DOI : https://doi.org/10.7186/wg521202603

Characterisation and palaeoenvironmental significance of amber from the Tukau Formation, NW Sarawak, Malaysia

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Abstract: Amber fragments recovered *in situ* from the Tukau Formation (Middle Miocene to Pliocene) in northwest Sarawak were analysed to assess their physical and chemical characteristics. Amber samples were collected from ten different localities and underwent diagnostic tests to evaluate hardness, solvent solubility, buoyancy, UV fluorescence, and burning reaction. The samples display melting points above 160 °C, hardness between 3-4 on the Mohs scale, non-reactivity to acetone, and a characteristic resinous odour upon heating, properties consistent with fossil amber. Fourier Transform Infrared (FTIR) spectra reveal consistent absorption bands at approximately 2920, 2863, 1694, 1454, 1374, 1042, and 887 cm^{-1}, and display absorption patterns comparable to fossil dipterocarp (Class II) resins and distinct from succinite. When considered together with the diagnostic physical properties and the Neogene age of the host sediments, these observations support classification of the material as fossil amber rather than weakly polymerised resin. The spectral profile closely corresponds to that of resins from Dipterocarpaceae trees, suggesting a tropical lowland forest origin. The preservation of amber within fluvio-deltaic to shallow marine deposits indicates burial under conditions favourable for the preservation of organic matter. Tukau amber is thus comparable to Neogene dipterocarp-derived amber elsewhere in Borneo, providing insights into Miocene palaeoenvironments and vegetation in the region.

Keywords: Borneo amber, Tukau Formation, palaeoenvironment, Miocene, Dipterocarpaceae

INTRODUCTION

Organic constituents preserved within sedimentary successions provide valuable proxies for reconstructing past terrestrial environments. Natural resins, organic hydrocarbon compounds produced by plants, are commonly classified as copal or amber based on their degree of polymerisation and diagenetic maturation (Grimaldi *et al*., 1994; Lambert *et al*., 2012). Copal forms through the evaporation of volatile components from fresh resins, while progressive burial and diagenetic processes, such as devolatilisation, polymerisation, and oxidation, may eventually transform copal into amber (Brody *et al*., 2001; Lambert *et al*., 2012). It is important to note that the chemical pathways and maturation indicators of this transformation may vary depending on the botanical origin and resin class. Amber is particularly informative for palaeoenvironmental and palaeoecological reconstructions (Karolina *et al*., 2022; Garcia-Valles *et al*., 2023; Li *et al*., 2023; Murillo-Barroso *et al*., 2023), as it retains chemical signatures of its botanical source plant and depositional history, thereby bridging palaeobotany, organic geochemistry, and sedimentology. Analytical techniques, such as Fourier Transform Infrared (FTIR) spectroscopy, enable the identification of diagnostic functional groups in fossil resins, providing insights into their botanical affinity, maturation state, and diagenetic history (Langenheim, 2003; Seyfullah *et al*., 2018).

Amber occurrences are globally significant indicators of terrestrial forest ecosystems and resin-producing flora, often associated with tropical and subtropical climates conducive to resin exudation and preservation (Bisulca *et al*., 2012; Álvarez-Parra *et al*., 2024). The earliest known amber record dates to the Early Pennsylvanian (~320 Ma), although macroscopic biological inclusions do not become common until the mid-Early Cretaceous (~125 Ma) (Labandeira, 2014). Fossiliferous amber from Cenozoic deposits originates mainly from two angiosperm lineages with distinct chemical compositions, as summarised in Sadowski *et al*. (2021). Eocene and Miocene ambers from India and China primarily derived from Dipterocarpaceae

0126-5539; 2682-7549 / Published by the Geological Society of Malaysia.

and are classified as Class II dammar resins (Dutta *et al*., 2009; Rust *et al*., 2010; Shi *et al*., 2014). In contrast, Baltic amber succinites originate from conifers and are classified as Class Ia resins (Bray & Anderson, 2009).

