JOURNAL OF GEOSCIENCES INSIGHTS
Apr-Jun 2026, VOL. 4, ISSUE 2, pp. 27-34
https://doi.org/10.61577/jgi.2026.100008

ORIGINAL ARTICLE

Refining the Late Carboniferous - Permian Stratigraphy of the Kati Formation, Kinta Valley, Malaysia

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ABSTRACT

The present study supplies a wealth of new data to supplement earlier research and enhances understanding of the underrepresented Kati Formation. It comprises two members: the Tronoh Member, as the parent rock and lower succession and the Parit Member, as the replacement origin and upper succession. The Kati Formation, exhibiting segmented exposures and limited distribution in the lowland area of the Kinta Valley, is unconformably overlain by Quaternary Sediment, unconformably underlain by the Paleozoic metamorphic basement, and supported by Mesozoic Granite bodies with intrusive contact. The formation is attributed to two great catastrophic events. (i) A first event of ferruginous mineralization, mediated by bacterial iron mineralization, occurred at the end of the Permian. It resembles the Parit Member, comprising hematite- and magnetite-beds with *Thalassinoides*, which is defined as sedimentary-derived laterite, known in Asian countries as a source of building material for more than a thousand years. It comprises highly distinct, easily recognizable, and widespread hematite- and magnetite-beds with abundant *Thalassinoides* and is utilized as a marker bed for correlation in the upper Paleozoic sequences. Lithological similarities between the sedimentaryderived laterite and the Parit Member suggest that the Kati Formation correlates with the Sungai Patani Formation in northern Malaysia and with the Melaka Series in southern Malaysia. (ii) A second event of the region-wide unconformity between the Kati Formation and the overlying Quaternary Sediment is encountered in the Early Pleistocene or Pliocene, resulting in mass removal by erosion and a variety of physical diagenetic alterations. The Quaternary Sediment resting on the seafloor of the Kati Formation indicates that fluvial deposits are distributed across inland flood-prone areas associated with major river systems, particularly along the Perak River, and that beach deposits occur across the swashbackwash zone, rocky beach, and marine estuarine environments.

KEY WORDS

Kati Formation; Hematite; Magnetite; *Thalassinoides;* Laterites

ARTICLE HISTORY

Received 10 April 2026;
Accepted 14 May 2026;
Published 21 May 2026

Introduction

In Peninsular Malaysia, the stratigraphic classification and nomenclature for the Paleozoic successions comprise 42 formations, and some have been revised to establish new lithostratigraphic units [1-3]. The fine-clastic sequence with hematite-magnetite beds of the Kati Formation is one of the previously underrepresented Permian strata in northwest Malaysia, eg., [4]. Most geologists neglect to conduct research on the formation due to the preservation of the sequence's lithology.

The Carboniferous–Permian Singa Formation of Langkawi Island contains *Thalassinoides*, which is assigned to the Cruziana Ichnofacies of shallow-marine conditions [5]. Moreover, the Kubang Pasu Formation in Perlis hosts *Chondrites*, representing distal offshore settings below the fair-weather wave base but above the storm wave base [6]. Trace fossils, characterized by tube-like burrows and root casts, were discovered in the upper Carboniferous to middle Permian Kenny Hill Formation in the Rawang area [7,8]. Based on comparisons with previously described trace fossils, these assemblages have been interpreted to reflect deposition in a marine estuarine environment [9]. Therefore, trace fossil analysis has widely emerged in the 21st century as a powerful indicator of palaeoenvironmental evolution and associated alterations. It now stands as a pivotal element supporting sedimentological and stratigraphic interpretations, thus a key in sedimentary basin research [10]. The trace fossil analysis of the Kati Formation is also a powerful indicator of stratigraphic evidence, paleoenvironmental evolution, and associated alterations, including post-colonization diagenetic modification of trace fossil assemblages.

Furthermore, stratigraphic correlation is the process of determining which rock layers in different locations are of the same age, even when geographically separated. It essentially involves matching rock layers to create a continuous record of Earth's history across different areas. Even in the absence of macrofossil evidence, one of the most significant orthodoxies among Malaysian geologists in recent years has been the acceptance that the Late Carboniferous to Permian period was assigned to the Kati Formation. The successful stratigraphic correlation of Carboniferous-Permian successions elsewhere in Peninsular Malaysia has encouraged the development of alternative approaches and identified the unique characteristics of Upper Paleozoic sediments [10]. However, due to complex structural and thermal histories, coupled with the absence of accessible stratigraphic markers or even distinct marker beds, correlating Upper Paleozoic strata remains a challenging and often elusive endeavour.

Laterite, first described by Francis Buchanan-Hamilton in 1807 based on rock exposures along the western coast of India, has long been used as a building material across many Asian countries. The properties and definition of laterites, which introduced this term in geosciences, have been discussed [11]. The great interest of so many scientists with different viewpoints produced not only a substantial increase in knowledge but also considerable confusion in the basic understanding and interpretation of laterite formation [12]. The term laterite is restricted to highly weathered material: rich in secondary forms of iron, aluminum, or both; poor in humus; depleted of bases and combined silica; with or without nondiagnostic substances [13]. A modern definition of laterite encompasses all products of intensive tropical weathering, irrespective of their properties or parent rock composition, while excluding materials formed under weaker weathering conditions typical of more moderate climates [12]. In the study sedimentary-derived laterite is redefined using a new, approach based on lithology and trace fossil content, in contrast to other laterites, such as igneous (basalt/serpentine) -derived laterite.

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Tectonic Setting

It is widely accepted that Peninsular Malaysia comprises two continental blocks, the Gondwana-derived Sibumasu block to the west and the Indochina block to the east, which came together in the Late Triassic. The Sibumasu block was a microcontinent, rifted from the Australian Plate, part of Gondwana, in the Permian. It collided with the Indochina block to the east and the South China blocks to the north, almost simultaneously in the Middle Triassic [14-16]. The adjacent fragments often have vastly different fossil assemblages, such as the Late Paleozoic sediments on Sibumasu, which have coolweather flora and fauna and evidence of the Early Permian Gondwana glaciation [5,17,18]. In contrast, Indochina's Late Paleozoic climate was tropical [19-21]. Paleomagnetic data suggest a northward movement of Sibumasu, from high southern latitudes to the equator. Provenance studies using zircon geochronology are useful for Gondwana reconstructions and for dating the rifting and collision events among the various pieces [16]. The emplacement of the tinrich S-type granite plutons that coalesced into the main range granite batholith suggests that heat generated and partially melted the crust, forming magma driven by crustal thickening and decay of radioactive elements or slab break-off [15,16,22].

Known as the Bentong-Raub Suture Zone, it can be traced from the edge of the Sibumasu to the Inthanon Zone in Thailand, and similar zones are found between microcontinental fragments throughout Southeast Asia [15,16,20]. The Bentong-Raub Suture Zone separates the Western Belt of the Sibumasu from the Indochina/East Malay Block, which also includes the Sukothai Arc. Together, these three northwest–southeast-trending elongate terranes across Peninsular Malaysia (Figure 1(B)) are distinguished by contrasting geological, structural, and metamorphic characteristics, as well as styles of mineral emplacement, eg., [2,23]. The Kinta Valley is in the Western Belt of Peninsular Malaysia.

Objectives of the study

The formation forms low-relief landforms and isolated exposures, contrasting markedly with the surrounding metamorphic rocks and granite mountains, carbonate pinnacles, and Quaternary sediment hills. The parent rock of the Tronoh Member and the replacement origin of hematite- and magnetite-beds of the Parit Member have been classified [4]. Moreover, the Parit Member comprises diverse preservation styles of lithological features and ichnological characteristics, which are affected by the obliteration of three modes of diagenetic modification.

The primary objective is to synthesize newly recognized stratigraphical evidence of the Kati Formation. The following objectives are outlined: (i) to upgrade and redefine the stratigraphic contents, with emphasised on physiography, distribution, occurrence, ferruginous mineralization, lithological and ichnological features of the formation; (ii) to reconstruct the stratigraphic boundaries of the formation with the overlying and underlying sequences; (iii) to explore the paleoenvironmental evolution, serving as the seafloor to reconstruct the paleogeography of the Quaternary Period; (iv) to correlate the formation with its equivalent units in the region, utilizing a marker bed; and (v) to refine sedimentary-derived laterites.

To fulfill the objectives, an extensive field investigation was conducted from 2016 to 2019. Here, segmented distribution, limited exposures, and various styles of preservation influenced by postcolonization diagenesis at each location hindered the collection of the primary composition of rocks and the reconstruction of the position of sequences. However, precise and careful observation of postcolonization diagenetic effects was utilized in an individual outcrop. I collected stratigraphic evidence to refine the stratigraphic framework and investigate post-colonization diagenetic events in both trace fossils and substrates to understand the products of lithological character and to correlate stratigraphic units in the region, using a unique analog of sedimentary-derived laterites.

Methodology

The formation, investigated based on eleven exposures in the Kinta Valley, is shown in Figure 1. Combined, the exposures in the narrow strip area provide an almost discontinuous exposure of the formation. Data were collected through detailed bed-by-bed ichnological and sedimentological analyses across the limited and discontinuous exposures in the study area (Figures 1-2). Each trace fossil-bearing outcrop was systematically surveyed by recording ichnotaxa, bioturbation intensity, mode of preservation, cross-cutting patterns, and sedimentary features, as well as taphonomic indicators associated with diagenetic processes.

