

ORIGINAL ARTICLE



Burrow preservation and diagenetic events: An example from the Late Carboniferous to Permian Kati Formation, Kinta Valley, Malaysia

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ABSTRACT

The new insights into the Kati Formation include two members: the Tronoh Member and the Parit Member, in descending order. The Tronoh Member, as the parent rock and lower succession, comprises dark grey, bedded-to-massive shale intercalated with thin-bedded, fine-grained sandstone. The Parit Member, as a replacement origin and upper succession, contains hematite- and magnetite-beds. Two modes of burrow preservation are classified: Primary Preservation and Diagenetic Preservation. The primary preservation reflects tiering, and two styles are distinguished: deep tiering, marked by *Chondrites* and *Thalassinoides*; and shallow tiering, represented by *Planolites* and root traces. Based on the diverse styles of diagenetic preservation, three stages of diagenetic events are examined: (i) Early-stage diagenesis: marks the replacement of *Thalassinoides* and root traces by hematite and magnetite, with both bedding surfaces and entire beds, mediated by bacterial iron mineralization. It occurs after colonization but before infilling of *Thalassinoides*, in which roots were altered following root disintegration. (ii) Mid-stage diagenesis: Occurs during Quaternary seafloor and coastline migration, forming secondary infill of yellowish-brown sandy siltstone from the overlying sediment in the voids of eroded *Thalassinoides*. Several eroded hematite- and magnetite-boulders from the Parit Member are redeposited. (iii) Late-stage diagenesis: marks recent to subrecent weathering processes, producing red-stained shale, limonite- and goethite-replacement roots, eroded empty infill of *Thalassinoides*, and hematite- and magnetite-fragments lying on the unconformity surface, obscured burrows and mottled textures.

KEYWORDS

Kati formation;
Chondrites; *Planolites*;
Thalassinoides; Root traces

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Introduction

Trace fossil analysis has emerged in the 21st century as a powerful indicator of palaeoenvironmental evolution and associated changes. It now stands as a pivotal element supporting sedimentological and stratigraphic interpretations, thus a key in sedimentary basin research [1]. A trace fossil is a fossil record of biological activities by lifeforms, but not the preserved remains of the organism itself [2]. Furthermore, trace-maker behaviour records responding to biotic and abiotic factors (e.g., salinity, oxygen, nutrients, hydrodynamic energy, rate of sedimentation, and substrate, among others); therefore, a trace fossil can be defined as a fossil that records the interaction of an organism with a substrate [3].

Moreover, the nature of the substrate significantly influences the energy expenditure, burrowing strategies, and risk of tunnel collapse, leading to a range of adaptations among burrowing organisms. Different substrate types present distinct challenges and opportunities, shaping the morphology and behaviour of the trace-making animals. In addition, the axis of ichnological studies resides in the relationship between trace fossils and palaeoenvironmental conditions.

In ichnology, the preservation of burrows in relation to the infill and substrate, as a pivotal component, helps differentiate ichnotaxa, interpret behaviour (Ichnofacies), assess environmental and ecological conditions, locate true tracks, and enhance stratigraphy and geologic history. In addition, diagenetic events, as evidence of enhancement or obscuration at all scales, tend to replace and obliterate the primary architecture of a trace fossil and are now recognized as playing a major role in interpretation for ichnological and sedimentological realms. Recognizing a trace fossil as a record of organism-substrate interaction is well agreed upon; still, some organisms, some interactions and some post-depositional changes are not considered by some workers to be tracemakers or to have produced trace fossils or to have induced mineralogical

changes in both substrates and infills [4].

The term diagenesis (post-depositional changes) is commonly used in geology. Studying diagenesis in rocks helps us understand the geologic history they have undergone and the nature and type of fluids that have circulated through them. Diagenesis is defined as the totality of post-sedimentation processes that lead to the formation of rocks, encompassing all changes occurring from the burial of plant materials in sediment until the sediment becomes rock and the material turns into fossils, involving various physical, chemical, and biological processes, including microbiological degradation, compression, cementation, and mineral precipitation [5]. Diagenesis begins as soon as sediment is deposited [6]. Moreover, diagenesis is classified into three distinct stages: syndiagenesis, anadiagenesis, and epidiagenesis [7]. Additionally, the diagenetic event of the present study is divided into three distinct stages: early-stage, mid-stage and late-stage, based on the characteristics of ichnological evidence, lithological changes and their phases.

This is because a new approach to post-depositional chemical and physical alterations, referred to as a diagenetic event, often enhances and obliterates the contrast between the trace and the surrounding rock, sometimes through mineral concentration at all scales. Consequently, the preservation of burrows provides critical insights into the stratigraphic, sedimentological, palaeoecological, and palaeogeographic framework of a formation, thereby aiding the reconstruction of its geological history.

Therefore, the primary focus is on the ichnological record, in the form of the various styles of burrow preservation and their diagenetic events, particularly evidence of ferruginous mineralization, erosion and deposition, and recent-to-subrecent weathering processes.

Objective of the study

In addition, the Kati Formation forms low-relief landforms with isolated exposures, which are obliterated by various stages of diagenesis, hindering interpretation of the primary architecture of

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trace fossils and lithological features. As a result, this formation has been largely overlooked by geologists in their research. The widespread occurrence of hematite and magnetite is notably associated with trace fossils such as *Thalassinoides* and root traces, which exhibit diverse styles of diagenetic preservation. Moreover, the diagenetic preservation of trace fossils such as *Thalassinoides*, particularly the relationship between burrow substrate and infill, which is strongly influenced and obscured by chemical and physical diagenetic alterations, remains problematic in this stratigraphic sequence. Hematite- and magnetite-boulders are conspicuously present as float within the Quaternary Sediment, and the origin of these widespread boulders embedded within the sediment remains enigmatic. An unclear and unresolved problem has been encountered in the stratigraphic occurrence and position of the formation, as well as evidence of trace fossils and their origin and mechanism of ferruginous mineralization.