In Southeast Asia, particularly in Borneo, amber has been documented in several Neogene formations, including the Liang, Seria, Miri and Belait formations. It has generally been attributed to resins secreted by Dipterocarpaceae trees (Kocsis *et al*., 2020). Amber pebbles and flakes have been reported from the Tukau Formation by several researchers (Hutchison, 2005; Kessler & Padmanabhan, 2008; Kessler & Jong, 2014, 2015, 2016; Nagarajan *et al*., 2022; Kessler, 2023; Kessler *et al*., 2023). Despite these observations, the amber from the Tukau Formation has not been systematically characterised, and its botanical affinity and depositional significance remain poorly constrained. This study aims to characterise and classify the amber pebbles of the formation through a combination of diagnostic physical and chemical tests, as well as FTIR spectroscopy. By comparing the resulting spectral data with those of known fossil and modern resins, this study seeks to identify probable botanical sources and to interpret the depositional and diagenetic conditions under which these resins were preserved.

GEOLOGICAL SETTING

The Tukau Formation is situated within the Miri Zone, the youngest of three tectonostratigraphic zones in onshore Sarawak, which also includes the Kuching and Sibu Zones (Liechti *et al*., 1960; Madon, 1999). These zones are separated by the Lupar Line and the Tatau-Mersing Line, with ages becoming progressively younger northward; the Miri Zone represents the youngest succession (Upper Eocene to Recent) (Liechti *et al*., 1960; Madon, 1999). The Miri Zone comprises a stratigraphic sequence that includes the Rajang Group, Mulu, Kelalan, Tatau, Melinau Limestone, Nyalau, Setap Shale, Subis Limestone, Lambir, Belait, Tukau, Miri, Seria, Bergrih, and Liang Formations (Jong & Kessler, 2019).

The Tukau Formation forms part of the Neogene succession within the Baram Delta Province (BDP), which also includes the Setap Shale, Lambir, Tukau, Miri and Liang formations (Togunwa *et al*., 2015). The Neogene succession represents a substantial 9 to 12 km thick sequence of primarily progradational to strongly aggradational coastal-deltaic to shelf deposits, interpreted as mixed-energy-influenced deposition (Collins *et al*., 2017, 2018). The formation occurs within the BDP, which evolved as a deltaic province from the Middle Miocene to the present day, transitioning from a foreland basin to a shelf margin setting (Morley *et al*., 2003; Collins *et al*., 2017, 2018).

While some researchers have combined the Lambir and Tukau formations due to their lithostratigraphic similarities and uncertain ages (Banda & Honza, 1997; Collins *et al*., 2020), this study follows the formation boundaries delineated by Liechti *et al*. (1960), recognising them as distinct stratigraphic units. The age of the Tukau Formation spans from Tf to Tgh (equivalent to Middle Miocene to Pliocene) based on strike correlation with the fossiliferous Miri and Seria formations (Liechti *et al*., 1960; Wilford, 1961). Hutchison (2005) refined this age assignment to Late Miocene to Early Pliocene. The finding from Nagarajan *et al*. (2017) aligns with the statement, as they suggested that the Tukau rocks were deposited approximately 10 to 2.58 Ma. Two significant unconformities bound the Tukau Formation: 1) an Intra-Pliocene Unconformity (IPU) separating the Tukau Formation from the overlying Liang Formation, and 2) a Lower Pleistocene Unconformity (LPU) between the Tukau Formation and the overlying Pleistocene coastal terraces (Kessler & Jong, 2017).

METHODOLOGY

Thirteen amber samples were collected *in situ* from outcrops using a geological hammer and chisel during fieldwork. The host rocks of the ambers are all organic-rich mudstones and heterolithic units. The collected samples were cleaned with a soft brush and an ultrasonic cleaner to remove sediments, then air-dried at room temperature for several days. Sample C1Abr1 was chosen for thin section preparation and microscopic study as it was among the larger and more intact specimens, allowing for proper embedding and sectioning without fracturing. The amber thin section was prepared using standard petrography procedures described by Brasier *et al*. (2009); Lewis & McConchie (2012).

