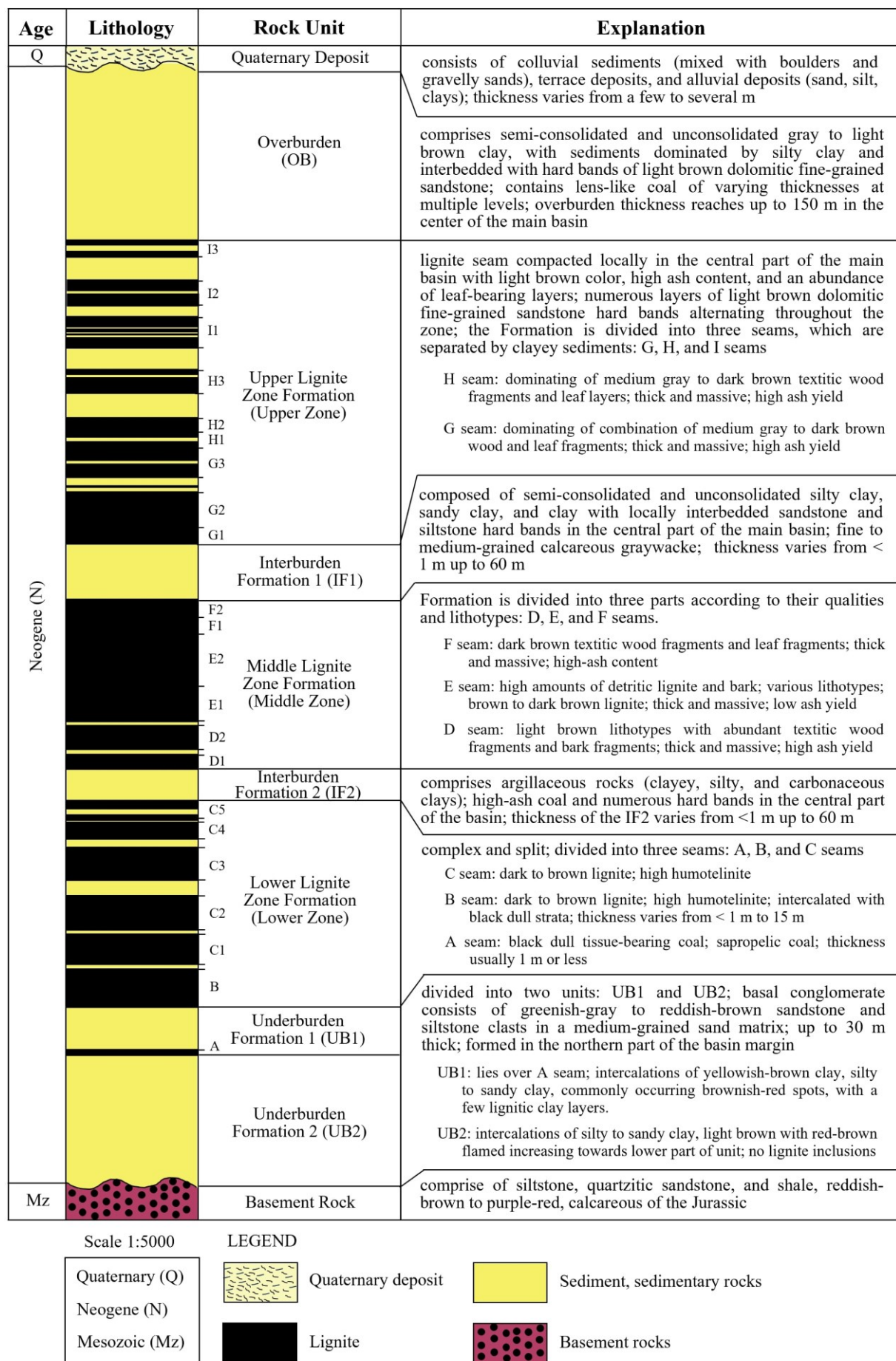


FIGURE 6. Schematic stratigraphy of Hongsa coal deposit (modified after Hofmann et al., 2008; Sattraburut et al., 2021a).