Therefore, to address these problematic issues, an extensive field investigation was conducted between 2016 and 2019. This study gathered a wide range of geological data, including newly identified trace fossils and detailed documentation of their diagenetic preservation and alteration processes. The objective is to reveal new paleoichnological evidence and clarify its diagenetic implications for the evolution of the Kati Formation.

Materials and Method

Data were collected through detailed bed-by-bed ichnological and sedimentological analyses across the limited and discontinuous exposures in the study area (Figure 1). Each trace fossil-bearing outcrop was systematically surveyed, recording ichnotaxa, bioturbation intensity, mode of preservation, cross-cutting patterns and sedimentary features, as well as taphonomic indicators associated with diagenetic processes. Trace fossils were carefully measured and photographed. Selected specimens were collected for laboratory analysis to examine internal structures and finer features. The term “primary preservation”, known as Ichnofabrics in many ichnological studies, follows the description and concept by Droser et al and Droser et al. [8,9]. Moreover, the term “diagenetic preservation,” referring to replacement and obliteration of the primary architectures such as orientation, shape, size, infill and substrate of a trace fossil, is controlled and affected by diagenesis.

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). Particular attention was given to the presence of iron oxide minerals, which produce a range of strong pigments - red, yellow, orange, brown, and occasionally blue-green. These colours provide important insights into the mineralogical composition of the rocks and the conditions under which iron oxides formed.

Brief Geology of the Kati Formation

In Peninsular Malaysia, the Kinta Valley forms a lowland region in the western part, extending as a narrow north-south strip bounded by high mountain ranges (Figure 1(C)). It lies within the western zone of Peninsular Malaysia [10-13]. In the Kuala Kangsar and Taiping areas, the Late Carboniferous to Permian succession comprises three sedimentary formations: the Pondok Marbles, the Kati Beds, and the Salak Baharu Beds [14]. In the Lumut and Teluk Intan areas, three sedimentary successions and their metamorphic equivalents are recognized: the Kati Beds (arenaceous and argillaceous series), the Tualang Limestone (part of the Kinta Valley's Silurian - Permian limestone belt), and the Gelubi Schists [15].

The Kati Formation is one of the major exposed rock units in the Kinta Valley, forming low-relief landforms and exhibiting a narrow east-west and linear north-south belt. Exposures are discontinuous and are mainly observed in Kati village in the north through Kampong Gajah village in the south (Figure 1). Earlier studies compiled and formally revised the term “Kati Beds” to “Kati Formation” [16]. The

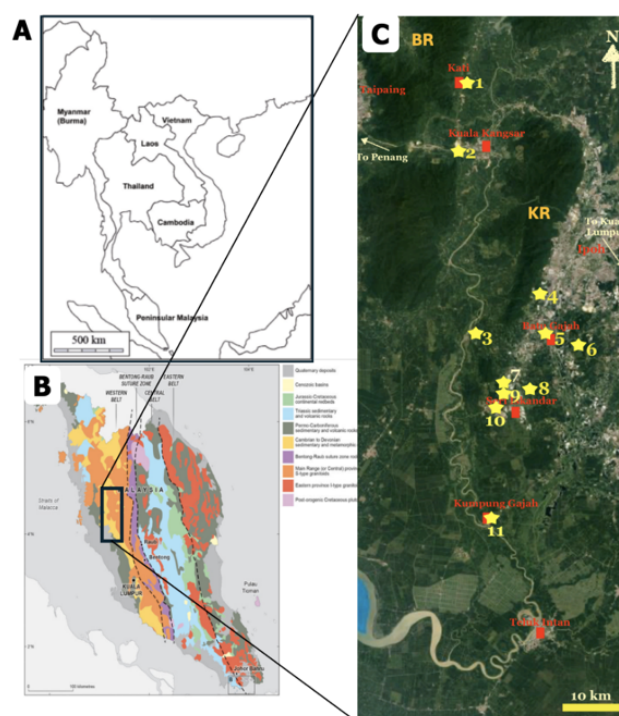


Figure 1. Maps illustrating the study area location: A. Location of Malaysia in Southeast Asia; B. Geological map of Malaysia, showing the location of Figure 1C; C. Kinta Valley, exposures of the Kati Formation in the present study area: 1. Kati village (type section); 2. Kuala Kangsar Interchange; 3. 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. Kampong Gajah. (BR = Bintang Range; KR = Kledang Range).

stratigraphic type section is at Kati village in northern Perak (Figure 1(C)). Four main lithological units are identified: (i) Paleozoic metamorphic rocks, (ii) Kati Formation, (iii) Mesozoic granite and (iv) Quaternary sediment [10,14-16]. Based on gravity anomaly data, the Kati Formation overlies the Kinta Limestone [17]. Further work on the boundaries and lithofacies of the Kati Formation in southwest Perak was presented [18].

Based on lithological characteristics, the Kati Formation can be subdivided into two members, the Tronoh Member (lower succession) and the Parit Member (upper succession), in accordance with the International Stratigraphic Guide [19]. Tronoh Member: The type section is located at Tronoh village (location 7) (Figure 1). It is the parent rock and comprises dark grey, soft, bedded-to-massive shale intercalated with fine-grained sandstone (Figure 2 and 3). Parit Member: The type section is located at Parit village (location 3) (Figure 1). It contains replaced hematite- and magnetite-beds formed through ferruginous mineralization of the parent lithologies (Figure 2 and 4). The transition between the two members is initially confined to bedding planes and subsequently extends to affect entire beds (Figure 2). The age of the Kati Formation is poorly constrained due to the lack of stratigraphic index fossils; however, a probable Late Carboniferous to Permian age is inarguably assigned. Moreover, a few researchers and numerous Malaysian geologists have accepted that the clastic sequence of the Kati Formation and the rocks at Seri Iskandar are all consistent with a deep-marine slope environment [14-16].