Chemical and physical tests were conducted to distinguish amber from other types of resins. They examined the melting point, hardness, solubility, flotation, solvent reaction, UV fluorescence, and burning behaviour of the samples. Samples were heated at 160 °C to differentiate amber (melting point 200–380 °C) from copal (<150 °C) (Poinar, 1992). Hardness was tested using the Mohs scale, and solubility in acetone was observed after 5 minutes and overnight. Seawater from Lutong Beach (salinity 27–28 ppt) was used for flotation testing to assess buoyancy under natural marine conditions. Long-wave UV light (365 nm) was used to examine the appearance of the samples, as amber will demonstrate luminescence properties under UV illumination.

FTIR analysis was employed to identify differences in functional group composition among amber samples from the Tukau Formation, offering insight into the resin-producing vegetation and palaeoenvironmental conditions. For this, the Tukau ambers were crushed with an agate mortar and pestle, sieved to 63 µm, and pressed onto the Attenuated Total Reflectance (ATR) crystal. Analyses were performed using an Agilent Cary 630 FTIR spectrometer

with MicroLab 1.0.0.7 software at Curtin University Malaysia, covering a wavelength range of 4000–650 cm^{-1} at a resolution of 4 cm^{-1}. The purpose of the background scan is to exclude the effect of background signals on the samples. Location of the outcrops is shown in Figure 1, and Figure 2 shows some of the fossilised amber *in situ*. Table 1 lists the amber samples collected from each outcrop and their coordinates.

RESULTS

Physical and chemical characteristics of ambers

The results of the diagnostic physical and chemical tests performed on the Tukau amber samples are summarised in Table 2.

Thirteen samples were tested, and all exhibited melting points above 160 °C. Most specimens exhibited hardness values of 3 on the Mohs scale, with one specimen reaching a hardness value of 4 (Table 2). When samples were submerged in acetone, no changes were observed after 5 minutes; however, after overnight submersion, the acetone turned yellow in three cases (C2, M1, REB), and all samples developed a whitish surface. These limited reactions indicate a high degree of polymerisation and chemical stability, as less mature or subfossil resins typically exhibit stronger dissolution or surface degradation in acetone.

All samples sank in the local seawater when tested for buoyancy. Given that seawater at a salinity of 27 to 28 ppt, has a density slightly above 1.02 g/cm^3, the negative buoyancy of the samples indicates a higher specific gravity, which suggests that the samples are relatively dense and chemically mature. Progressive polymerisation and loss of volatile components during diagenesis increase resin density; therefore, fresh resin or weakly polymerised copal may float, whereas mature amber commonly exhibits negative buoyancy in seawater. Each sample exhibited a faint bluish fluorescence under UV light, typical of fossilised amber. Freshly broken and polished surfaces were uniformly dark brown and opaque to translucent. When subjected to a hot needle, the samples melted easily and emitted white smoke accompanied by a resinous odour.

The combination of these characteristics, including melting points above 160 °C, hardness between 3 and 4, non-reactivity to acetone, and the resinous odour upon heating, confirms the samples as true amber. Petrographic observations of C1Abr1 revealed fine, irregular fractures and minor impurities, with no visible plant or animal inclusions. Stress lines were absent, and no clear flow structures were identified.

FTIR spectra of ambers

The FTIR spectra of all the Tukau amber samples and the approximate vibrational assignments of the specimens are shown in Figure 3 and Table 3. Although minor variations exist among samples, the spectral profiles consistently exhibit a set of major absorption bands at approximately 2920, 2863, 1694, 1454, 1374, 1042,