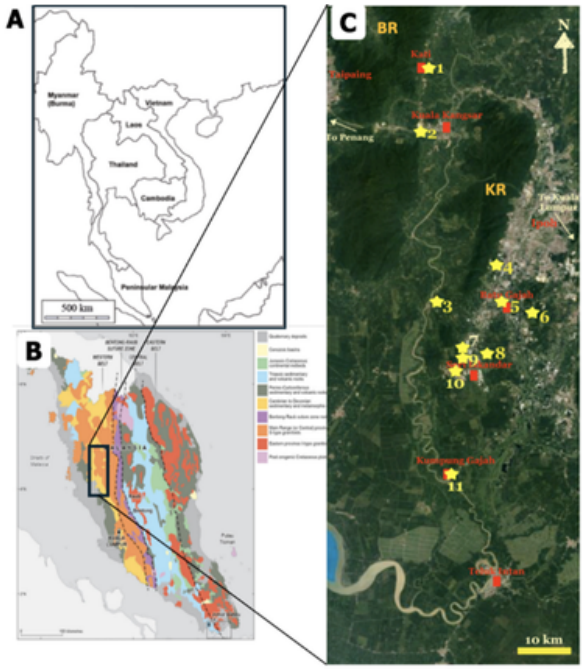

Figure 1. Maps illustrating the study area location: A. Location of Malaysia in Southeast Asia; B. Geological map of Malaysia, black box showing the location of Fig. 1C; C. Kinta Valley and Exposures of the Kati Formation in the present study area: 1. Kati village; 2. Kuala Kangsar Interchange; 3. Parit; 4. Lahat; 5. Batu Gajah; 6. Junction of highways A8 and A117; 7. Tronoh; 8. Highway Kampung Bali; 9. Universiti Teknologi PETRONAS (UTP); 10. East Seri Iskandar; 11. Kampung Gajah. (BR = Bintang Range; KR = Kledang Range).

Trace fossils strongly obliterated by diagenesis were carefully measured and photographed in situ. The diagenetic minerals and alterations were carefully examined in the field and laboratory. Selected specimens were collected for laboratory analysis to examine internal structures and finer features. Sedimentological analysis followed standard procedures and included descriptions of lithology, colour (using the Munsell colour chart), composition, grain size, bedding geometry, and sedimentary structures (e.g., erosional features, bed boundaries, and depositional/post-depositional structures). The presence of iron oxide minerals, with

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their strong pigmenting capabilities, was noted. These colours, suchas red, yellow, orange, brown, or even blue-green hues, provide valuable information, as they are linked to the mineralogical composition and the conditions under which iron oxides formed.

Stratigraphy of the Kati Formation

The stratigraphy of the formation, with emphasis on physiography, stratigraphic name and type sections, distribution, lithological features, ichnological characteristics, stratigraphic relationships, paleontology, depositional environment, diagenetic events, ferruginous mineralization, redefinition of laterite, and age and correlation, is summarized below.

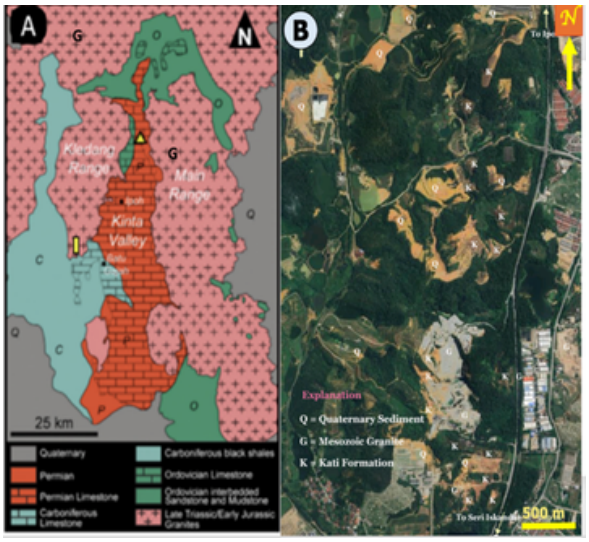

Figure 2. Geological maps of the Kati Formation and adjacent units: A. Geological map of the Kinta Valley, Fig. B is outlined in a yellow box, note: C = Kati Formation, P = Kinta Limestone, G = Mesozoic Granite, O = Ordovician Limestone, Q = Quaternary Sediment (adapted from [90]); B. Satellite image of the Lahat area (a yellow box in Fig. A), the southern edge of Kledang Range: K = Parit Member (reddish brown), Q = Quaternary Sediment (yellowish brown with dark green plantations), and G = Mesozoic Granite (dark grey) (yellow star showing in Fig. 7(A).

Physiography

The formation in the Kinta Valley belongs to the Western Belt of Peninsular Malaysia and forms part of the Sibumasu Block (Figure 1(B)). The valley is a lowland region in western Peninsular Malaysia, extending as a narrow north–south strip bounded by high mountain ranges (Figure 2). Due to a combination of geological factors (e.g., soft lithologies, human settlement, agriculture, and infrastructure development) and current weathered conditions (e.g., tropical rainfall and high temperatures), rapid weathering dominates the lowland area, resulting in limited and sporadic exposures (Figure 2). In the study area, it occurs in a narrow E-W and linear N-S belt, forming lowrelief landforms. Despite segmented exposures stretching from Kati village to the north and Kampung Gajah to the south, they remain isolated and disconnected (Figures 1-2).

Stratigraphic name and type section

The formation, located at Kati village, northern Perak (Figure 1(C)), renamed and descended from the "Kati Beds", as first proposed by, is an underrepresented upper Paleozoic stratigraphic sequence in the western belt of Peninsular Malaysia [24-26]. Two members were classified: (i) Tronoh Member: The type section is located at Tronoh village (location 7) (Figure 1(C)), and the member is referred to as the parent rock and lower succession. (ii) Parit Member: The type section is located at Parit village (location 3) (Figure 1(C)), and the member is referred to as the replacement origin of hematite and magnetite and the upper succession [4].

Lithological characteristics

The lithology of the formation, as stated by the previous authors, remained uncertain and controversial. It typically consists of arenaceous-argillaceous sediments interbedded with phyllite, metaquartzite, sandstone, shale, and siltstone, with the finer sediments laminated and grey in colour [25]. It is generally composed of a predominantly monotonous sequence of interbedded metamorphosed reddish-brown carbonaceous shale, mudstones, and sandstones, with minor siltstone "argillaceous and arenaceous rocks" [26,27]. The siltstone and shale beds are characteristically laminated or thinly banded and vary from gray to dark gray. The thickness of sandstone and siltstone beds ranges from 7 to 10 centimetres to 1 meter. Gray to light-gray shale beds are much thicker, approximately 30 cm in some places. Pinkish mottled and red-stained mudstone is observed [24].

Based on lithological characteristics, it comprises dark grey, bedded-to-massive shale intercalated with fine-grained sandstone named Tronoh Member (Figures 3, 4, 5(A), 7(C)), and hematite- and magnetite-beds formed through replacement-related ferruginous mineralization of parent lithologies as Parit Member (Figures 5(C-D), 6(A-B), 7(A-B, D)). The transition between the two members is marked by ferruginous replacement initially confined to bedding planes and subsequently extending to affect entire beds [4].

The Tronoh Member comprises variable centimetre-scale thickness of quartz veins, running in the N-S direction, quartz-filled en echelon tension gashes aligned with the N-S trend, and synsedimentary normal faults (Figure 3(A-C)), which reflect the smallscale normal faults without well-defined (discrete) fault planes or with cemented narrow zones are early (syn-sedimentary or syndiagenetic) tectonic faults and occur before complete consolidation (Figure 3A). Moreover, the red-stained nature of primary dark-grey shale is commonly visible (Figures 4, 7(A)).

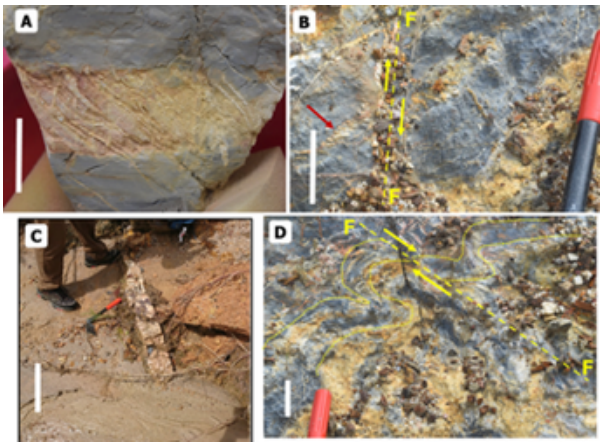

Figure 3. Lithological and Structural Features of the Tronoh Member: A. Sand-Filled Syn-Sedimentary Faults, preserved in lenticular finegrained sandstone intercalated with shale; B. Quartz-filled en-echelon tension gashes in shale, reflecting North-South trending (red arrow), indicating extensional stress orientation, likely associated with faulting (F = fault, yellow dashed line) with movement (arrows); C. North-South direction of quartz vein in shale (source of quart pebbles), interpreting post-depositional fluid

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infiltration along fractures; D. Fault-Related fold in shale, folding associated with fault movement (F = fault, yellow dashed line) with movement (arrows); bedding plane (dotted line); Location 7, stream section, north of Tronoh; Scale bars: 15 cm (A-B, D) and 50 cm (C).

The Phillips–Perron unit root results indicate that the variables are non-stationary in levels, which justifies the use of a dynamic time-series framework for further analysis. After confirming the order of integration, the study proceeds to estimate the ARDL model, which is appropriate for examining relationships among variables that are a mixture of I(0) and I(1) but not I(2). The estimated ARDL(4,1,1) specification shows that both the dependent variable and the educational variables exhibit meaningful dynamic effects over time. The current and lagged values of the Mean International Wealth Index remain highly significant, suggesting strong persistence in wealth formation in Arunachal Pradesh. Similarly, the current and lagged effects of children's educational attendance and adults' mean years of education indicate that the relationship between education and wealth operates through both immediate and delayed channels. The negative contemporaneous effect of children's attendance may reflect short-run household resource constraints associated with schooling costs, while the positive lagged effect suggests that educational investment pays off in the long run. Conversely, adult education seems to be the strongest positive correlate of wealth, suggesting that the accumulated human capital of adults is an important factor in generating current wealth.