Moreover, the Tronoh Member unconformably overlies schist and phyllite, and is in faulted contact with phyllite of the Paleozoic metamorphic basement, particularly evident in the Batu Gajah area (Figure 3(C)). Mesozoic granites intrude the Tronoh Member and are exposed near Tronoh and Lahat, south of the Kledang Range (Figure 3(D)). Unconformable boundaries between the Kati Formation and the

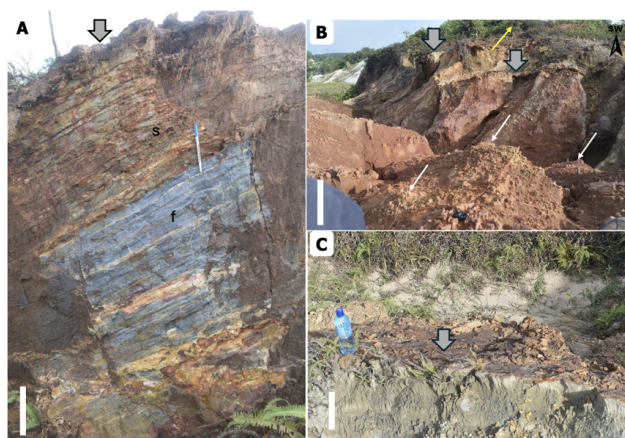


Figure 2. Tronoh Member of the Kati Formation (parent rocks): A. Dark grey bedded shale intercalated with white, thin-bedded, fine-grained sandstone (SE-dipping), showing hematite and magnetite replacement (grey arrow) on bedding surfaces; s = iron oxide staining, f = fresh surface; B. Iron oxide staining on SE-dipping bedded shale replaced by hematite and magnetite (grey arrow), with three locations of roots (Rhizoliths) (white arrows) (see Figure 7 and 8); Parit Member consisting of hematite and magnetite (yellow arrow), with trace fossils including roots and *Thalassinoides*, (see Figure 6(A-B), 7(C-D), and 8 (C,D,G,H)); C. Tronoh Member characterizing replacement origin of hematite and magnetite (grey arrow) occurred on bedding surfaces of dark grey shale, assuming initial stage of ferruginous replacement; Location 7, near Tronoh; Scale bars: 20 cm (A-C), 1 m (B).

Quaternary Sediment – predominantly unconsolidated, yellowish-brown sandy siltstone – are marked by conglomeratic horizons and distinct lithological contrasts (Figure 3(A-B), 4(A)) [20]. This succession corresponds to the Lower-Middle Pleistocene to Holocene of the Simpang Formation [21-25].

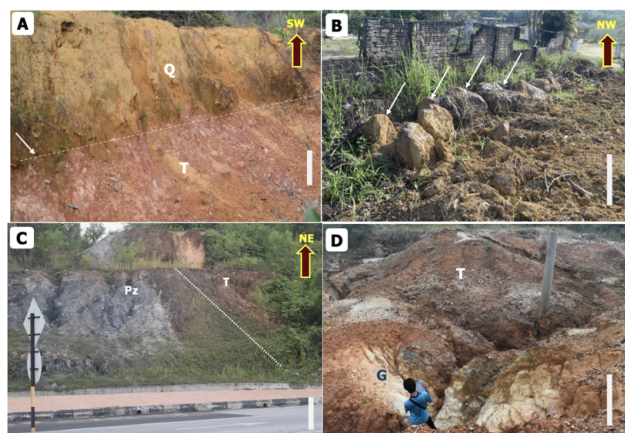


Figure 3. Stratigraphic contacts of the Kati Formation: A. Unconformable boundary (dot line) between yellowish brown colour, unconsolidated sandy siltstone, the Quaternary Sediment (Q) and shale with red stained, the Tronoh Member (T), Location 9, near roundabout, Road Teknologi 1, south gate of UTP; B. Conglomerate band of moderately rounded shape and well sorted magnetite cobbles (beach pebbles) derived from the Parit Member and embedded in the Quaternary Sediment (arrow), Location 8, Gerai Mak Miah, east of Kampung Bali; C. Faulted contact (dashed line) between the Tronoh Member (reddish-brown) (T) and Paleozoic metamorphic rock (dark grey) (Pz), Location 5, near Bur-Interchange, Batu Gajah; D. Intrusive contact with Mesozoic Granite (G) and Tronoh Member (T), Location 7, north Tronoh; Scale bars: 1 m.

Occurrence and preservation of trace fossils

The preservation potential of biogenic structures formed near the sediment-water interface is particularly important for detecting early benthic activity and is controlled by taphonomic factors such as fragmentation, abrasion, bioerosion, dissolution, mineralization, and infill [26,27]. Taphonomy plays an important role in ichnological analyses to evaluate the processes involved in trace fossil preservation [28-40]. Two key parameters describe the taphonomic condition of ichnofossil assemblages: ichnologic fidelity and visibility [41].

In ichnology, **open burrows** are structures that were originally open cavities during the organism's activity and were subsequently filled either passively by sediment from the surrounding environment or purposefully lined by the organism. The infill sediment often differs from the host sediment, which assists in preservation and identification in the rock record. The composition and nature of the infill are pivotal components in interpreting both the behaviour of the trace maker and the conditions of the palaeoenvironment. Infill types are generally classified as **passive infill** and **active backfill**. The suitability of substrate for burrowing depends on several key factors, such as physical and chemical characteristics, although optimal conditions vary, ensuring the organism and its burrowing mechanism.

Among the four trace fossils preserved in the Kati Formation, the Tronoh Member contains *Chondrites*, *Planolites*, and root traces [42]. In contrast, the Parit Member is characterized by *Thalassinoides* and root traces. The Parit Member has undergone various stages of chemical and physical diagenesis, including ferruginous mineralization, secondary erosion, transport, redeposition, limonitization, and recent-to-subrecent tropical weathering. The trace fossils preserve full-relief burrows, typical of post-depositional structures formed within the sediment after initial deposition [43-45].