The elevation of the Hongsa Basin was obtained from ASTER GDEM V3 (<http://www.jspace-systems.or.jp/ersdac/GDEM/E/index.html>) (NASA/METI/AIST/Japan Spacesystems, and U.S./Japan ASTER Science Team, 2018). Contour lines with a 100 m interval were created. The rock unit data was modified from the original mapping obtained from Hofmann et al. (2008) through a geospatial procedure, which included 1) image georeferencing and 2) polygon drawing (via digitizing and snapping toolbars, and digitizing tools (Ströbl and Tzotsos, 2023)). Geospatial analysis, as well as the topography and geology map creation, was performed using QGIS software version 3.22.10 (QGIS.org, 2022).

MATERIALS AND METHODS

Thirty-two samples were obtained from a single continuous drill core of Neogene organic-rich fine-grained sediments from the Hongsa coal deposit and provided by Hongsa Power Company Limited. The samples span a total core length of 331.40 m, ranging from the Lower Lignite Zone Formation to the Overburden. Most samples comprised carbonaceous clay with minor amounts of carbonaceous silty clay.

Palynological processing and analysis were conducted as follows:

Sample preparation followed standard palynological techniques (Traverse, 1988; Faegri and Iversen, 1989; Moore et al., 1991), without the use of oxidation. Inorganic material was removed using hydrochloric acid (HCl) and hydrofluoric acid (HF). The remaining residues were sieved through 150 μm nylon mesh. Sporomorphs retained on the sieve were mounted individually in colorless glycerin jelly.

Microscopic examination was performed using a transmitted-light microscope at 400x magnification at the Department of Geological Sciences, Faculty of Science, Chiang Mai University.

Spore Color Index (SCI) analysis was based on well-preserved, unfolded sporoderms, using the SCI chart developed by Pearson (1984). The SCI ranges from 1 to 10, representing a gradient from colorless or light yellow to black (Fig. 7). The Thermal Alteration Index (TAI), which correlates with vitrinite reflectance, was used to supplement interpretations of thermal maturity.

Selection criteria and interpretation: Monolete fern spores were selected for analysis, as they represented the most abundant and consistently preserved

morphotype across the samples. Although trilete spores were occasionally observed, their limited occurrence and inconsistent preservation precluded their use in the SCI assessment. Selection criteria and interpretation followed the method of Pross et al. (2007), in which only the lightest 50% of counted sporomorphs per sample were analyzed to minimize the influence of reworked specimens. Monolete spores were preferred due to their simple morphology, wide stratigraphic range, and demonstrated reliability in color-based thermal maturity evaluation (Staplin, 1969; Marshall, 1990; Olivier and Atud, 2017). Progressive color changes in these sporomorphs—from yellow to black—were interpreted as indicators of increasing thermal maturity resulting from burial depth or thermal alteration (Traverse, 1988). These observations were used to infer the thermal evolution of the sediments and to distinguish between in situ and reworked palynomorphs.

RESULTS AND DISCUSSION

Spore color

The investigation shows the distribution of color of monolete spores compared with SCI (Fig. 8 and Table 1). The representative of sporomorphs (monolete spores) based on SCI from scale 1 to 10 is shown in Fig. 9. The result shows that almost all 50% lightest color monolete spores show pale yellow to light yellow color, which indicate a thermally immature zone and equivalence to SCI=1-3, TAI=1-(2-), and vitrinite reflectance %Ro less than 0.4. This suggests that the coal rank should be lignite under diagenesis organic stage (Senftle et al., 1993). This group with the lightest color is assumed to represent autochthonous or in situ materials due to its concordance of coal rank and vitrinite reflectance.

Apart from the consideration of the 50% lightest color, yellow to brown sporomorphs are also present, corresponding to SCI = 4-9, TAI = 2-4, and vitrinite reflectance %Ro greater than 0.38. This suggests the catagenetic stage, with the coal rank ranging from subbituminous to low volatile bituminous.

According to previous investigations by Schneider and Göthel (2001) and Sattraburut et al. (2021a), the coal of Hongsa is classified as lignite B to lignite A with %Ro = 0.16-0.2. Thus, the Hongsa coal should not have %Ro greater than ~0.40 (Stach et al., 1982). This clearly indicates that the presence of varying colors of spores at the same depth consists of both autochthonous and reworked materials, with the reworked spores showing darker colors than the autochthonous materials.