Distribution

Segmented exposures and limited distribution of the formation occur in the lowland area of the Valley, which align with approximately E-W narrow strips and N-S trend shapes (Figure 1). They stretch from north to south, covering eleven exposures, including the Kati Village (North of Kuala Kangsar), Kuala Kangsar Interchange, Parit, Batu Gajah, Tronoh, UTP compound, Siri Iskandar, and Kampung Gajah (MRSM) of Pasir Salak of Teluk Intan (Figures 1-2). In addition, the major portion of the formation is capped by the Quaternary Sediment. The formation is intruded by the Mesozoic Granite. It is overlain by the Paleozoic metamorphic basement and juxtaposed against the highland carbonate pinnacle of the Kinta Limestone (Figures 2, 8). Because of the condition of composing soft parent rocks of the Tronoh Member Segmented exposures and limited distribution of the formation occur in the lowland area of the Valley, which align with approximately E-W narrow strips and N-S trend shapes (Figure 1). They stretch from north to south, covering eleven exposures, including the Kati Village (North of Kuala Kangsar), Kuala Kangsar Interchange, Parit, Batu Gajah, Tronoh, UTP compound, Siri Iskandar, and Kampung Gajah (MRSM) of Pasir Salak of Teluk Intan (Figures 1-2). In addition, the major portion of the formation is capped by the Quaternary Sediment. The formation is intruded by the Mesozoic Granite. It is overlain by the Paleozoic metamorphic basement and juxtaposed against the highland carbonate pinnacle of the Kinta Limestone (Figures 2, 8). Because of the condition of composing soft parent rocks of the Tronoh Member

Stratigraphic relationship

Although the formation can be traced along strike northward between the granites of the Bintang and Kledang ranges, no contact with younger sediments or calcareous rocks has been observed apart from Quaternary alluvium [2,26-28]. Moreover, because there is no evidence of an unconformity between the Kati Formation and Salak Baharu Beds, the formation is interpreted as a lateral facies hange in the Salak Baharu Beds [24,26]. Due to complex structural styles and thermal events, limited accessibility and the c discontinuity of stratigraphic units, the stratigraphic boundaries of the major Paleozoic successions in the Western Belt of Peninsular Malaysia remain controversial, eg., [29].

Based on the field observations, four rock formations have been well investigated in the area: (i) Paleozoic metamorphic rock, (ii) Kati Formation, (iii) Mesozoic Granite, and (iv) Quaternary Sediment, in which the Kati Formation is mainly emphasized. The characteristics of the stratigraphic boundaries among those successions are examined below:

Stratigraphic boundary with the underlying Palaeozoic metamorphic rock

The boundary is well exposed in the Batu Gajah area of Location 5 (Figures 1, 4, 8). The basement unit of the Paleozoic metamorphic rock comprises predominantly dark grey to black phyllite and reddish-brown to dark grey schist, ranging in age from Devonian to Silurian [25-27,30].

The vertically erected, thin-bedded red shale interbedded with white sandy siltstone to clayey material of the Tronoh Member, with the dropstone showing an exotic clast, overlies the Paleozoic Metamorphic rock (Figure 4(C-D)). This boundary resembles the structural contact between them. Furthermore, the massive hematite bed of the Parit Member overlies the Paleozoic Metamorphic rock (Figure 4(A-C)), which represents a stratigraphic boundary between them. The nature of the contacts of the normal and strike-slip faults is present [4]. Based on observations at both boundaries, the seafloor of the Kati Formation is inferred to originate from Paleozoic metamorphic rock; however, the structural boundary remains poorly constrained.

Stratigraphic boundary with the Palaeozoic sequences

The present study reveals that the juxtaposition between the two successions remains uncertain due to a limited exposure (Figure 5). Based on a gravity anomaly map of the formations of the Kinta Valley, the Kati Formation lies on the Kinta Limestone [31]. No exposure of the contact between them has been found.

Stratigraphic boundary with the intruded Mesozoic granite

Triassic-aged tin-tungsten granite (Mesozoic granite) intrudes into the Tronoh Member without a baking effect (Figure 5). Near the granite intrusion, these rocks show metamorphosed hornfelses [26,27]. An intrusion contact between the Mesozoic Granite and the Kati Formation, exposed in some locations (Location 5, Lahat, and Location 7, Tronoh (Figures 1-2), is noted. A fault contact between the Kati Formation and the granite has occurred along Sungai Dal, in Kampong Buaya [26].

Stratigraphic boundary with the overlying Quaternary sediment

The Quaternary Sediment consists predominantly of the unconsolidated, yellowish-brown sandy siltstone [32]. It forms highrelief morphology and overlies the Tronoh Member and the Parit Member. It corresponds to the Simpang Formation to the north, which forms high-relief mountains, and the Younger Alluvium, equivalent to the Beruas Formation to the south, which serves as a lowland alluvial plain [33]. Its age ranges from the Early to Middle Pleistocene and the Late Pliocene to Early Pleistocene [7,34-36]. The Quaternary deposits contain ash layers, basaltic lava flows, and residual sediments (bauxite and laterites) [37,38].

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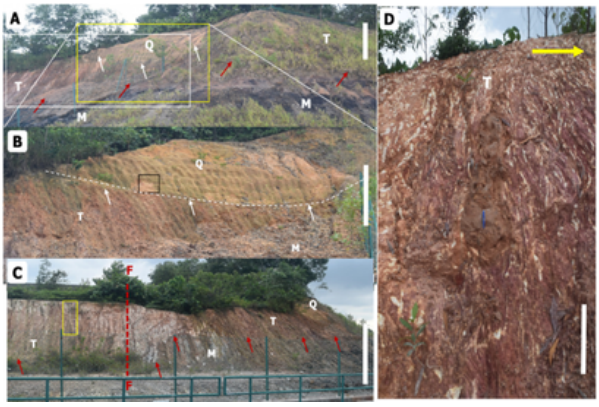

Figure 4. Tronoh Member (T) exposing along roadside, in relationship with the underlying Paleozoic Metamorphic rock (M) and the overlying Quaternary Sediment (Q): A. Unconformity (red arrows) between the Tronoh Member (T) and the Paleozoic Metamorphic rock (M), and Unconformity (white arrows) between the Quaternary Sediment (Q) and the Tronoh Member (T), yellow box is marked with Fig. B, and white box is marked with Fig. C; B. Concave-based shape unconformity (dashed line, white arrows) between the Quaternary Sediment, comprising quartz-pebble basal lag with siltstone (Q) and the Tronoh Member (T) resting on Paleozoic Metamorphic rock (M) (note: Parit member are missing), a black box is marked with Fig. 5B; C. Unconformity (red arrows) and faulted contact (F = fault, red dashed line) between the Tronoh Member (T) and the Paleozoic Metamorphic rock (M), a yellow box is marked with Fig. D; D. Dropstone in the Tronoh Member (T), including exotic clasts, such as reddish-brown phyllite pebbles derived from the Paleozoic Metamorphic rocks (blue pen), interlayered with vertically erected, wavy-bedded red-stained shale. Axis dimensions of the pebble are c > b ≈ a, with yellow arrows indicating way-up structures; Location 5, near Chinese cemetery, Batu Gajah; Scale bars: 3 m (A-C), 0.5 m (D).

Based on the lithological characteristics and sedimentological geometric patterns of the formations, the eight patterns of unconformable boundaries between the Quaternary Sediment and the Kati Formation are examined. They are (1) Concave-based boundary between the Tronoh Member and Siltstone with quartz pebble basal lag of the Quaternary Sediment, (2) Flat-based boundary between the Tronoh Member and Shale with conglomerate band of the Quaternary Sediment, (3) Concave-based boundary between the Parit Member and Siltstone of the Quaternary Sediment, (4) Flatbased boundary between the Parit Member and Siltstone with a conglomerate band comprising *Thalassinoides* hematite pebbles of the Quaternary Sediment, (5) Flat-based boundary between the Parit Member with *Thalassinoides* and Siltstone of the Quaternary Sediment, (6) Flat-based boundary between the Tronoh Member and Siltstone of the Quaternary Sediment, (7) Flat-based boundary between the Parit Member and Siltstone of the Quaternary Sediment, and (8) Flat-based boundary between the Tronoh Member and Siltstone with hematite and magnetite cobbles to boulders of the Quaternary Sediment.

Concave-based boundary between the Tronoh Member and Siltstone with quartz pebble basal lag of the Quaternary Sediment

This is exposed near Chinese Cemetery, Batu Gujar at Location 5 (Figures 1(C), 4(A-C)). The Quaternary Sediment consists of wellrounded, moderately sorted quartz pebbles embedded in unconsolidated, yellowish-brown sandy siltstone to shale. It appears as a basal lag of intraformational, monolithic, grain-supported conglomerate (Figure 5(B)). Faint giant crossbedding and indistinct graded bedding are visible. Quartz pebbles are assumed to be derived from the quartz veins of the Tronoh Member (Figure 3(C)). The underlying Tronoh Member consists of massive shale with red stainare stable over the sample period and that the model specification is structurally sound. Taken together, these diagnostic findings support the adequacy of the ARDL framework for analyzing the relationship between children's educational attendance, adults' mean years of education, and household wealth in Arunachal Pradesh.