In the Present study, two modes of burrow preservation are classified: (i) primary preservation (known as "Ichnofabrics") and (ii) diagenetic preservation. Bioturbation at all scales, which tends to replace the primary fabric of a sediment with the ichnofabric (the overall fabric of a sediment that has been bioturbated), is now recognized as playing a major role in facies interpretation [46]. The manner in which the substrate may be colonized, and the physical, chemical and ecological controls (grain size, sedimentation rate, oxygenation, nutrition, salinity, ethology, community structure and succession), together with the several ways in which the substrate is tiered by bioturbators, are the factors and processes that determine the nature of the ichnofabric [46].

The primary preservation reflects the substrate tiered by bioturbators, and two styles are distinguished: (a) deep tiering, formed several meters below the sediment-water interface, marked by *Chondrites* and *Thalassinoides* (Figure 4(B)); and (b) shallow tiering, formed less than a few centimeters below the sediment-water surface, represented by *Planolites* and root traces [8,9]. On the other hand, diagenetic preservation indicates evidence of enhancement or obscuration at all scales, which tends to reshape and obliterate the primary architecture of a burrow. Notably, diagenetic preservation is often more pervasive than traditional bedding-junction preservation [47]. Diverse styles of diagenetic preservation of burrows, particularly *Thalassinoides* and roots, are present. In contrast, *Chondrites* and *Planolites* remain largely unaltered and unaffected by diagenetic events.

Descriptions of trace fossils

The four trace fossils exhibiting diverse styles of diagenetic preservation and their related three modes of diagenetic events are analyzed below.

Ichnogenus: *Thalassinoides*

Thalassinoides was originally described by Woodward as a fossil furoid (seaweed) but was later reinterpreted by Ehrenberg as an invertebrate trace fossil [48,49]. It shows a complex, three-dimensional boxwork of branched, cylindrical burrows and an irregularly anastomosing network of horizontal tunnels connected by vertical shafts, which is common in marine sediments from the Early Paleozoic to the present.

In this study, *Thalassinoides* is pervasively preserved and notably

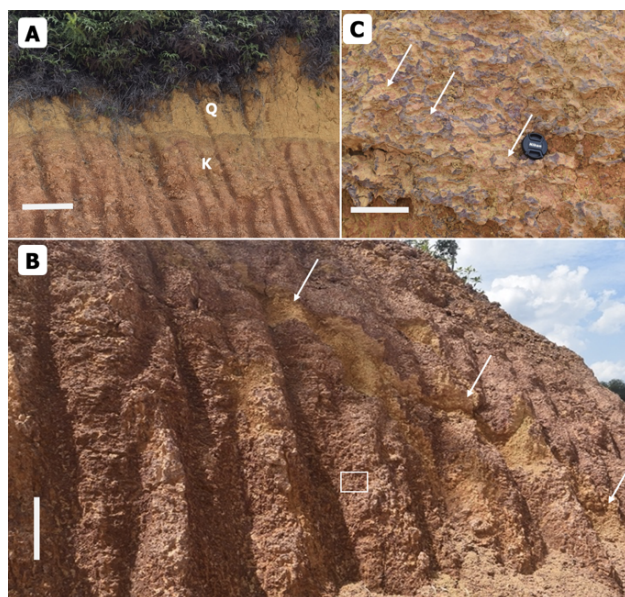


Figure 4. A. Unconformable boundary between Quaternary Sediment (Q) and the Parit Member of Kati Formation with abundant *Thalassinoides* (K); B. Abundant *Thalassinoides*, characterizing deep-tier, reopened fractures refilled by unconsolidated yellowish-brown sandy siltstone of the overlying Quaternary Sediment (arrows), Figure 4C is marked with a white box; C. *Thalassinoides* substrate composed of red hematite; primary burrow infill has been dissolved and eroded, and the cavity subsequently reoccupied by yellowish-brown sandy siltstone (arrows) derived from the Quaternary Sediment (see Figure 2); Location 4, Lahat; Scale bars: 1 m (A-B), 10 cm (C).

recognizable in the hematite- and magnetite-beds of the Parit Member. Exposures occur at several locations, including Kati village (Location 1), Kuala Kangsar interchange (Location 2), Parit (Location 3), Lahat (Location 4), Batu Gajah (Location 5), the junction of highways A8 and A117 (Location 6), near Tronoh (Location 7), and the UTP campus (Location 9) (Figure 1(C)).

The burrows exhibit a complex boxwork of vertically and horizontally interconnected tubes forming a three-dimensional anastomosing network. They can extend more than 1.5 meters deeper from the bedding surface (Figure 4(B)). The burrows are unlined, smooth-walled, open, and typically less than 5 mm in diameter, and vertical shafts and tunnels are also present (Figure 4(C), 5(A-C); 6(A-B)). In some cases, the burrow diameter is enlarged by the removal of the primary infill due to erosion processes. The surrounding substrate was altered to hematite and magnetite affected by ferruginous mineralization after colonization.

Three types of burrow infill are examined: primary infill (Figure 5(A-B)), secondary infill (Figure 4(C) and 5(A-C)), and void (absent infill) (Figure 6(A-B)). Some burrows exhibit a mottled or patchy appearance (Figure 5(B-C)).