Subjective Colour	Spores/ pollen colour	Correlation to other scales			Organic Stage	Coal Rank
		SCI	TAI	Vitrinite reflectance		
Colourless to light yellow		1	1	0.2	Diagenesis	Peat
Light yellow		2	1+	0.3		Lignite
Yellow		3	2-	0.38		
Orange		4	2	0.45	Catagenesis	Sub-bituminous
Dark yellow		5	2+	0.61		High Volatile Bituminous
Light yellowish brown		6	3-	0.78		
Yellow brown		7	3	0.98		Medium Volatile Bituminous
Brown		8	3+	1.16		Low Volatile Bituminous
Dark brown		9	4-	1.71		
Brownish black		10	4	2.58	Metagenesis	Semi-anthracite
Black and Deformed			5	8.3		Anthracite

FIGURE 7. Color chart for spores and pollen correlated with the SCI, TAI, vitrinite reflectance, organic stage, and coal rank (modified from Pearson, 1984; Senftle et al., 1993).

Considering the predominance of sporomorph colors generally found as pale yellow to light yellow, the spore color certainly relates to the rank of the coals, which is lignite. Based on the distribution of sporomorph color variations in each sample, two groups were identified based on spore color variations related to the coalification of lignite (Fig. 10). The first group presents sporomorphs corresponding to the SCI scale of 1-3, ranging from 1.82% to 100% (mean 62.99%), which are considered to be in situ materials. The second group represents sporomorphs corresponding to the SCI scale of 4-10, ranging between 0% and 98.18% (mean 37.01%). This group is regarded as reworked materials.

Almost all samples consist of more indigenous sporomorphs deposited with sediments than reworked sporomorphs, except for sample 81. Sample 81 is characterized by the presence of almost all reworked sporomorphs (98.18%), suggesting that recycled sediments along with sporomorphs from older and more distant outcrops were transported to the depositional area, or the site of deposition had been completely removed by erosion (Batten, 1991). Some samples also show a high percentage of reworked

sporomorphs (e.g., samples 32, 33, 36, 69, 75, 76, and 77). These are shown in the high reworked sporomorphs zone (Fig. 10).

On the other hand, sample 27 consists entirely of indigenous sporomorphs. Although only the lightest 50% were formally analyzed, consistent coloration and preservation among all observed specimens suggest an absence of reworked material in this sample.

The sequence of sporomorph zones (Fig. 10) shows alternations between low and high reworked sporomorphs, which can approximately determine the relationship between rock units and sporomorph zones. The low reworked sporomorph zones can be correlated with the upper lignite zone formation and the lower lignite zone formation, while the high reworked sporomorph zone is tentatively correlated with the middle lignite zone formation. The accumulation of reworked sporomorphs could have been caused by strong monsoons or catastrophic flooding that eroded older sediments and carried a strong current of water to the deposit area.