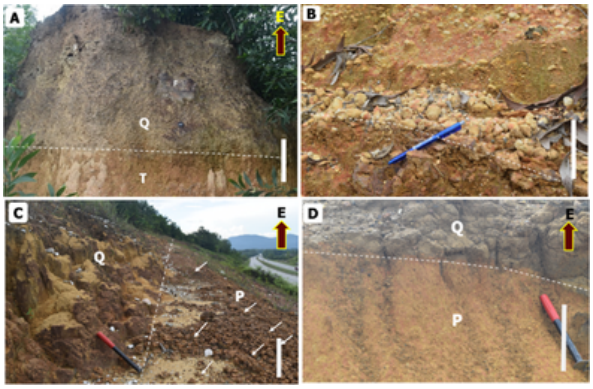

Figure 5. Various patterns of unconformable boundaries (dashed lines) between Kati Formation and Quaternary Sediment (Q): A. Flatbased shape boundary between the shale matrix-supported conglomerate containing magnetite fragments (F) of Quaternary Sediment (Q) resting on massive, red-stained shale of Tronoh Member (T), Location 5, near Bur-Interchange, Batu Gajah; B. Closeup view of concave-based shape boundary of monolithic basal conglomerate lag, comprising well-rounded and moderately sorted quartz pebbles, cemented by yellow siltstone of Quaternary Sediment (see Fig. 4B), Location 5, near Chinese cemetery, Batu Gajah; C. Flatbased shape boundary of Quaternary Sediment (Q) lying on Parit Formation (P), Note: small-sized eroded fragments of *Thalassinoides* substrate preserving on unconformity plane (white arrows), Location 6, junction of highways A8 and A117; D. Flat-based shape boundary Quaternary Sediment (or dump Soil?) (Q) lying on Parit Formation (P), note: *Thalassinoides* substrate indicating red specks and secondary infill indicating yellow brown colour, obliterated by the mid-stage diagenesis and late-stage diagenesis, and sandy siltstone of Quaternary Sediment stained by greenish brown colour by recent weathering processes of the late-stage of diagenetic modification, Location 7, near Tronoh; Scale bars: 1 m (A), 15 cm (B) and 50 cm (CD).

The concave-based boundary suggests a channel-filled river deposit. It resembles the paleo-river channels and NE-to-SW direction of the Perak River in the Quaternary period (Figures 1, 4(A-C)). Similarly, complex, unconsolidated sands and gravels, together with silt and clay, overlie the bedrock and were interpreted as lenticular, discontinuous beds of fluvial origin [39]. Conglomerates deposited in fluvial environments are typically well-rounded and poorly sorted. Clasts of this size are carried as bedload and only at times of high flow rate, so conglomerates are more characteristic of river systems. In the sediments deposited by mature rivers, conglomerates are generally confined to the basal part of a channel fill, where they are known as pebble lags (Figures 4(A-C), 5(B)) [40]. It is assumed that the paleogeomorphological character resembles the paleo-river channels of the Perak River in the fluvial environment. It is estimated that the Parit Member and the upper portion of the Tronoh Member were missing because a reason is that mass removal by erosion occurred during the Quaternary transgressive time.

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Flat-based boundary between the Tronoh Member and Shale with a conglomerate band of the Quaternary Sediment

This exposure is observed near the bus interchange of Batu Gujar at Location 5 (Figure 1(C)). The Quaternary Sediment consists of matrixsupported conglomerate containing poorly rounded and poorly sorted magnetite fragments embedded in unconsolidated, darkbrown shale

poorly sorted magnetite fragments embedded in unconsolidated, darkbrown shale The Tronoh Member consists of red-stained, friable massive shale. The Parit Member has disappeared. A sharp- and flat-based boundary between them is observed (Figure 5(A)).

The bulk of conglomerates deposited in this setting are matrixsupported conglomerates because of debris-flow deposition and are quite commonly associated with many alluvial fans [41]. This could be interpreted as debris flow sediments deposited on alluvial fans owing to poorly defined internal bedding [42,43]. Therefore, the magnetite fragments have been derived from the upper Parit Member. A sharpand flat-based boundary suggests a channel-filled river deposit in the form of debris flow of fluvial sedimentation. It resembles the paleoriver channels of the Perak River in the Quaternary period.

Concave-based boundary between the Parit Member and Siltstone of the Quaternary Sediment

This is exposed at JLN V5, the gate of Road Teknologi V5 at UTP Location 9 (Figure 1(C)). The Parit Member comprises hematite- and magnetite-beds, and the Quaternary Sediment consists of unconsolidated, homogeneous, yellowish-brown sandy siltstone. It is assumed that a broad, concave-based, and sharp unconformable boundary between them reflects a possible river mouth near the shoreline as a marine estuarine environment (Figures 1, 6(A))

Flat-based boundary between the Parit Member and Siltstone with a conglomerate band comprising *Thalassinoides* hematite pebbles of the Quaternary Sediment

This is exposed at the south gate of the UTP of location 9 (Figure 1(C)). The Quaternary Sediment consists of unconsolidated, yellowish-brown sandy siltstone at the upper and a hard, 30- to 50-centimetre-thick conglomerate band comprising weathered fragments/clasts of *Thalassinoides* substrate and magnetite pebbles at the lower (Figure 6(B-D)). The conglomerate band contains monolithic clasts of *Thalassinoides* hematite and magnetite, tightly to closed-packed, sometimes preserving diffuse, vague boundaries of clasts, cemented by yellowish-brown sandy siltstone (Figure 6(D)). An intraformational conglomerate that was penecontemporaneously derived through erosion, transportation, and deposition of material from within the depositional basin itself is interpreted. The basal conglomerate band is assumed to have been deposited during the swash zone of marine transgression (Figure 6(B)). The swash zone forms the land-ocean boundary at the landward edge of the surf zone, where waves run up the beach face [44,45]. It reflects the shoreline position at a particular time and is diachronous [46]. Moreover, the source rock was derived from the underlying Parit Member and was deposited at the shoreline of the Parit Member swash zone in the Quaternary Sea (Figure 6(B-D)).

In the Parit Member, the NE-trending hematite and magnetite beds with abundant Thalassinoides are interpreted as the seafloor of the Quaternary coastline (Figure 6(B-C)). Based on the recent weathering grade of the late-stage diagenesis, two divisional zones

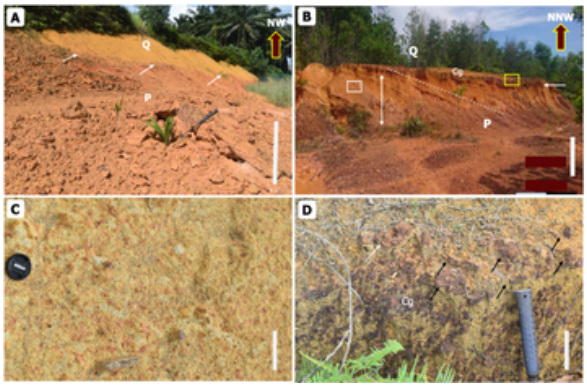

Figure 6. Various patterns of unconformable boundaries between Parit Member (P) and Quaternary Sediment (Q): A. Concave-based boundary (arrows) between Parit Member (P) and Quaternary Sediment (Q), Location 9, near gate, Road Teknologi V5, south gate of UTP; B. Indurated, intraformational monolithic basal conglomerate band (Cg) comprising *Thalassinoides*-bearing hematite and magnetite pebbles derived from the underlying Parit Member, contrasting between Parit Member (P) and Quaternary Sediment (Q) (white arrow), a white colour box is marked with Fig. C, and a yellow colour box is marked with Fig. D, Parit Member showing a highly weathered portion (white double arrow) and NE direction of faint bedding plane (white dashed line), corresponding to lateritic soil at the upper (see Figure. C) and unweathered zone at the lower. C. Close-up view of a highly weathered portion of Parit Member comprising red spots of *Thalassinoides* substrate and clayey silty as secondary infill derived from the Quaternary Sediment, resembling lateritic soil (see white box in Figure. B); D. Close-up view of intraformational, monolithic grainsupported conglomerate band (see Figure. B), containing erosional fragments and pebble-sized grains of hematite substrate (black arrows) and hematite substrate with *Thalassinoides* (white arrow) derived from the Parit Member and embedded in sandy siltstone of Quaternary Sediment (Q). Location 9, near roundabout, Road Teknologi 1, south gate of UTP; Scale bars: 1 m (A–B), 10 cm (C), 30 cm (D).

in the outcrop are observed (Figure 6(C)), named the unweathered zone at the lower and the weathered zone at the upper [4].

Unweathered zone

The primary rocks of the unweathered zone are hard, uneroded surfaces of hematite and magnetite beds with abundant *Thalassinoides* of the Parit Member, in which the *Thalassinoides* infill was already obliterated by the mid-stage of diagenetic modification (Figure 6(B)), eg., [4]. The bed is interpreted as a source of *Thalassinoides*-bearing hematite and magnetite clasts of the conglomerate band, and it is interpreted as an unconformity of the underlying Parit Member (Figure 6(B-D)).

Weathered zone

Due to recent to subrecent weathering and late-stage diagenesis, the upper part of the hematite bed with *Thalassinoides* of the Parit Member is altered to a red to brownish-red colour, highly eroded, and consists of soft, silty clay with iron specks, where faint bedding planes are encountered (Figure 6(B-C)). The silty clay is known as lateritic soil.

Flat-based boundary between the Parit Member with *Thalassinoides* and Siltstone of the Quaternary Sediment

These exposures are distributed to the west of Lahat, on the car road between Ipoh and Seri Iskandar, Location 4, and near the junction of

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highways A8 and A117, Location 6, and near Tronoh, Location 7 (Figure 1(C)). The unconsolidated, yellowish-brown sandy siltstone of the Quaternary Sediment and hematite- and magnetite-beds with abundant *Thalassinoides* of the Parit Member reflect a flat-based sharp contact (Figures 5(C-D), 7(A)). The extensive erosion of *Thalassinoides* on the unconformable plane occurred during the midstage diagenesis [4]. It is assumed to have been deposited at a sandy beach.

Flat-based boundary between the Tronoh Member and Siltstone of the Quaternary Sediment

These exposures are distributed in the east of Siri Iskandar at Location 10 and near the roundabout, Road Teknologi 1, south gate of UTP, Location 9 (Figure 1(C)). The unconsolidated, yellowish-brown sandy siltstone of the Quaternary Sediment and the red-stained, massive shale of the Tronoh Member have a flat-based sharp boundary (Figure 7(C)).