The six styles of diagenetic preservation that exhibit a reshaping burrow are:

(i) Ferruginous mineralization (hematite and magnetite) replaces the parent rock of shale (burrow substrate): It takes place after burrowing and colonization but before occupation of primary infill (Figure 4-5 and 6(A-B)). The ferruginous activity results from microbial iron mineralization, as proposed by [50–52], and occurs at early-stage diagenesis. However, burrow mineralization commonly takes place in an early phase of diagenesis and is promoted by localized geochemical conditions and the contribution of microorganisms [53]. Common minerals include calcite, siderite, dolomite, pyrite, goethite, glauconite, quartz and phosphate [53]. A similar widespread distribution has been found in the equivalent stratigraphic units throughout Southeast Asia (Indonesia, Malaysia,

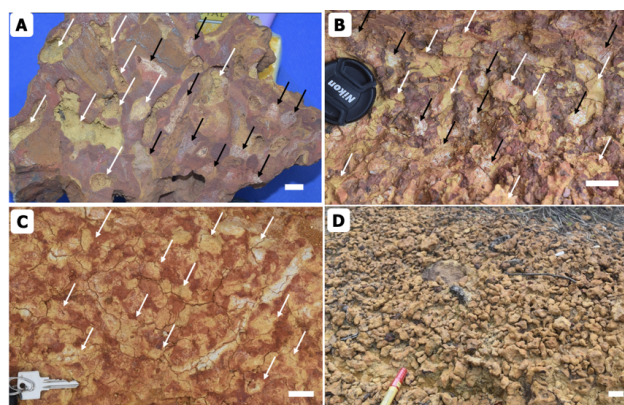


Figure 5. Ichnogenus *Thalassinoides* with various modes of diagenetic preservation in the Parit Member: A. Cutting surface (unknown position) consisting of primary infill as light grey to white-coloured clay (volcanic ash) (black arrows) and secondary infill as yellowish-brown sandy siltstone (white arrow) derived from the overlying Quaternary sediment, characterizing rigid surface and enlarged diameter of burrow and obliterated by coarse-grained material of secondary infill with high gravity flow; B-C. Erosional surface (diagonal to bedding) composed of primary infill as white-coloured clay (volcanic ash) (black arrows) and secondary infill as yellowish-brown sandy siltstone derived from the overlying Quaternary sediment (white arrows), and characterizing indistinct burrow boundary (mottled appearance); primary infill partly to completely removed and obliterated by coarse-grained material of secondary infill with high gravity flow; Location 4, Lahat (B); Location 9, near roundabout on Road Teknologi 1, south gate of UTP (C); D. Erosional fragments of centimeter-size hematite- and magnetite-replaced substrate *Thalassinoides* residing and floating on the erosional surface of Parit Member, assuming unconformity between the Parit Member and the Quaternary Sediment; Location 5, west of Batu Gajah; Scale bars: 2 cm.

Thailand, and Myanmar), as part of the Sibumasu block.

(ii) Primary infill: Light grey to white colour clay occurs in hematite and magnetite substrates in which infill escapes from mineralization. It indicates that the infilling process occurred after the ferruginous mineralization. The precise origin of this material remains a mystery; however, it contains volcanic ash (Figure 5(A-B)).

(iii) Secondary infill: The primary infill was partly to completely corroded. This corrosion process creates secondary voids, which are filled by secondary infill. It comprises yellowish-brown sandy siltstone from the overlying Quaternary sediments. The Quaternary coastline migration is a major event of the corrosion of the primary infill and the filling of secondary infill, which occurs during the Late Pleistocene to Holocene period, as evidence of the mid-stage diagenesis (Figure 4(C) and 5(A-C)).

(iv) Void (empty infill): Infill is invisible (infill dissolution) because both primary and secondary infills have been removed through recent- to subrecent-weathering of the late-stage diagenesis (Figure 6(A-B)).

(v) Mottled or patchy burrow architecture: It commonly exposes at erosional surfaces and shows an indistinct burrow boundary between substrate and secondary infill, which resembles patchy texture but likely originates from degraded burrows. This feature relies on intensive recent-to-subrecent physical weathering and is the product of late-stage diagenesis (Figure 5(B-C)) [54].

(vi) Fragments of Hematite substrate: centimetre-sized hematite and magnetite fragments of substrate are found floating on the erosional surface along the unconformity between the Kati Formation and the Quaternary sediments, indicating the intensive recent-to-subrecent physical weathering product of the late-stage diagenesis (Figure 5(D)).

Although *Thalassinoides* is a deep-tier burrow, it has been

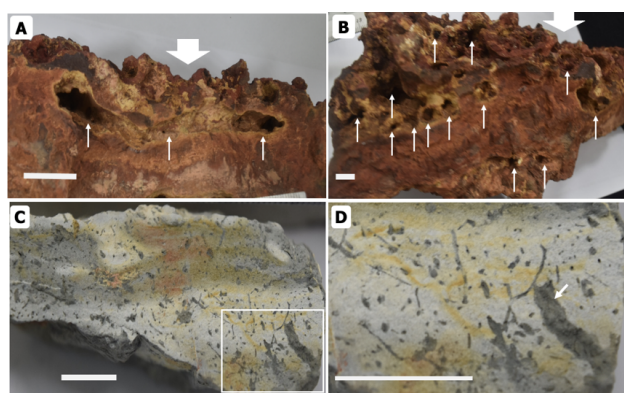


Figure 6. Ichnogenes *Thalassinoides* in Parit Member, and Chondrites and Planolites in Tronoh Member: A-B. *Thalassinoides* exposed in erosional surface (perpendicular to bedding), displaying voids of horizontal tunnels with empty burrows (arrows) where infill has been removed by recent to sub-recent weathering; Location 7, near Tronoh; C-D. Chondrites (deep-tier trace fossil) and Planolites (shallow-tier trace fossil) in light grey, thick-bedded shale of Tronoh Member, Chondrites (C); Planolites (arrow in D), parallel to bedding surface; Location 7, stream section, north of Tronoh; Scale bars: 1 cm.

significantly obliterated by diagenesis due to its open burrow and associated porosity and permeability, which facilitated water percolation. As a result, its original architecture, morphology, and infill characteristics were often obliterated or obscured during three stages of diagenesis. Therefore, a precise taxonomic interpretation at the species level is impossible, as the original burrow architecture has been compromised and obscured. *Thalassinoides* can be identified, although burrow architecture is obscured by diagenesis.