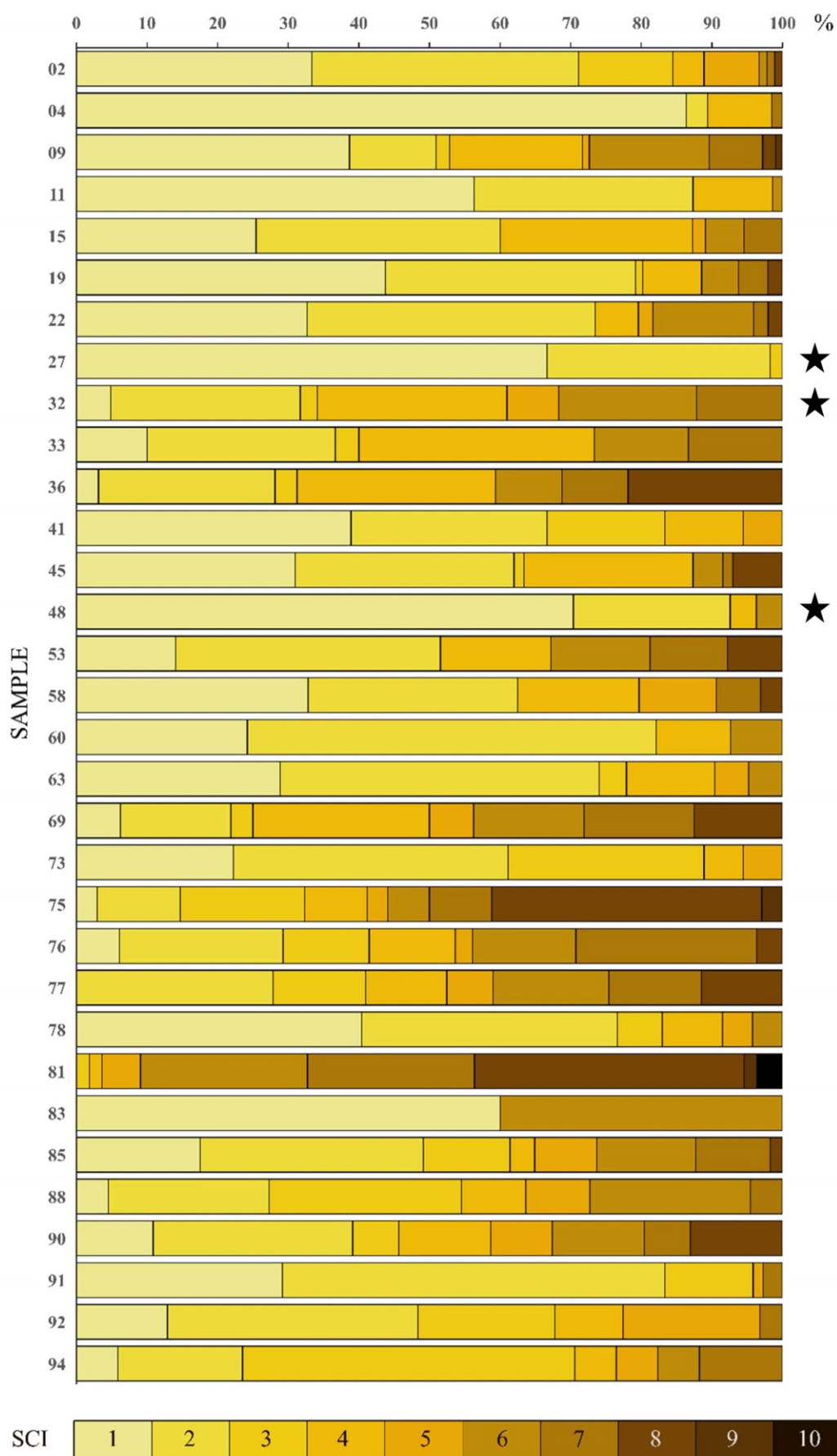


FIGURE 8. Spore color variation is determined based on the SCI. Black stars indicate the sample where *Schizaeoisporites* was found.

TABLE 1. Percentage of sporomorphs color based on Spore Color Index.

Sample	Spore Color Index									
	1	2	3	4	5	6	7	8	9	10
2	33	38	13	5	8	1	1	1	0	0
4	86	3	0	9	0	0	2	0	0	0
9	39	12	2	19	1	17	7	2	1	0
11	56	31	0	11	0	2	0	0	0	0
15	26	35	0	27	2	5	5	0	0	0
19	44	36	1	8	0	5	4	2	0	0
22	33	41	0	6	2	14	2	2	0	0
27	67	31	2	0	0	0	0	0	0	0
32	5	27	2	27	7	20	12	0	0	0
33	10	27	4	33	0	13	13	0	0	0
36	3	25	3	28	0	10	9	22	0	0
41	39	28	17	11	5	0	0	0	0	0
45	31	31	2	24	0	4	1	7	0	0
48	70	22	0	4	0	4	0	0	0	0
53	14	37	0	16	0	14	11	8	0	0
58	33	30	0	17	11	0	6	3	0	0
60	24	58	0	11	0	7	0	0	0	0
63	29	45	4	12	5	5	0	0	0	0
69	6	16	3	25	6	16	16	12	0	0
73	21	39	28	6	6	0	0	0	0	0
75	3	12	17	9	3	6	9	38	3	0
76	6	23	12	12	2	15	26	4	0	0
77	0	28	13	12	7	16	13	11	0	0
78	41	36	6	9	4	4	0	0	0	0
81	0	0	2	2	5	24	24	38	2	3
83	60	0	0	0	0	40	0	0	0	0
85	17	32	12	3	9	14	11	2	0	0
88	5	23	27	9	9	23	4	0	0	0
90	11	28	6	13	9	13	7	13	0	0
91	29	54	13	0	1	0	3	0	0	0
92	13	36	19	10	19	0	3	0	0	0
94	6	17	47	6	6	6	12	0	0	0