The erosion of the Parit Member reflects high-energy destructive waves within the swash-backwash zone of the Quaternary Sea, where wave energy peaked during extreme storm events [4]. Coastal erosion in the Parit Member is more extensive than deposition. Erosion in the coastal zone is a primary function of destructive waves. The very high energy of the powerful stormy conditions leads to destructive waves,

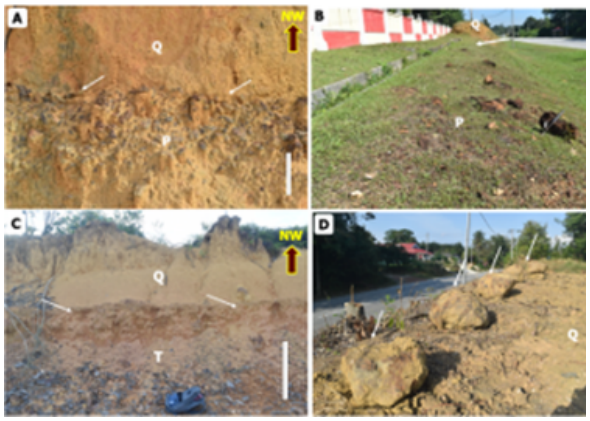

Figure 7. Flat-based shape of unconformable boundary between Kati Formation and Quaternary Sediment (Q): A. Unconformity (arrow) of the Quaternary Sediment (Q) resting on Parit Member with *Thalassinoides* (P), Location 6, near Lahat; B. Unconformity (arrow) of Quaternary Sediment (Q) lying on Parit Member (P), Location 11, Kampung Gajah; C. Unconformity (arrows) of Quaternary Sediment (Q) lying on red-stained shale of Tronoh Member (T), Location 10, near Seri Iskandar; D. Unconformity of Quaternary Sediment (Q) accompanying with hematite and magnetite cobbles derived from Parit Member (arrows) lying on the Tronoh Member, Location 8, near Kampung Bali; Scale bars: 1 m (A–B), 50 cm (C-D).

The erosion of the Parit Member reflects high-energy destructive waves within the swash-backwash zone of the Quaternary Sea, where wave energy peaked during extreme storm events [4]. Coastal erosion in the Parit Member is more extensive than deposition. Erosion in the coastal zone is a primary function of destructive waves. The very high energy of the powerful stormy conditions leads to destructive waves.

Flat-based boundary between the Tronoh Member and Siltstone of the Quaternary Sediment

This exposure is found at Kampung Gajah, Location 11 (Figure 1(C)). It is the southern end exposure of the study area. The Quaternary Sediment consists of unconsolidated, yellowish-brown sandy siltstone, and the Parit Member comprises the hematite and magnetite beds. A sharp- and flat-based boundary between them is observed (Figure 7(B)). It is assumed that the Quaternary sediment was deposited under constructive waves. This circumstance indicates the creation of beaches on the seafloor of the Parit Formation. Its depositional environment is the same as the Flat-based boundary of the Tronoh Member (Figure 8).

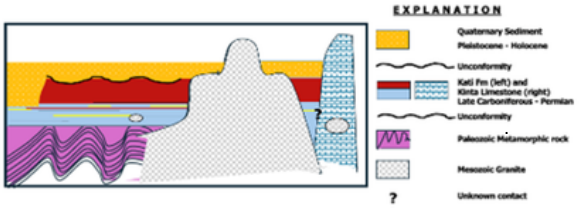

Figure 8. Schematic diagram of the reconstruction of stratigraphic distribution and boundaries of Kati Formation, adjacent to the underlying and overlying stratigraphic successions in the Kinta Valley (Not to scale).

Flat-based boundary between the Tronoh Member and Siltstone with hematite and magnetite cobbles to boulders of the Quaternary Sediment

This exposure is found in Gerai Mak Miah, Highway Kampung Bali, at Location 8 (Figure 1(C)). The number of subrounded shapes and smooth surfaces of magnetite cobbles (a few are boulder-sized), well embedded in the unconsolidated, yellowish-brown sandy siltstone of the Quaternary Sediment (Figure 7(D)), which is lying on the massive shale of the Tronoh Member. The source rock is derived from the Parit Member. The member forms the hilly areas of high concentration of hematite and magnetite beds, which are exposed along the seacoast during the initial stage of the first transgressive phase of the Quaternary Sea. Those concentrated hilly areas are a source of magnetite boulders.

Therefore, it is concluded that those magnetic cobbles are eroded, transported, and laid down along the rocky beach of the Tronoh Member of the Kati Formation seafloor of the Quaternary Sea. Moreover, those processes are accompanied by major physical postdepositional events, which are referred to as the mid-stage of diagenetic modification by [4]. Therefore, it is interpreted as the Kati Formation, which is preserved as a gravel beach along the Quaternary Sea. The large clasts comprising the gravel beach are interpreted to have been derived directly from erosion of the underlying bedrock and transported to the beach by slope processes such as rockfall. It can therefore be interpreted that the mechanism of forming beach boulders is the gravity collapse of cliffs by toppling or numerous forms of landsliding, which is a common phenomenon on rocky shorelines, where it causes boulder deposition or re-deposition [48- 50].

A brief geological evolution of the Kati Formation serving as the seafloor of both fluvial and marine environments in the Quaternary transgressive sea

Two modes of unconformable boundaries are present: concave-based boundary (Figs. 4(A-B), 5(B), 6(A)) and flat-based boundary (Figures 5(A, C-D), 6(B), 7(A-C)). Three types of rock of the Kati Formation are observable: bedded to massive shale of the

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Tronoh Member (Figures 5(A), 7(C)), hematite- and magnetite-beds with *Thalassinoides* and an occurrence of intensively weathered, defined lateritic soil of the Parit Member (Figures 4(B), 5(C-D), 6(B)), and magnetite- and magnetite-beds of the Parit Member (Figures 6(A), 7(B)). Five types of rocks in the Quaternary sediment resting on the Kat Formation have been observed: quartz pebble lag with shale matrix (Figure 5(B)), magnetite fragments basal lag with shale matrix (Figure 5(A)), *Thalassinoides* clasts bearing a conglomerate band with sandy siltstone matrix (Figure 6(B, D)), Hematite and magnetite gravels cemented with sandy siltstone (Figure 7(D)), and unconsolidated sandy siltstone (Figures 5(C-D), 6(A), 7(A-D)).

Two modes of unconformable boundaries are present: concave-based boundary (Figs. 4(A-B), 5(B), 6(A)) and flat-based boundary (Figures 5(A, C-D), 6(B), 7(A-C)). Three types of rock of the Kati Formation are observable: bedded to massive shale of the Tronoh Member (Figures 5(A), 7(C)), hematite- and magnetite-beds with *Thalassinoides* and an occurrence of intensively weathered, defined lateritic soil of the Parit Member (Figures 4(B), 5(C-D), 6(B)), and magnetite- and magnetite-beds of the Parit Member (Figures 6(A), 7(B)). Five types of rocks in the Quaternary sediment resting on the Kat Formation have been observed: quartz pebble lag with shale matrix (Figure 5(B)), magnetite fragments basal lag with shale matrix (Figure 5(A)), *Thalassinoides* clasts bearing a conglomerate band with sandy siltstone matrix (Figure 6(B, D)), Hematite and magnetite gravels cemented with sandy siltstone (Figure 7(D)), and unconsolidated sandy siltstone (Figures 5(C-D), 6(A), 7(A-D)).

A brief reconstruction of the summary of the history of the sedimentological evolution and paleogeography of the Quaternary Sea reflects that both members performed as seafloor during the deposition of the Quaternary Sediments at the initial stage of the transgressive phase. The Parit Member performs as a major seafloor in most of the area. The Tronoh Member is also preserved as seafloor because the Parit Member has occasionally disappeared due to erosion by destructive wave energy in the swash-backwash zone along the beach (Figure 7(C)). In addition, the Tronoh Member characterizes the seafloor of a deeply eroded fluvial channel (Figure 5(A)).

The depositional environments of the Quaternary sediments are: (i) beach area (swash-backwash zone) and estuaries of the marine system, and (ii) fluvial river system (Figures 4(A-C), 5, 6, 7). The fluvial environment is distributed across inland flood-prone areas associated with major river systems, particularly along the Perak River. They are exposed in the northern region, especially around the Batu Gajah area (Figures 1, 4(A-C), 5(A-B)). The swash-backwash zone is the beach area; sediment distribution is dependent on the interaction of swash deposition, swash erosion, backwash deposition, and backwash erosion, encompassing the estuaries of the Perak River (Figures 5(C-D), 6(A-B, 7)), with notable exposures in the southern region, especially around Lahat, Tronoh, Universiti Teknologi (UTP), east Seri Iskandar and Kampung Gajah [47]. Additionally, the hilly areas and cliffs of hematite- and magnetite-beds have been encountered, alongside carbonate and granitic hills that rise above sea level and face the coastline, with notable exposures in Tronoh and UTP's compound.

Based on sequence-stratigraphical orientation, shoreline, and the alluvial and coastal-plain deposits at the base, and a thick succession of Quaternary Sediments (approximately 50 m thick) at the top, suggest an enlarging shelf area, upward deepening, and the coastline s on the West coast of the Peninsula Malaysia [51].

The coastal plains in the peninsula, which are widest at the mouth of the Perak River, where they are about 45 kilometres wide, were documented [52]. The width of coastal plains on the West Coast ranges from 20 km to 30 km [53]. The present study reveals that the west coastline is about 30 kilometres from the Quaternary coastline, located at the UTP (Location 9) (Figure 6(A-B)). In addition, the current coastline near Pulau Upe ghost mine in Melaka comprises hematite- and magnetitebeds with *Thalassinoides* of the equivalent succession of the Kati Formation, which is an analogue to the Quaternary coastline in the study area. "Stage 2" is the period when sea levels and precipitation began to rise, first initiating slumping of disintegrated mineralized regolith downslope to form piedmont fans (Boulder Beds), later reworked by increasingly active braided fluvial processes, which facilitated aggrading alluvial plains (Old Alluvium or Simpang Formation) [36].