However, the preserved boxwork geometry and depth of the galleries suggest an endogenic origin, likely formed by infaunal organisms engaged in both deposit-feeding and dwelling activities, and possibly also as an agrichnion [55-57]. Although the trace maker is presumed to be of decapod crustacean origin, the paleontological record of decapods begins in the Devonian, but most of these interpretations lack definitive evidence or broader applicability, leaving the precise producer of these Paleozoic traces still uncertain [56,58,59].

Ichnogenus: *Planolites*

Planolites is a common trace fossil ranging from the Cambrian to the Recent [60,61]. In the Kati Formation, *Planolites* occurs in bedded-to-massive shale of the Tronoh Member and is exposed at the stream section north of Tronoh at Location 7 (Figure 1(C)). The burrows are unlined, occasionally branched, tortuous, and smooth, measuring 2-3 mm in diameter and full-relief, deep-tier burrows. The dark colour infilling is homogeneous and structureless and differs from the surrounding shale.

Planolites is interpreted as both a fodinichnion (deposit-feeding) and a domichnion (dwelling) trace, typically produced by polyphyletic vermiform organisms of a possible deep-marine environment [61-64]. In the Tronoh Member, *Planolites* occurs in association with *Chondrites*.

Ichnogenus: *Chondrites*

Chondrites is one of the most iconic and extensively studied trace fossils [65-79]. In the formation, *Chondrites* is found in the bedded shale of the Tronoh Member, exposed at the stream section, north of Tronoh at Location 7 (Figure 1(C)). The burrows are unlined, regularly branching, and generally 0.5-0.8 mm in diameter. They display active fill at the basal part of the burrow, as in bedding-plane exposures. Burrow density is high, typically 5-6 numbers per 1 cm². Branching is consistent, and burrows intersect bedding obliquely to vertically. Shafts noticeably decrease in diameter in response to lithological changes. These are full-relief and deep-tier trace fossils. *Chondrites* are

found in the Tronoh Member in association with *Planolites* (Figure 6(C-D)).

Ichnogenus: Root Traces (Rhizolith)

Much earlier, Pemberton and Frey stated that "both animals and plants produce biogenic structures [62]. However, they did not clarify if they considered these biogenic structures to be trace fossils [4]. "Ichnology involves the study of traces produced by organisms (both animals and plants) on or within a substrate and includes all issues related to bioturbation, bioerosion, and biodeposition" [72]. Clearly, according to some ichnologists, there are trace fossils made by plants and micro-organisms [4]. Moreover, biogenic structures such as borings, phytoliths, galls, rhizoliths and stromatolites identified by Sarjeant, as well as plant-corrosive structures such as algal and fungal microborings interpreted by Mikuláš, are also known as trace fossils [80,81]. The possible plant and microbialite trace fossils discussed here, there is the most substantial agreement that rhizoliths should be considered trace fossils, though there is some minor disagreement on what aspects of rhizoliths are traces [4,81-86].

Klappa introduced the term "rhizolith" to describe all trace fossils of roots, later refined by Kraus and Hasiotis, who proposed a classification based on modes of preservation [87]. The term "root" refers to a multicellular plant organ characterized by features such as gravitropic response, endogenous branching, root hairs, and a protective root cap [90]. Fossil root traces is defined as continental deposits [80,87,90-94].

In this formation, both members contain root traces that occurred near Tronoh at Location 7 (Figure 1(C), 2(B), 7-8). The Tronoh Member comprises root traces replaced by limonite and goethite preserved on the erosional surface, although the surrounding substrate remains unaltered (Figure 2(B), 7(A-B), 8(A, B, E)). The Parit Member contains more extensive replacement by hematite and magnetite, affecting both root traces and substrate. In this horizon, disintegrated root fragments floating on the bedding planes are visible (Figure 7(C)). However, the primary position of root traces is also present (Figure 7(D)).

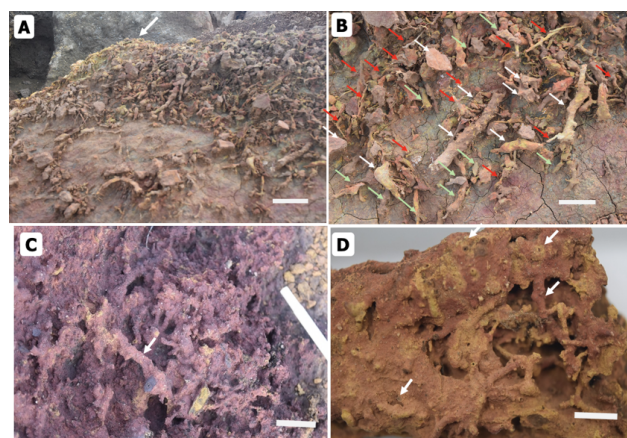


Figure 7. Ichnogenus Rhizoliths (root traces) with various modes of diagenetic preservation, exposed in the Tronoh Member, roots replaced by limonite and goethite, escaped substrate (A-B) and the Parit Member, both substrate and roots replaced by hematite and magnetite (C-D): A. In situ root (arrow) with eroded root fragments; B. Eroded root fragments on the surface of dark grey shale. Three root sizes identified: First-order lateral roots (5-10 mm, thick-walled, white arrows); Second-order lateral roots (1-5 mm, green arrows); Tertiary lateral roots (<1 mm, red arrows) (see Figure 2(B-C)); C. Disintegrated roots (eroded form) exposed on bedding plane; eroded tertiary lateral roots; D. Primary position of roots exposed on longitudinal section of bed, showing fork points of second-order lateral roots (white arrows) and tertiary roots, forming dichotomous branching (in situ form); Location 7, near Tronoh; Scale bars: 1 cm.

A classification of types of rooting structures can be combined with

Klappa's analysis to develop an ichnotaxobase for rhizoliths [94,95]. Nevertheless, all these approaches to an ichnotaxobase have not been utilized, as discussed below.