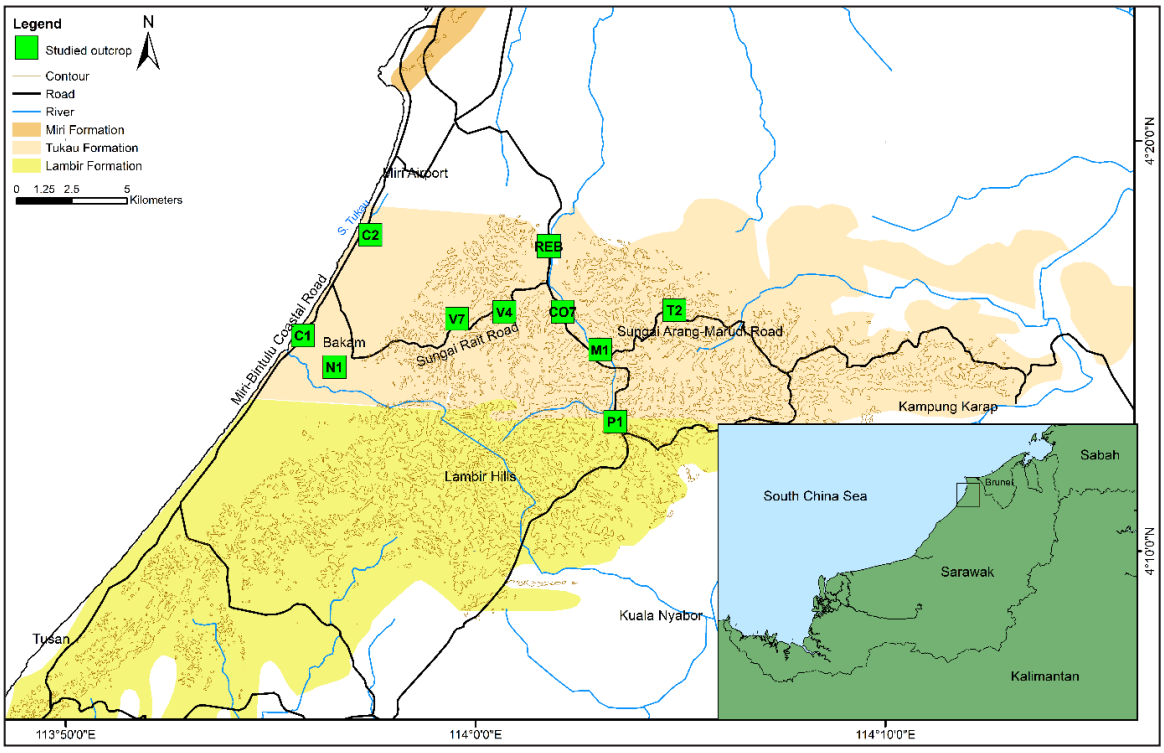

Figure 1: Geological map showing the locations of outcrops visited in this study (modified after Liechti *et al*., 1960).

Table 1: List of amber samples, corresponding outcrops and coordinates examined in this study. Detailed graphic logs for several of these outcrops are provided in Fong *et al*. (2024). Additional stratigraphic logs will be made publicly available upon the release of the author's forthcoming publications and doctoral thesis.

Sample	Outcrop	Coordinates (°N, °E)	Log height where the samples were collected (m)
C1Abr1	C1	4.2543, 113.9298	11.5
C1Abr2	C1	4.2543, 113.9298	20.5
C1Abr3	C1	4.2543, 113.9298	31.2
C1Abr4	C1	4.2543, 113.9298	34.8
C2Abr1	C2	4.2952, 113.9572	0.2
V4Abr1	V4	4.2638, 114.0117	11.0
V7Abr1	V7	4.2611, 113.9925	1.5
N1Abr1	N1	4.2415, 113.9427	0.6
M1Abr1	M1	4.2485, 114.0507	7.0
T2Abr1	T2	4.2646, 114.0808	0.1
P1Abr1	P1	4.2193, 114.0568	61.2
CO7Abr1	CO7	4.2639, 114.0354	51.5
REBAbr1	REB	4.2906, 114.0298	4.0