Diagenesis and thermal maturity

The optical method based on the property of organic matter undergoing irreversible changes in color with increasing thermal maturity has been used. Spore color variations can be used to determine the levels of maturation of organic matter and maximum burial temperature. Based on earlier studies conducted by Schneider and Göthel (2001) and Sattraburut et al. (2017), it is suggested that the coal found in Hongsa ranges from lignite B to lignite A with an %Ro of 0.16-0.2. As a result, it is expected that the %Ro of Hongsa coal should not exceed approximately 0.40. This clearly indicates that the presence of varying colors of spores at the same depth consists of both autochthonous and reworked materials, with the

reworked spores showing darker colors than autochthonous materials. To avoid some disadvantages of reworking, the overwhelming presence of in situ sporomorphs, which equate to SCI = 1-3, TAI = 1-(2-), and vitrinite reflectance %Ro less than 0.4, are used as criteria to obtain the thermal evolution of sediments in the Hongsa Basin. The SCI indicates that sediments in the basin experienced a maximum burial temperature of approximately 65°C (Demaision and Moore, 1980; North 1985), considered as low-temperature diagenesis and immature thermal maturity. It has also been found that the slight and gradual changes in colors observed from monolete spores through the studied borehole section have slightly increased with increasing depth.

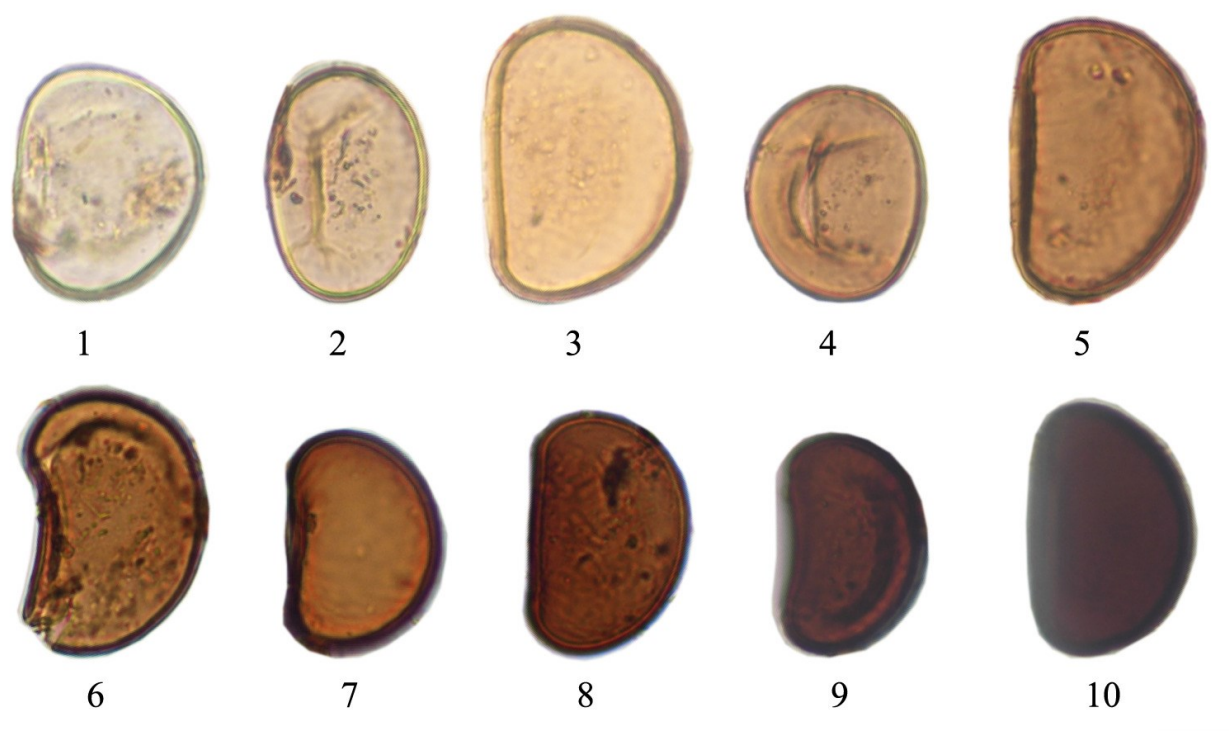


FIGURE 9. Representative monolete sporomorphs illustrating SCI values from scale 1 to 10. Scale bars represent 10 μ m.