Root traces are classified into four groups based on diameter and branching order: primary roots, first-order lateral roots, second-order lateral roots, and tertiary lateral roots [90]. These are: (i) primary and first-order lateral roots exhibit 5-10 mm in diameter, are thick-walled, and often have voids filled by host rock. (ii) Second-order lateral roots show 1-5 mm in diameter, with solid material. (iii) Tertiary lateral roots are <1 mm in diameter (commonly 0.3-0.6 mm), are also solid, and are the most common in the outcrop. Branching patterns include dichotomous, lateral, and combined types (Figure 2,7-8). External surfaces are generally smooth but can exhibit rigidity. Root clusters do not appear to be interconnected.

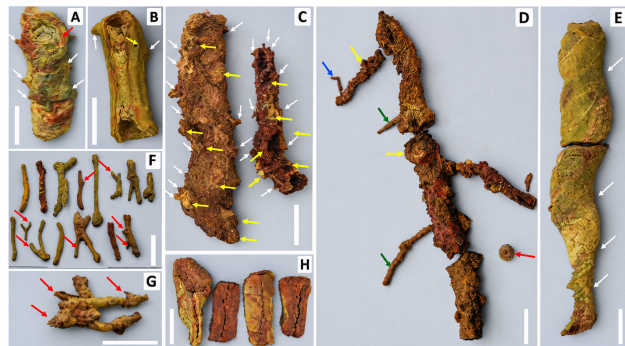


Figure 8. Ichnogenus Rhizoliths, showing a variety of root architectures with diagenetic preservation (unknown position): A-B. Inclined cast and mold of first-order lateral root (red arrow at ~45° inclination), with fork points of second-order lateral roots (white arrows), replaced by limonite and goethite (late-stage diagenesis); C. Cast (with voids) of primary root; fork points of first- (yellow arrows) and second-order lateral roots (white arrow), replaced by hematite and magnetite (early-stage diagenesis); D. Reconstruction of root system: inclined cast (voids) of primary root (white arrow), first-order lateral roots (yellow arrows), numerous fork points of second- and tertiary-order roots (yellow, green, blue arrows, respectively), all replaced by hematite and magnetite; E. Inclined mold of first-order root (void-filled), tapering downward (~40°), indicating bedding orientation, replaced by limonite and goethite in unaltered white fine-grained sandstone (late-stage diagenesis); F-G. Fragments of second- and tertiary-order roots (red arrows), replaced by limonite/goethite (brown) and hematite/magnetite (red), showing dichotomous branching; H. Mold of root on cutting surface, showing millimetre-scale central canal; Location 7, near Tronoh; Scale bars: 1 cm.

Four significant styles of diagenetic preservation of the roots that demonstrate a reshaping burrow are:

(i) Replacement of hematite and magnetite in roots and substrates (primary position), occurring in the early-stage diagenesis (Figure 7(D), 8(C, D, F, G, H)),

(ii) Replacement of hematite and magnetite in disintegrated roots and substrates (bedding plane position), which reflects that those roots were redeposited and later transformed into hematite and magnetite during the early-stage diagenesis (Figure 7(C)),

(iii) Replacement of limonite and goethite root traces hosts in unaltered shale substrate emplaced in the late-stage diagenesis (Figure 2, 7(A-B), 8(A-B, E)), and

(iv) Root cavity filling: It is assumed that disintegration and cavity-filling of the roots occur just a few centimetres below the sediment-water interface and are interpreted as full-relief, shallow-tier (Figure 8(A-B, E)) [96].

As a result, no preservation of plant anatomical structures (e.g., root hair or cap) and intensive replacement by mineralization; the approach to systematic classification of ichnotaxobase remains. The vascular systems present root casts with thick walls, cavities, and

cavity-filling materials (Figure 8(A-E)). The millimetre-scale central canal is preserved in the mold (Figure 8(H)). Disintegrated lateral roots from primary plants transform hematite- and magnetite-fragments floating on bedding planes, whereas the primary position of hematite- and magnetite-replaced roots and substrate remains visible (Figure 7(D), 8).

Results

The following results of the present study are highlighted below:

Lithological significance: Newly subdivided into two members: (i) Tronoh Member (parent rock and lower succession): comprises dark grey, bedded-to-massive shale intercalated with fine-grained sandstone (Figure 2(A)); and (ii) Parit Member (replacement rock and upper succession): contains hematite- and magnetite-beds (Figure 2 and 4). A gradual transition between the two members is evident, initially confined to bedding planes and later affecting entire beds (Figure 2 and 11).

Preservation significance: Two modes of preservation are classified: (i) primary preservation and (ii) diagenetic preservation. Two styles of primary preservation, known as "ichnofabrics," are differentiated: (a) deep tiering, marked by *Chondrites* and *Thalassinoides*, and (b) shallow tiering, represented by *Planolites* and root traces. (Figure 10).

Diagenetic significance: Based on the diverse styles of diagenetic preservation, three stages of diagenesis are examined (Figure 9 and 10): (i) Early-stage diagenesis: marks the replacement of *Thalassinoides* and root traces by hematite and magnetite, with both bedding surfaces and entire beds, mediated by bacterial iron mineralization. It occurs after colonization but before infilling of *Thalassinoides*, in which roots were altered following root disintegration (Figure 2, 4-10). (ii) Mid-stage diagenesis shows that the primary infill of *Thalassinoides* was eroded, and the secondary infill of yellowish-brown sandy siltstone derived from the overlying sediment was redeposited in the voids of eroded *Thalassinoides* (Figure 4(A-C), 5, 6(A-B) and 10). It exhibits a reshaping of *Thalassinoides*. Several hematite and magnetite boulders derived from the Parit Member were redeposited along the coastline (Figure 3(B)). The features reflect evidence of region-wide unconformities between the Kati Formation and the overlying sediment during Quaternary seafloor and coastline migration (Figure 9-11). (iii) Late-stage diagenesis: marks recent to subrecent weathering processes, producing red-stained shale, limonite- and goethite-replacement roots,