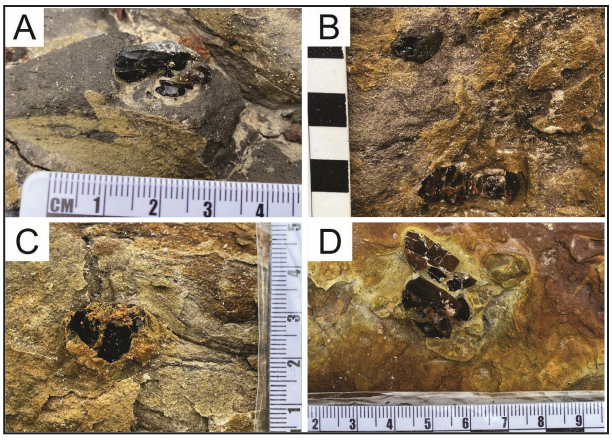

Figure 2: In situ ambers found at respective outcrops. A: Outcrop M1; B: Outcrop T2; C: Outcrop C1; and D: Outcrop V4.

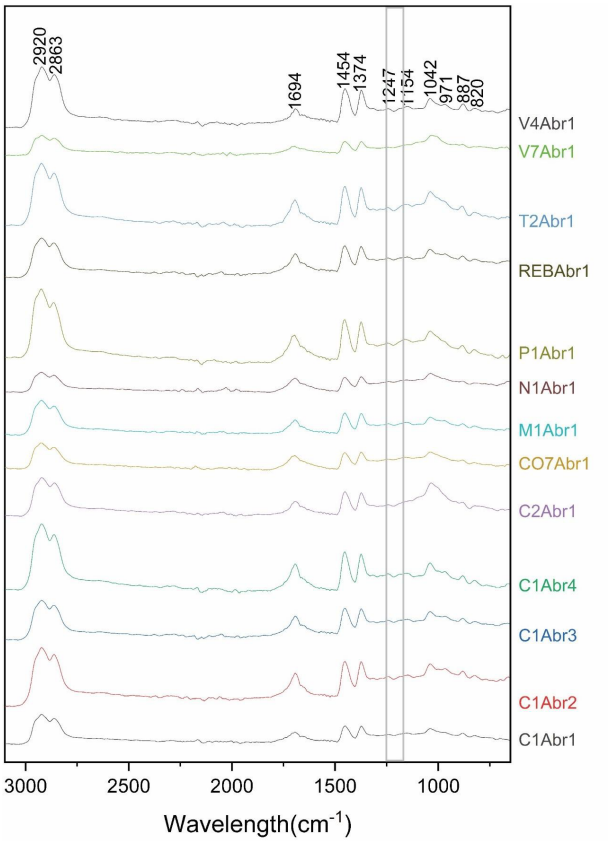

Figure 3: FTIR spectra of thirteen amber samples from the Tukau Formation. The vertical axis is not to scale; this figure is intended only to illustrate peak positions. The grey box highlights the "Baltic shoulder".

and 887 cm^{-1}, respectively. In the region of symmetric and asymmetric C-H stretching, the most prominent absorbance peaks occur around the wavelength of 2920 and 2863 cm^{-1}. The carbonyl (C=O) stretch commonly occurs around 1694 cm^{-1}, while bands in the single-bond regions (C-O and C-H) are observed at approximately 1454, 1374, and 1042 cm^{-1}, reflecting the general functional group composition of the samples. These absorption features describe the general functional group composition of the Tukau amber samples and provide a basis for comparison with fossil and modern resins of known botanical affinity.

DISCUSSION

The occurrence and preservation of amber clasts in the Tukau Formation provide important insights into deposition conditions and the resin's original botanical source. The observed physical and chemical characteristics: melting points above 160 °C, hardness of 3-4 on the Mohs scale, and minimal reaction to solvents, are consistent with those of fossil amber rather than subfossil copal (Anderson, 1994; Langenheim, 2003). FTIR analyses provide additional compositional context

Table 2: Summary of the physical and chemical test results for thirteen Tukau amber samples. Common properties for all samples include a melting point >160 °C, no reaction in the acetone test, and consistent faint blue UV fluorescence with a resinous odour upon burning. Abbreviation: X = No visible changes in acetone or amber; Y = Acetone turned yellow and the amber surface turned white.