In conclusion, the second great event of the region-wide unconformity between the Kati Formation and the overlying Quaternary Sediment is encountered in the Early Pleistocene or Pliocene, resulting in mass removal by erosion and a variety of physical diagenetic alterations. In this event, the Kati Formation, serving as the seafloor of a fluvial river system and a marine environment, resulted in the coastline swash-backwash zone with estuaries of the Perak River in the Quaternary period.

Geological structure

The broad folding in the formation is noted; however, the exact location was unknown [26]. The bedded nature of some outcrops, especially Tronoh of Location 7 and UTP of Location 9, shows their direction in NE and NW with low to moderate dip amount (Figure 6(B)), and exhibit their direction in N with low dip amount are encountered (Figure 3). Thin-bedded red-stained shale intercalated with fine-grained sandstone, embedded with phyllite boulders derived from the underlying Paleozoic Metamorphic rock, is exposed vertically (Figure 4(D)). It is rather challenging to reconstruct the geological structure of the formation because it has dissected and isolated outcrops, covering thick Quaternary Sediment and undergoing three stages of diagenetic events, eg., [4].

Diagenetic events (Post-depositional changes)

Three stages of diagenesis, in which the primary lithological feature and ichnological preservation change to diverse styles of diagenetic preservation:

(i) Early-stage diagenesis: The alteration indicates a first great event of ferruginous mineralization in the end-Permian, mediated by bacterial iron mineralization after colonization and before infill of *Thalassinoides* (Figures 5(C-D), 6(A-C), 7(A-B, D), 9, 10).

(ii) Mid-stage diagenesis: The features reflect a second great event of the region-wide unconformity between the Kati Formation and the overlying Quaternary Sediment in the Early Pleistocene or Pliocene (Figures 4(A-B), 5, 6(A-B), 7(A-C, 10(A)), along with the Quaternary coastline migration and seafloor positioning.

(iii) Late-stage diagenesis: the features mark the recent to subrecent weathering processes (Figures 5(C-D), 6(B-C), 9(C), 10(C)).

Paleoichnological significance and possible depositional environment

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The Tronoh Member comprises *Chondrites, Planolites,* and root traces, and the Parit Member contains *Thalassinoides* and root traces. Due to widespread ferruginous mineralization, a paucity of concrete information for deciding on the depositional environment has been noted. The ichnogenus *Chondrites* is the only reliable and representative trace fossil to interpret the depositional environment. Although several key environmental characteristics distinguish depositional environments for *Chondrites*, it is primarily a marine, facies-crossing trace fossil that can occur from shallow-shelf to deep-marine pelagic and hemipelagic deposits. Its widest, globally widespread distribution is in deep-sea settings, such as bathyal to abyssal marine basins, submarine fans, and abyssal plains.

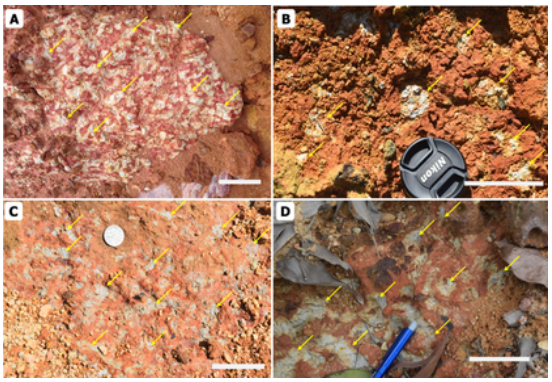

Figure 7. Flat-based shape of unconformable boundary between Kati Formation and Quaternary Sediment (Q): A. Unconformity (arrow) of the Quaternary Sediment (Q) resting on Parit Member with *Thalassinoides* (P), Location 6, near Lahat; B. Unconformity (arrow) of Quaternary Sediment (Q) lying on Parit Member (P), Location 11, Kampung Gajah; C. Unconformity (arrows) of Quaternary Sediment (Q) lying on red-stained shale of Tronoh Member (T), Location 10, near Seri Iskandar; D. Unconformity of Quaternary Sediment (Q) accompanying with hematite and magnetite cobbles derived from Parit Member (arrows) lying on the Tronoh Member, Location 8, near Kampung Bali; Scale bars: 1 m (A–B), 50 cm (C-D).

A few researchers and numerous Malaysian geologists widely accept that the clastic sequence of the Kati Formation and the rocks at Seri Iskandar are all consistent with a deep-marine slope environment [24,26,27]. Nevertheless, the heterolithic succession of the Tronoh Member, consisting predominantly of bedded to massive shale and the replacement origin of the Parit Member, is analogous to the turbidite lithological suite. The trace fossils - Chondrites, Planolites, Thalassinoides, and root traces - presumably representing the characteristics of the Zoophycos Ichnofacies, were recorded; they were considered to correspond to the deep-marine environment, such as pelagite/hemipelagite deposits, eg., [54].

In addition, the deep-marine environment is a complex setting in which numerous processes - settling of pelagic and hemipelagic particles in the water column, sediment gravity flows (downslope density currents; turbid flows), and bottom currents - determine sediment deposition; hence, a variety of facies, including pelagites/hemipelagites, contourites, turbidites, and hyperpycnites [54]. However, the deep sea is the largest ecosystem on Earth, yet it is still one of the least understood. Ichnological information is now included in many studies as a criterion to discern pelagites/hemipelagites, contourites, turbidites, and hyperpycnites, eg., [54-59].

Moreover, it is strongly constrained and challenging to conclude the depositional environment of the Kati Formation. However, the depositional environment of the Kati Formation. However, Carboniferous-Permian successions in the Sibumasu block of the Gondwana Supercontinent have recorded a wide range of depositional environments. Massive limestones indicated extensive carbonate platforms, thick-bedded cherts reflected deep-marine settings, coal, bauxite, and clastic deposits pointed to continental settings, and pebbly mudstones interpreted as glacial deposits have been documented [60]. Collectively, these lithologies represent

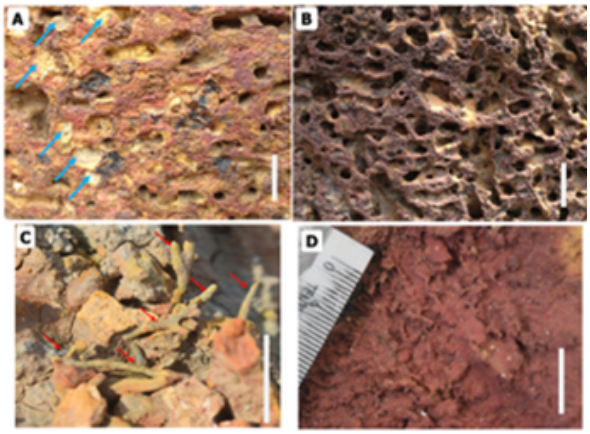

Figure 10. *Thalassinoides* and root traces: A-B. Close-up views of *Thalassinoides* in hematite and magnetite beds, replaced during early-stage diagenesis, showing void infill (open cavities or invisible infill), but secondary infill made of yellowish-brown siltstone derived from the overlying Quaternary sediment (blue arrows), preserved in an erosional surface perpendicular to bedding, Location 4, Lahat (Figure A), and building stone with open cavities (void infill), the Middelburg Bastion, Melaka, Malaysia (Figure B); C-D. Close-up view of root traces: eroded fragments of tertiary lateral roots, altered to limonite and goethite, exposed on dark grey shale of unaltered substrate, Tronoh Member, replaced during the late-stage diagenesis (Figure C), and both eroded fragments of tertiary lateral roots and country rock (substrate) replaced by hematite and magnetite, replaced during the early-stage diagenesis, Parit Member, preserved on bedding plane (Fig. D); Location 7, near Tronoh; Scale bars: 1 cm.

both shelfal and continental facies. In contrast, siliceous deep-marine sediments - such as cherts that commonly lack macrofossils - remain poorly studied. These deposits are frequently associated with serpentinite, mafic, and ultramafic bodies and are generally interpreted as deepsea in origin. Consequently, it is noted that the depositional and paleoecological environment in relation to a great event, such as ferruginous mineralization of the Kati Formation, is a

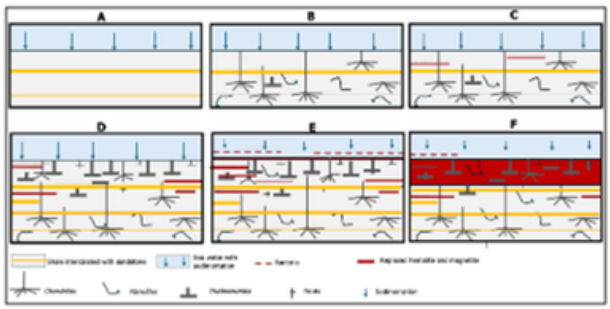

Figure 11. Schematic model illustrating the reconstruction of the assemblages of the trace fossils, showing sedimentation processes in a deep-marine environment, associated paleoichnological assemblages, and the early-stage diagenesis (ferruginous mineralization occurring after colonization but before infill) within the Kati Formation during deposition (stages A to F, not to scale).

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unique depositional site and is also quite different from the various depositional settings of the Sibumasu block of the Gondwana

The present investigation provided insufficient information to interpret the depositional setting due to limited exposure and ferruginous mineralization of the primary Tronoh Member. The conclusion of the depositional setting remains controversial. Therefore, further research activities are required in the Sibumasu block. Nonetheless, the paleoenvironment of the trace fossil assemblages and related Ichnofacies is summarized (Figure 11).

Ferruginous mineralization

Iron formations are economically important sedimentary rocks that are most common in Precambrian sedimentary successions. In the valley, iron formation not only accounts for a substantial share of the global iron supply but also offers critical insights into ecosystem evolution, mediation of bacterial iron mineralization, and microbial activity during the Permian period. Although many aspects of their origin remain unresolved, it is widely accepted that secular changes in the style of their deposition are linked to environmental and geochemical evolution of Earth [61].