The possible sources of reworked sporomorphs in Hongsa coal deposit

Microscopic analysis of 32 samples from the Hongsa coal deposit yielded abundant and well-preserved sporomorphs, including spores and pollen. A total of 64 palyno-taxa were identified, with ferns (28.67%) comprising a substantial portion of the assemblage (Sattraburut et al., 2021b). Monolete fern spores, particularly *Polypodium*, were dominant, while fungal spores were also frequently encountered (Sattraburut et al., 2023). The diversity and abundance of fern and herbaceous sporomorphs—alongside taxa such as *Quercus*, Fabaceae, and Myrtaceae—suggest a humid, shaded forest understory within a mixed deciduous–evergreen vegetation structure (Zhang et al., 2012; Sattraburut et al., 2021b). The low frequency of coniferous pollen implies possible long-distance transport rather than local origin.

Based on both spore color and taxonomic evidence, some palynomorphs and sporomorphs are interpreted as reworked from older sedimentary sources. Sporomorphs of ferns exhibit both high abundance and significant variation in color, suggesting multiple phases of deposition. Moreover, *Schizaeoisporites* (Fig. 11), a taxon abundant in the Mesozoic—particularly the Cretaceous (Traverse, 2007)—was also identified in the assemblage. Most palynomorphs recovered from Hongsa’s organic-rich sediments exhibit uniform coloration, whereas fern-derived sporomorphs—

particularly monolete spores—display a broader range of colors, suggesting variable thermal alteration or possible reworking.

The presence of reworked palynomorphs provides important clues about the basin’s sedimentary history. Reworked sporomorphs are key indicators of sediment provenance (Batten, 1991). The color of *Schizaeoisporites* closely matches that of monolete spores interpreted as reworked. Its peak abundance in the Cretaceous (Traverse, 2007) supports a Mesozoic origin, likely from surrounding bedrock. However, the color variation observed in monolete spores does not appear to correlate with the occurrence of *Schizaeoisporites*. Although *Schizaeoisporites* was identified at specific depths, the overall spore color distribution at those levels still suggests a predominance of in situ sporomorphs rather than reworked material.

The basement rocks of the Hongsa Basin, consisting of Late Mesozoic red terrigenous sedimentary rocks (Salyapongse et al., 2000; Hofmann et al., 2008), are likely sources of the reworked palynomorphs. These rocks may correlate with the Sao Khua Formation of the Khorat Group, assigned to the Early Cretaceous (Department of Mineral Resources, 2007). They are composed mainly of reddish-brown siltstones, sandstones, and conglomerates deposited in a fluvial system under semi-arid to arid conditions (Racey et al., 1996; Buffetaut et al., 2005).