Sample	Colour (Munsell)	Clarity	Hardness	Floatation Test	Acetone Test (5 mins)	Acetone Test (Overnight)	UV Fluorescence	Burning Reaction
C1Abr1-C1Abr4	5Y 7/10 to 7.5RP 3/2	Opaque–translucent	3	Sank	X	X	Faint bluish	Melted easily, white smoke, resin smell
C2Abr1	Ditto	Semi-transparent	3	Sank	X	Y	Faint bluish	Ditto
V4Abr1	Ditto	Translucent	3	Sank	X	X	Faint bluish	Ditto
V7Abr1	Ditto	Translucent	3	Sank	X	X	Faint bluish	Ditto
N1Abr1	Ditto	Opaque	3	Sank	X	X	Faint bluish	Ditto
M1Abr1	Ditto	Translucent	3	Sank	X	Y	Faint bluish	Ditto
T2Abr1	Ditto	Semi-transparent	3	Sank	X	X	Faint bluish	Ditto
P1Abr1	Ditto	Translucent	3	Sank	X	X	Faint bluish	Ditto
CO7Abr1	Ditto	Translucent	4	Sank	X	X	Faint bluish	Ditto
REBAbr1	Ditto	Opaque	3	Sank	X	Y	Faint bluish	Ditto

Table 3: The wavelength and approximate vibrational assignments for the Tukau samples tested.

Assignment Samples	C-H stretching		C=O stretching	C-H bending	C-H symmetric bending	C-O stretching			C-H bending		
C1Abr1	2922	2868	1695	1454	1373	1244	1155	1039	970	885	823
C1Abr2	2922	2870	1695	1457	1375	1243	1157	1041	969	885	823
C1Abr3	2918	2866	1697	1457	1375	1243	1155	1045	970	883	825
C1Abr4	2920	2866	1699	1457	1375	1243	1151	1043	971	881	827
V4Abr1	2922	2861	1694	1452	1374	1243	1152	1038	970	880	824
V7Abr1	2922	2861	1703	1454	1372	1245	1157	1032	921	883	796
C2Abr1	2922	2861	1694	1452	1372	1247		1034		883	818
M1Abr1	2924	2861	1694	1452	1372	1245	1155	1040	971	883	826
T2Abr1	2922	2861	1696	1452	1374	1245	1152	1040		885	827
N1Abr1	2926	2863	1696	1452	1375	1241		1040		880	826
P1Abr1	2924	2864	1696	1454	1374	1249	1167	1040	970	883	827
CO7Abr1	2924	2863	1696	1452	1374	1247	1161	1038		885	827
REBAbr1	2922	2863	1707	1454	1374			1032			

when evaluated in conjunction with these physical properties and the geological age of the host sediments. Comparative spectral data (Figure 4) show that the Tukau amber lacks absorption features characteristic of Class I labdane-based diterpenoid resins, such as those reported for some copals (Abduriyim *et al*., 2009; Montoro *et al*., 2018). This observation should be interpreted in the context of resin class, as Dipterocarpaceae produce Class II resins, which are dominated by sesquiterpenes and triterpenes; in such resins, these features may be weak or absent, even in modern resins. Likewise, the "Baltic shoulder", a broad absorption feature between 1250-1200 cm^{-1} associated with succinic acid in Baltic succinite (Karolina *et al*., 2022; Murillo-Barroso *et al*., 2023), is absent in all the 13 Tukau samples. Instead, the Tukau amber spectra display a pattern consistent with