Based on replacement-related ferruginous mineralization, two groups of ferruginous minerals are recognized, corresponding to two stages of diagenetic events dominated by chemical alteration [4]. Those are: (i) hematite and magnetite replacement, found in the Parit Member, which replaced *Thalassinoides* (after colonization but before occupation of primary infill) and roots, and initially affected bedding planes and subsequently extended to replace entire beds, mediated by bacterial iron mineralization and attributed to the early-stage diagenesis (Figures 9, 10(A, D), 11), and (ii) limonite and goethite replacement, found in the Tronoh Member, which occurs primarily within root traces and as partly staining of the host rock, mediated by source of iron from the Parit Member and attributed to the late-stage diagenesis (recent to subrecent) (Figures 4(D), 7(C), 10(C)).

The origin of ferruginous mineralization as hematite and magnetite replacement is still debated, and more research activities are required; however, microbial mediation, specifically bacterial iron mineralization is considered a plausible mechanism at the end of the Permian [62-64,4]. Although its importance in geochemical cycling is well recognized, the evolutionary history and environmental controls of this microbial process remain poorly understood.

Furthermore, it is defined as the first great event, resulting in widespread ferruginous mineralization, mediated by bacterial iron mineralization at the end of the Permian. A similar widespread distribution has been found in the equivalent stratigraphic units throughout Southeast Asia (Indonesia, Malaysia, Thailand, and Myanmar), as part of the Sibumasu block. The hematite and magnetite beds with Thalassinoides are defined as sedimentaryderived laterite of the Parit Member, as an indicator of the Maker bed.

The arenaceous facies include slightly metamorphosed sandstone in the Teluk Intan area and slightly metamorphosed sandstone interbedded with shale in Seri Iskandar [24,26,27]. The previous authors accepted that the arenaceous facies is part of the formation. The present study indicates that this facies is not part of the newly redefined Kati Formation. Those stratigraphic successions that resemble shallow-marine clastic facies are distinct from the newly

Age and stratigraphic correlation

The age of the formation is poorly constrained due to the lack of stratigraphic index fossils; however, a probable Late Carboniferous to Permian period is inarguably assigned, eg., [4,26]. It is a consensus that the formation was interpreted to be older than the Semanggol Formation in northern Perak, which is Triassic, based on dissimilarities in the lithology and the style of folding; the formation is more highly flexured (flexible) than the Semanggol Formation [26,27,30,65-67].

Numerous researchers, eg. believed that the Kati Formation in the Kinta Valley is equivalent to the Kubang Pasu Formation in Perlis area, distinguished by several authors, and correlates with the Upper Paleozoic Kenny Hill Formation in the Kuala Lumpur area, as distinguished by a great deal of authors [2,6,9,24,25,30,68-71].

redefined the Kati Formation and requires justification of their stratigraphic positions for further research.

In the study, the Parit Member is a distinguishable lithological character of replacement origin of hematite and magnetite beds with abundant *Thalassinoides*, assigned "sedimentary-derived laterites", and it has long been known in Asian countries as a building material, which is also utilized for the correlation of Paleozoic sequences in the region.

Laterite/Lateritic stone or soil

A variety of definitions of laterite have appeared in scientific literature since Buchanan coined the term in 1807. Laterite stones have become the subject of controversy due to the variety of parent rocks of the formation [72]. Numerous hypotheses have been advanced to differentiate between rock weathering processes and the mechanisms governing lateritization in soils. However, the differentiation revolved only around the unique process of achieving specific mineral and chemical content (Fe_2O_3 , SiO_2 , and Al_2O_3), which is enhanced by climate conditions (repetitive wet and dry seasons) to speed up the leaching [73].

A modern laterite definition should comprise all products of intensive tropical weathering, independent of their properties and parent rocks, so that all weathering products are formed by the same functions of the fundamental weathering process and are therefore different members of a laterite family. All laterites can be classified based on the parent rocks: (i) Laterites sourced from mafic and ultramafic rocks, (ii) Laterites on acidic rocks and sedimentary rocks, and (iii) banded iron formations (BIFs) [12].

In Peninsular Malaysia, the term lateritic soil (laterite) is mainly used to describe soils that have indurated ferruginous layers or hardened ironstone, concretions, and gravels; in this case, iron-coated (lateritization) parent materials that are formed in situ are also included in the definition of laterite (a specific mineral and chemical content (Fe_2O_3, SiO_2, and Al_2O_3) [74]. In addition, laterites emphasize the physiographic positions, physical properties, and other geological concerns, including a map of the distribution of the main laterite-bearing soil in Peninsular Malaysia, and modified after (Figure 12) [75-77]. Consequently, the largest areas of laterite (Sungai Patani of Kedah, the Port Dickson-Malacca coast and the MuarTemerloh strip) are in the portions of the peninsula with the smallest annual rainfall and/or the greatest susceptibility to dry periods [75,78-80].

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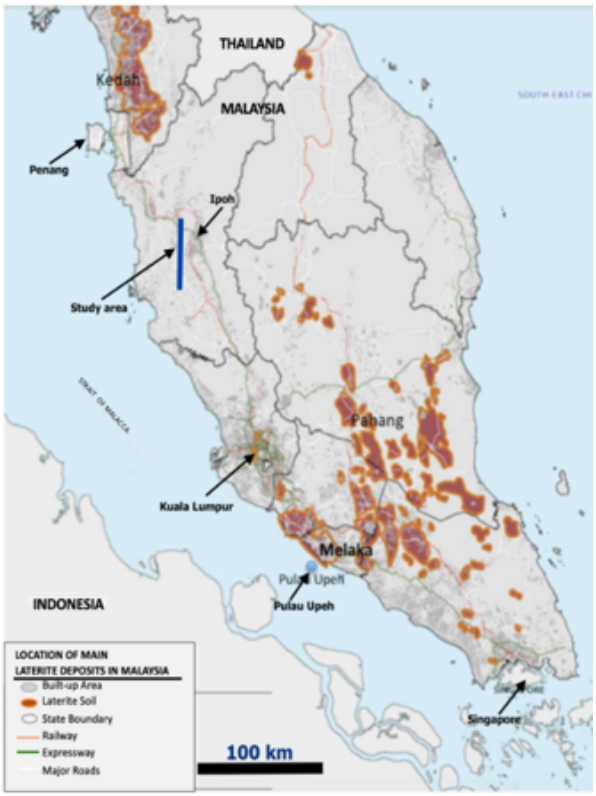

Figure 12. Map showing the distribution of laterite deposits in Peninsular Malaysia (red colour) (modified after; enhanced using data from the Malaysia National Physical Plan-2) [75-77]. Note: Sedimentary-derived laterite deposits from south to north: Melaka area (Melaka Series), the study area (blue strip) (Kati Formation) to Kedah area (Sugai Patani Formation), within the Western Belt, whereas deposits exposed around the Bentong–Raub Suture Zone and the Central Belt (Pahang area) reflect Ophiolite- and Basalt-derived laterite (graphical modification is included).

Furthermore, one of the most comprehensive is that of those who defined laterite as highly weathered materials in Malaysia [13]. After that, they are classified into two main groups: (i) soils with iron-coated or iron-indurated parent material (in situ), and (ii) soils with petroplinthite gravel (reworked type) [72,81]. Laterite stones have long been the subject of controversy due to uncertainties surrounding their formation processes and the genesis of lateritic materials [72]. However, the classification scheme they proposed does not apply to the present study.

In the present study, laterite contains a very large quantity of replacement iron. It is identified as full of cavities and pores with a variety of post-colonization diagenetic events, which is equated with and proposed as the Parit Member [4]. The cavities and pores represent the trace fossil *Thalassinoides* and were constructed by domicile burrowers [4]. The hematite- and magnetite-beds are of replacement origin of the primary shale of the Tronoh Member, and the mechanism of the ferruginous mineralization is assumed to be bacterial iron mineralization, which occurred after colonization and before infilling of *Thalassinoides* occurred in the early-stage diagenesis. Moreover, the hematite- and magnetite-beds with *Thalassinoides* are obliterated and characterized by new preservation styles, having undergone the physical diagenetic processes of the midstage diagenesis and late-stage diagenesis [4]. Consequently, the various lithological features of the diagenetic preservation, resembling laterite, are visible (Figures 5(D), 6(B-D), 9, 10(A)). Therefore, it is inexplicable that the formation, containing various lithological features affected by three stages of diagenetic events, is sedimentary-derived laterite in origin and not of mafic and ultramafic rocks, eg., [82,83].

Based on soil characteristics, lateritic soils in Malaysia are classified into seven series: Changloon, Chuping, Gajah Mati, Melaka, Pedu, Pokok Sena, and Terap Series. The Melaka series was distributed in Melaka, and the Gajah Mati series occurred in Sungai Patani of the Western zone of the region, respectively [74]. The two, the Melaka Series and the Gajah Mati Series, are lithologically similar successions, in correlation with the Kati Formation (Figure 12; Table 1).

Laterite/Lateritic stone or soil

Based on the literature review, the soils have been termed as 'Melaka Series', which belong to a member of laterite (lateritic soil), and are characterized by a bright red colour due to oxidation of the contained iron to the ferric state (hematite) under humid tropical surface conditions (Figures 10(B), 13). They usually show a thickness of about 1 m, but some are thicker. Laterites capping hill summits are mostly classified as Malacca Series in the following terms: Laterite boulders of varying sizes may be scattered throughout the profile, may litter the surface, but more commonly the laterite, which occurs in the form of well-rounded nodules in the top portion, rapidly increases in size and becomes very irregularly shaped at depth [82,75]. It is believed that those boulders coincide with the beach magnetite pebbles derived from the Parit Member (Figure 7(D)) [4].