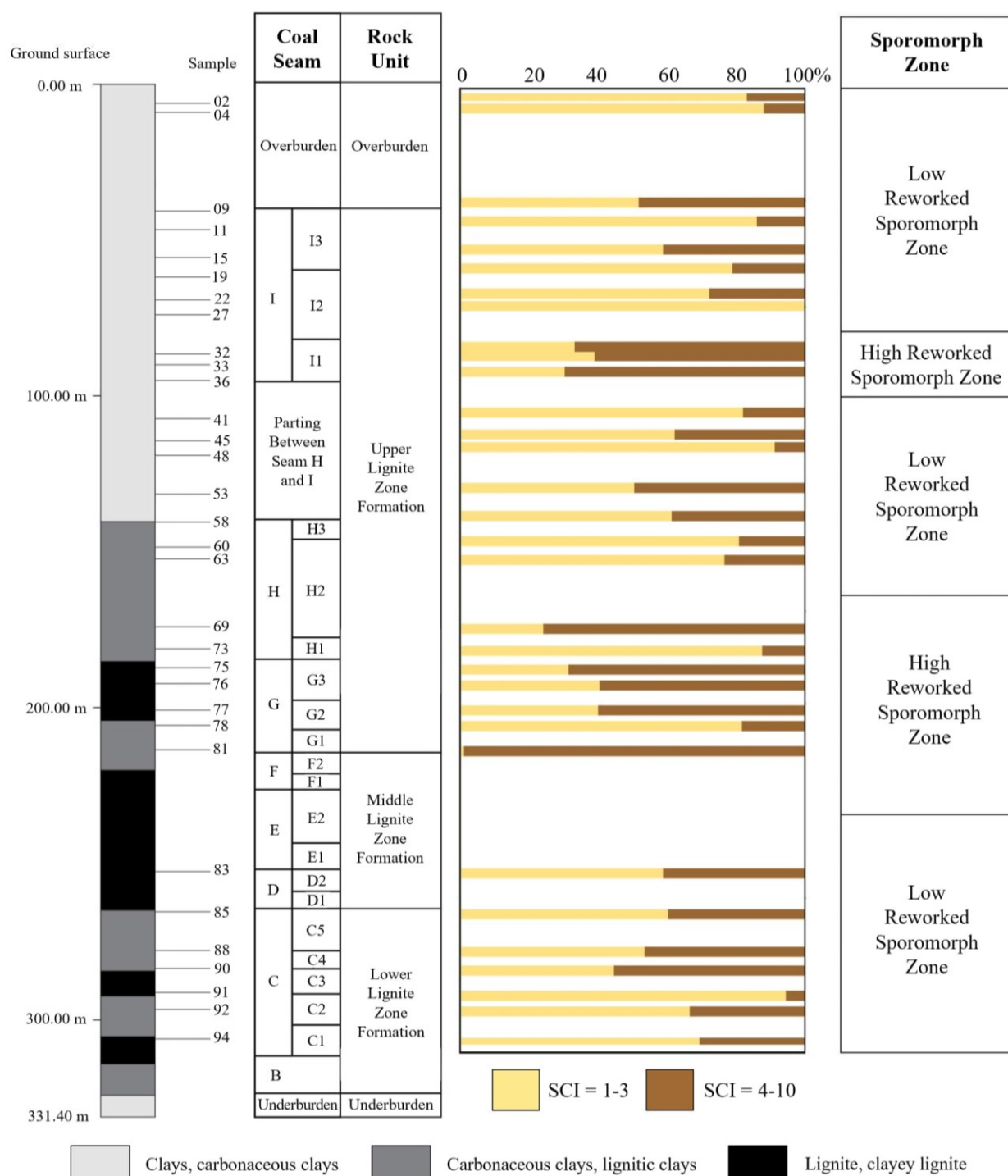


FIGURE 10. Vertical trend of sporomorphs on scales 1-3 and 4-10 based on the SCI.

In addition to palynological evidence, petrographic and sedimentological data further support this interpretation. Angular quartz grains and poor sorting observed in thin sections indicate minimal transport distance and local erosion (Sattraburut et al., 2024). The sediments also contain mineral assemblages (e.g.,

kaolinite, chlorite) consistent with recycled material from older sedimentary units. The high abundance of fungal spores—particularly in layers rich in darker-colored sporomorphs—is consistent with palynological signatures of reworked assemblages (Sattraburut et al., 2023).