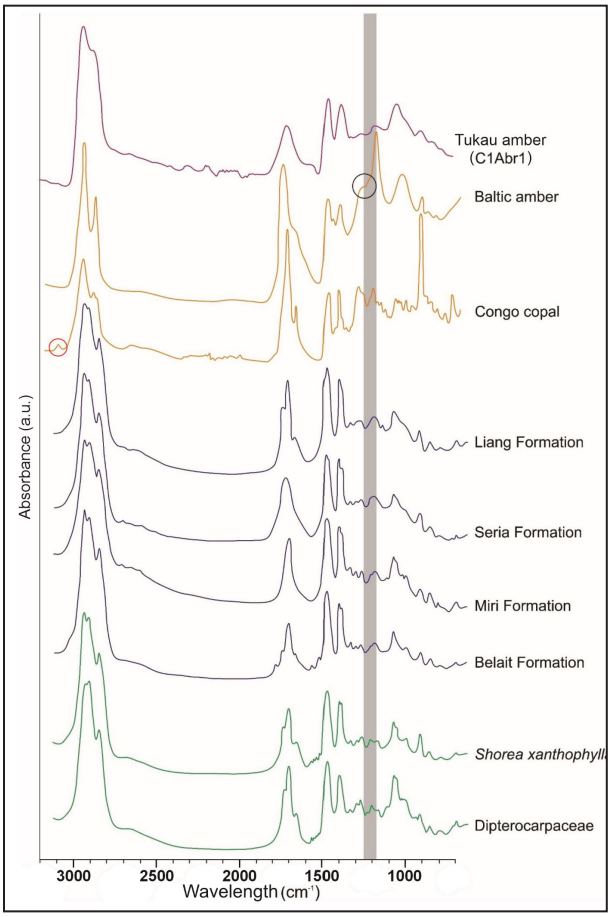

Figure 4: FTIR spectra of amber sample C1Abr1 from the Tukau Formation in comparison with spectra for Baltic amber, Congo copal (Garcia-Valles *et al*., 2023), fossil amber from Liang, Seria, Miri, and Belait formations, and the modern tree resins from *Shorea xanthophylla* and dipterocarpaceae trees (Kocsis *et al*., 2020). The black circle indicates the characteristic "Baltic shoulder" observed in the Baltic amber spectrum, and the grey band indicates the range of wavelength where the "Baltic shoulder" occurs. The red circle highlights the 3075 cm^{-1} absorption band commonly reported in Class I diterpenoid resins.

fossil and modern resins produced by Dipterocarpaceae trees (Kocsis *et al*., 2020).

Palynological data further support this interpretation: Dipterocarpaceae pollen is present within the formation (Fong *et al*., 2024), and similar amber has been reported from the Liang, Seria, Miri, and Belait formations of northwest Borneo (Kocsis *et al*., 2020). These regional occurrences confirm that dipterocarps were a persistent element of local Neogene Forest ecosystems, and their resins are preferentially preserved due to chemical resistance to corrosion. The Merit-Pila coal basin in Sarawak provides a key regional analogue: amber is abundant there and the locality is widely cited as one of the major amber-bearing coal deposits globally, with the botanical source commonly interpreted as dipterocarps (Langenheim, 2003). This interpretation is reinforced by recent palaeobotanical work from the Tebulan coal pit within the Merit-Pila succession, which documents abundant dipterocarp macrofloral remains, including leaf impressions attributed to *Dryobalanops* (Dipterocarpaceae) (Othman *et al*., 2026).

Dipterocarpaceae is a family of large, resinous, predominantly evergreen trees that dominate the canopy and emergent layers of Old World lowland tropical rainforests (Ashton, 2003). The family shows a pantropical but disjunct distribution, comprising three main evolutionary lineages: the species-rich Asian Dipterocarpoideae, the African-Madagascan and South American Monotoideae, and the South American monotypic Pakaraimoideae (Maury-Lechon & Curtet, 1998; Ashton, 2003; Ghazoul, 2016). The Asian subfamily Dipterocarpoideae comprises most genera and species, representing the principal centre within diversity of the family, with Southeast Asia supporting the highest concentration of species (Brearley *et al*., 2017). Within this region, Borneo is consistently recognised as the area of greatest dipterocarp diversity (Slik *et al*., 2003).

This compositional similarity suggests that the Tukau amber was derived from dipterocarp forests, either from localised resin production within lowland settings (autochthonous or parautochthonous) or from material transported downstream from upland forest communities (allochthonous) (Seyfullah *et al*., 2018). The robust chemical structure of amber (Martínez-Delclòs *et al*., 2004; Álvarez-Parra *et al*., 2024) enables long-distance transport without substantial alteration of its diagnostic infrared features.