The heritage buildings of the St. Paul Church and Fort Bastion Middelburg in Melaka were constructed with laterite (Figure 10(B)). Abundant *Thalassinoides* is visible and comprises hematite and magnetite substrates with empty infill (Figures 10(B), 13). The large availability of laterite stone at an old quarry located in Pulau Upeh, Melaka, Malaysia, could be optimized to ensure the feasibility and quality of future stone-replacement projects (Figure 13(A-B)) [76,77]. This succession coincides with the Parit Member, so the correlation between them is distinguished (Figure 12; Table 1).

Gajah Mati series

A dense layer of pisolithic nodules, which increases in abundance and compaction with depth in the Gajah Mati Series [81]. Poor documentation of the Gajah Mati Series makes it challenging to define not only the soil of the Gajah Mati Series but also a part of the primary rock, which resembles the Kati Formation. Therefore, advanced research is required. In the Sungai Tok Pawang locality, near Bedong town, Kedah, the rocks consist of black shales and mudstone country rocks, in close genetic relationship with pegmatite, commonly ferruginous (hematite and magnetite), that were defined as the Sungai Patani Formation of possible Silurian age, as exemplified by [83-85]. Geophysical studies of a sizable iron ore deposit of boulder-sized ore horizon, exposed near Bedong town, Kedah, have been conducted [71]. At the Bukit Choras archaeological complex in Kedah, XRD and XRF analyses of lateritic ironstones have been conducted to characterize the geochemical composition of construction materials [87]. These materials appear to be geochemically comparable, and potentially homologous, to those of the Kati Formation.

In conclusion, laterite deposits are widespread across Malaysia, occurring in the western zone, and some in the central zone are specifically associated with mafic and ultramafic parent rocks

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Table 1. Correlation table of the Late Carboniferous-Permian Kati Formation and its equivalent successions in the northwest Belt of Peninsular Malaysia.

Author	Name	Age	Distribution	Lithology	Thickness	Occurrence	Depositional Environment	Paleontology	Remarks
Myo Myint	Kati Formation	Late Carboniferous – Permian	Isolated and discontinuous outcrops, stretching in areas from Kati village, Kuala Kangsar, Parit, Lahat, Batu Gajah, Tronoh, UTP, Seri Iskandar, Kampung Bali.	Tronoh Member (lower): bedded to massive shale, intercalated with fine-grained sandstone, and Parit Member (upper): hematite- and magnetite-beds	Impossible to measure due to limited exposure	Kati Formation is overlain by Quaternary Sediment and underlain by Paleozoic metamorphic rocks, and intrusive contact with Mesozoic Granites	Deep - marine environment	Ichnogenera: Chondrites, Planolites, Thalassinoides, and root traces	Sungai Patani Fm and (Gajah Mati series?) in the north and Melaka series (*Thalassinoides*bearing hematite and magnetite beds (laterites)) in the south
Alkhali and Chow [24]	Kati Formation	Late Carboniferous – Permian	Kuala Kangsar area and extends southward along the western bank of Sungai Perak into Kinta Valley (west and southwest Kinta Valley)	Laminated or thinly bedded siltstone and shale beds; secondary staining may produce a pinkish, mottled color to shale and mudstone	780 m at Seri Iskandar	No contact with younger sediments or calcareous rocks was observed	Slope	No record	Kubang Pasu Formation in the north and Kenny Hill Formation in the south
Foo [52]	Kati Bed	Late Carboniferous – Permian	Between the granites of the Bintang and Kledang ranges.	Monotonous sequence of interbedded metamorphosed reddish brown carbonaceous shale, mudstones, and sandstones, with minor siltstone "argillaceous and arenaceous rocks"	Impossible to measure due to fold at Luala Kangsat	No contact with younger sediments or calcareous rocks was observed	No information	No record	Kubang Pasu Formation in the north and Kenny Hill Formation in the south
Wong [27]	Kati Bed	Late Carboniferous – Permian	Lumut and Teluk Intan areas (southern part of Kinta Valley)	Metamorphosed equivalents of the arenaceous and argillaceous series	900 m at Lumut and Teluk Intan	No contact with younger sediments or calcareous rocks was observed; lateral facies change in the Salak Baharu Beds	No information	No record	Kenny Hill Formation of the Kuala Lumpur area (in the south)

(Figure 13). No formally established stratigraphic units of sedimentary origin of laterite deposits have yet been identified in the western zone of Malaysia. This highlights the need for further investigation, particularly the systematic re-examination and refinement of currently unnamed laterite successions.

Conclusion

The conclusions in the present study are highlighted below:

A major portion of the formation is unconformably overlain by Quaternary Sediments, unconformably underlain by the Paleozoic metamorphic basement, surrounded by the massive granite bodies with intrusive contact, and juxtaposed against the highland carbonate pinnacle of the Kinta Limestone. Due to the composition of soft parent rocks of the Tronoh Member and heavily weathered rocks of replaced haematite- and magnetite-beds with abundant Thalassinoides of the Parit Member, covering agricultural land, human settlement and urbanization, and road construction, influenced by subtropical to intensive rainfall and high temperature leading to rapid weathering, the accessibility of horizontal and vertical exposures of the formation is very minimal.

The Kati Formation contains two members: (a) Tronoh Member: the heterolithic sequences of light- to dark-grey, soft, bedded-tomassive shale intercalated with fine-grained sandstone and (b) Parit Member: hematite- and magnetite-beds with Thalassinoides and roots and replacement origin of the upper portion of the Tronoh Member. Consequently, it is defined as the first great event, resulting in ferruginous mineralization, mediated by bacterial iron mineralization at the end of the Permian. Consequently, the hematiteand magnetite-beds with Thalassinoides of the Parit Member are defined as sedimentary-derived laterite.

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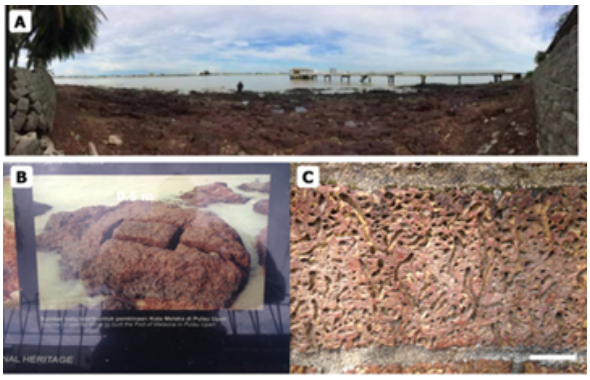

Figure 13. Laterite mine and *Thalassinoides* in a hematite and magnetite bed, resembling laterite stone, in Melaka, Malaysia. A. Old laterite stone quarry at Pulau Upeh, Melaka (modified after), equivalent unit of Malaka Series?; B. Source of laterite stone and extraction method used for producing building stones employed in the construction of Fort Malacca (Melaka), Pulau Upeh mine [76,77]. Photograph courtesy of Melaka Museum, Malaysia; C. Building stone exhibiting *Thalassinoides* with open cavities (void infill). Location: Fort Middelburg Bastion, Melaka, Malaysia; Scale = 1cm.

The Kati Formation contains two members: (a) Tronoh Member: the heterolithic sequences of light- to dark-grey, soft, bedded-tomassive shale intercalated with fine-grained sandstone and (b) Parit Member: hematite- and magnetite-beds with Thalassinoides and roots and replacement origin of the upper portion of the Tronoh Member. Consequently, it is defined as the first great event, resulting in ferruginous mineralization, mediated by bacterial iron mineralization at the end of the Permian. Consequently, the hematiteand magnetite-beds with Thalassinoides of the Parit Member are defined as sedimentary-derived laterite.

Based on observations at both stratigraphic and structural boundaries, the seafloor of the Kati Formation is inferred to originate from Paleozoic metamorphic rock; alternatively, the structural boundary remains poorly constrained.

Five rock types of the Quaternary Sediment resting uncomfortably on the Kati Formation reflect that fluvial deposits are distributed across inland flood-prone areas associated with major river systems, particularly along the Perak River. They are well exposed in the Batu Gajah area of the northern region. In addition, deposits of the swashbackwash zone, rocky beach, and the estuaries of the Perak River are encountered. They are distributed in the southern region, especially around Lahat, Tronoh, and Universiti Teknologi Petronas (UTP), east of Seri Iskandar and Kampung Gajah. Additionally, the hilly areas of hematite- and magnetite-beds have remained, alongside carbonate and granitic hills that rise above sea level and face the coastline, with notable exposures in Tronoh and the UTP compound.

Based on the traditional correlation assisted by the previous authors, the Kati Formation is correlated with the Kubaung Pasu Formation to the north and the Kenny Hill Formation to the south. Based on the lithological similarity to the Parit Member, the formation correlates with the Sugai Patani Formation to the north and the Melaka Series to the south.

Sedimentary-derived laterite resembles the Parit Member, comprising hematite- and magnetite-beds with abundant Thalassinoides, resulting in the various lithological features of diagenetic preservation affected by three stages of diagenetic events, which is utilized as a marker bed for correlation in the upper Paleozoic successions in Malaysia.

CRediT Authorship Contribution Statement

Not applicable. There are no authorship contributions to credit for this manuscript.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Ethics Approval

The author declares that appropriate research ethics were followed and that all standards of scientific and publishing ethics have been upheld.

Funding

Not applicable.

Declaration of Competing Interests

The authors declare no conflicts of interest.

Data Availability

The data underlying this paper were provided by Myo Myint, Consultant Geologist, with permission. Data will be shared on request to the corresponding author.

Acknowledgements

The author gratefully acknowledges the Human Resources and Management Association (HRMA) of Universiti Teknologi PETRONAS for their support during the research period (2016-2019). Special thanks to Dr. Chow Weng Sum (Head) and the academic and administrative staff of the Department of Geosciences, Faculty of Sciences, Universiti Teknologi PETRONAS, for facilitating fieldwork and laboratory access. Appreciation is extended to students: Mr. Muhammad Ekrahm Bin Nawas Khan, Mr. Min Wai Phyoe, and Ms. Nur Sabrina Binti Sobri for their valuable assistance.

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