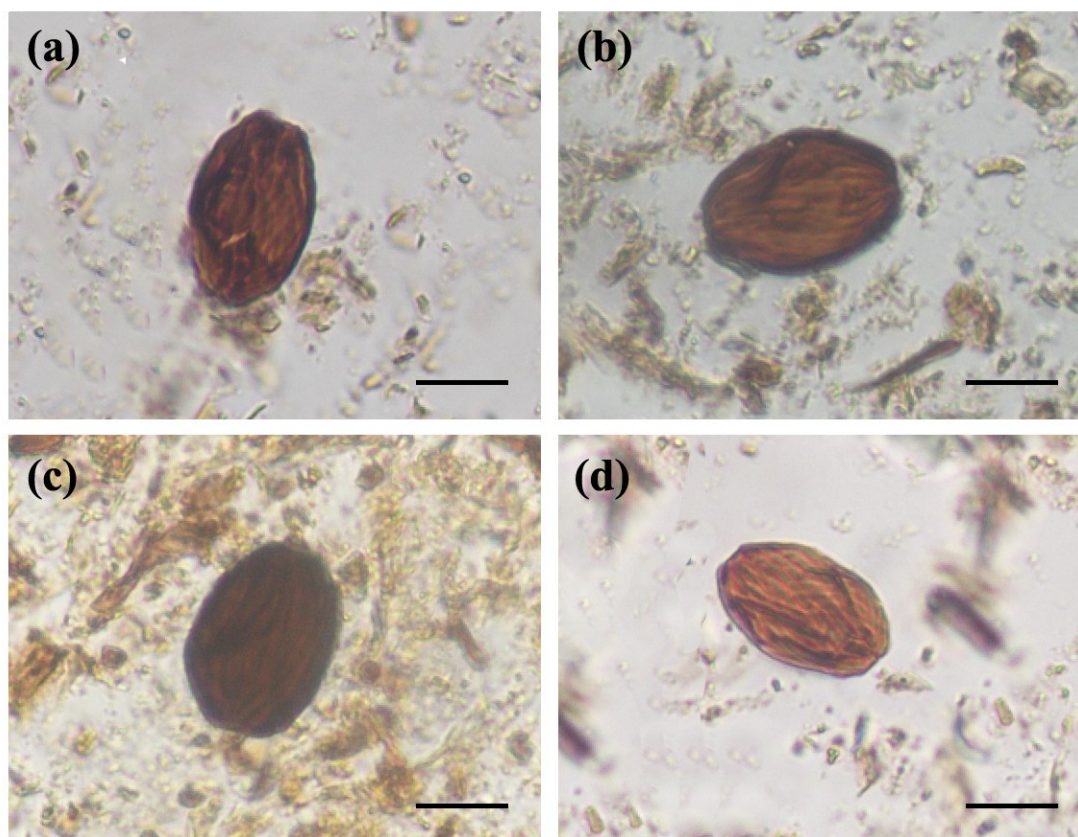


FIGURE 11. Sporomorphs of *Schizaeoisporites* from the Mesozoic. Scale bars represent 10 μm .

Moreover, tectonic uplift of the basin margin associated with regional deformation from the Indian–Eurasian plate collision likely contributed to erosion of Mesozoic strata (Hall and Morley, 2004; Charusiri and Pum-Im, 2009). The occurrence of Mesozoic indicator taxa such as *Schizaeoisporites*, also abundant in nearby Khorat Group units, further supports a local reworking origin. Alternations between clay-rich and coarser facies in the Hongsa core suggest episodes of high-energy depositional input, such as flooding or slope failure, that may have facilitated reworking.

The Hongsa Basin evolved through multiple tectonic phases, including pull-apart and syn-rifting, thermal subsidence, transpressional wrenching, and post-rifting (Charusiri and Pum-Im, 2009). Uplift associated with these stages likely exposed and eroded older rocks, contributing both sediment and palynomorphs to the basin. The dominant control on sediment input appears to be tectonic uplift rather than precipitation alone, as rainfall-driven erosion tends to be moderate in the absence of active deformation (Clift et al., 2006).

However, an alternative mechanism for reworked input is fluvial transport from the Mekong River. The Hongsa Basin lies approximately 10 km south of the Mekong, within the broader Mekong drainage basin.

Although the present elevation difference (~300 m) is significant, this may not have existed during the mid-Miocene. According to Nie et al. (2018), the Mekong River underwent rapid incision (>700 m) between 17–14 Ma in response to intensified monsoon precipitation. Prior to this incision, the river may have been at a comparable elevation to the Hongsa Basin, facilitating sediment transport into the basin. While speculative, this provides a secondary pathway for sporomorph reworking, complementing the primary mechanism of local erosion.

CONCLUSIONS

Neogene organic-rich fine-grained sediments from the Hongsa coal mine in Xayabouly Province, Lao PDR, were analyzed to estimate the thermal maturity of sediments using the Spore Color Index. Microscopic analysis of color variation in sporomorphs was conducted on monolete spores present at all depths. The results indicate that almost all 50% of the lightest-colored monolete spores show a pale yellow to light yellow color, suggesting a thermally immature zone in the diagenetic organic stage. This group represents in situ materials due to its concordance with coal rank and

vitrinite reflectance. Another group shows yellow to brown sporomorphs, suggesting the catagenetic stage and that the coal rank should be subbituminous to low volatile bituminous. The latter is considered as reworked sporomorphs. The uplift of the Tibetan Plateau, resulting from the interaction of the Indian and Eurasian plates, may have influenced mountain building in many regions in Asia. Weathering and erosion processes led to the transportation of sediments along with reworked sporomorphs from Mesozoic bedrock to a new deposit site, which is the Hongsa Basin, where they were then deposited alongside in situ palynomorphs.

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