Resin production likely originated as a defensive response in living dipterocarp trees, with viscous resin exuded following injury or environmental stress (Langenheim, 2003; Seyfullah *et al*., 2018). After secretion, resin either hardened on the tree surface or accumulated on the forest floor, where early dehydration and partial polymerisation occurred. Subsequent mobilisation by surface runoff, floods, or river systems

facilitated transport of resin clast together with other possible plant debris (Poinar, 1992; Seyfullah *et al*., 2018). Progressive polymerisation increased resin density, and rapid burial under reduced oxygen conditions limited microbial degradation and oxidation, allowing continued diagenetic maturation and transformation of the resin into amber (Seyfullah *et al*., 2018; Saitta & Kaye, 2025).

Amber deposition is typically favoured in lowland, nearshore, and deltaic environments where reduced oxygen conditions promote organic preservation (Bisulca *et al*., 2012; Seyfullah *et al*., 2018). This is consistent with sedimentological interpretations of the Tukau Formation as a mixed fluvio-deltaic to shallow marine setting influenced by marine incursions.

CONCLUSION

Amber clasts preserved within the Tukau Formation are fossil resins derived from Dipterocarpaceae trees that flourished in tropical lowland forests during the Neogene. Diagnostic physical and chemical characteristics, including melting points exceeding 160 °C, hardness of 3-4 on the Mohs scale, solvent resistance, negative buoyancy in seawater, and a resinous odour upon heating, indicate a high degree of polymerisation consistent with fossil amber rather than fresh or weakly polymerised resin. FTIR spectra provide complementary compositional information, displaying C-H, C=O, and C-O absorption patterns consistent with dipterocarp-derived fossil resins and lacking features characteristic of succinite. When considered together with the physical properties and the Neogene age of the Tukau Formation, these observations support the classification of the material as fossil resin, also known as amber.

The occurrence of amber within mixed fluvio-deltaic to shallow-marine facies of the Tukau Formation suggests resin production in nearby dipterocarp forests and subsequent transport and burial under low-oxygen conditions, which are favourable to preservation. Together with regional reports of similar ambers from the Liang, Seria, Miri, and Belait formations, the Tukau amber provides clear evidence for Dipterocarpaceae-dominated forests across northwest Borneo during the Middle Miocene or later. Its preservation within organic-rich mudstones and heterolithic units, and is associated with fluvial-deltaic sediments, further attests to the interplay between terrestrial vegetation, resin production, and sedimentary processes within tropical deltaic systems.

Beyond its botanical significance, the Tukau amber record contributes to a broader understanding of Neogene landscape evolution in northwest Borneo, reflecting the lowland forest cover and active sediment routing from terrestrial to marginal marine environments. This study represents the first systematic characterisation of amber from the Tukau Formation, providing new constraints on its botanical origin and depositional context. The result established Tukau amber as a palaeoenvironmental proxy for reconstructing Neogene tropical forest ecosystems, resin-producing vegetation, and deltaic conditions in northwest Borneo, and provides a framework for future comparative studies of Southeast Asian amber-bearing successions.

ACKNOWLEDGEMENT

The authors thank Curtin University for the Curtin Malaysia Postgraduate Research Scholarship (CMPRS) awarded to the first author and the Faculty of Engineering and Science for supporting this study by providing facilities and tools. Jessica Ling Siew Kiong is thanked for her assistance in the laboratory. The authors also thank the anonymous reviewers for their constructive comments and suggestions, which helped improve the quality of this manuscript.

AUTHORS CONTRIBUTION

YNF (70%): fieldwork (strata logging, sampling, sample preparation), data analysis, writing original draft; DDW (25%): manuscript review and editing; MVP (5%): manuscript editing.

CONFLICT OF INTEREST

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

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Manuscript received 26 November 2025;
Received in revised form 6 January 2026;
Accepted 11 February 2026
Available online 30 April 2026