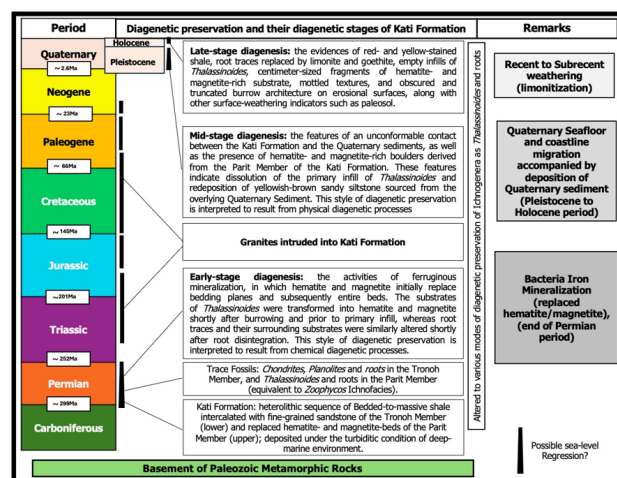


Figure 9. Time-relevant diagram of diagenetic modifications and their stages in the Kati Formation, highlighting two significant diagenetic episodes related to diagenetic preservation of trace fossils: (i) the end-Permian period reflecting significant episodes of chemical diagenetic modification; and (ii) the Pleistocene period representing remarkable episodes of physical diagenetic modification (Ma = Million years ago).

eroded empty infill of *Thalassinoides*, and hematite- and magnetite-fragments lying on the unconformity surface, obscured burrows and mottled textures (Figure 2, 5, 6(A-B), 7(A-B), 8(A-B, E) and 9-11).

Late Carboniferous - Permian Kati Formation		Trace Fossils				Diagenetic Alteration		
		Tronoh Member				Parit Member		
		Chondrites	Planolites	Root Traces	Thalassinoides	Process	Mechanism	Time
Mode of Preservation	Primary Preservation	Deep-tiering	yes	no	yes	Colonization		
		Shallow-tiering	no	yes	no			
		Root Disintegration	no	no	yes	PDC	After sedimentation	E
		Trace Fossils	unaltered	unaltered	H and M	CDC	BM	E
		Substrate	unaltered	unaltered	L and G	CDC	Iron source from Parit Mb.	L
			unaltered	H and M	H and M	CDC	BM	E
		Infill - primary	yes	yes	yes	PDC	volcanic sources?	E
		Primary infill - erosion	no	no	no	PDC	CH	M
		Infill - secondary	no	no	no	PDC	CH	M
		Unconformity between Kati Fm and Quaternary sediment	no	no	no	PDC	CH	M
	Diagenetic Preservation	Hematite and magnetite boulders	no	no	no	PDC	CH	M
		Burrow substrate fragmentation	no	no	no	PDC	RW	L
		Mottled structures	no	no	no	PDC	RW	L
		Eroded secondary infill (voids)	no	no	no	PDC	RW	L
		Red to yellow stain of shale	no	no	no	PDC	RW	L

Note: H and M=Replaced Hematite and Magnetite; L and G=Replaced Limonite and Goethite; CDC=Chemical Diagenetic Changes; PDC=Physical Diagenetic Changes; BM=Bacterial Iron Mineralization; CH=Coastline migration with deposition of Quaternary sediment; RW=Recent to subrecent weathering; E=Early-stage diagenesis; M=Mid-stage diagenesis; L=Late-stage diagenesis.

Figure 10. Summary of trace fossils, primary preservation and diagenetic preservation, and their diagenetic events and mechanisms of the Kati Formation.

Mineralization significance: Based on ferruginous mineralization, two groups are recognized, corresponding to two stages of diagenesis: (i) **hematite and magnetite replacement**, which replaced substrate and burrow of *Thalassinoides* and roots, attributed to the early-stage diagenesis (Figure 4-5, 6(A-B), 7(C-D), 8(C-D), 10), and (ii) **limonite and goethite replacement**, which occurs primarily within root traces, attributed to the late-stage diagenesis (Figure 2, 7(A-B), 8(A-B, E), 10).

Along with the mid-stage diagenesis, the formation served as the seafloor during the initial transgressive phase, contemporaneous with Quaternary sediment deposition (Figure 2(A-B), 3(A)). The Parit Member occupied a dominant seafloor position across much of the study area; however, it was locally removed by high-energy wave

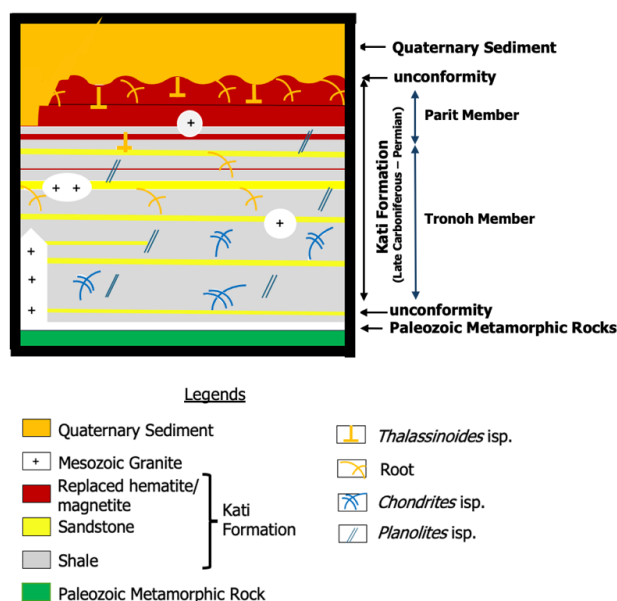


Figure 11. Schematic diagram of the reconstruction of stratigraphy of the Kati Formation (newly proposed members: Tronoh Member and Parit Member), adjacent to the underlying and overlying stratigraphic sequences (Not to scale).

action within the coastal swash zone. Consequently, the Tronoh Member was exposed at the seafloor in certain areas, where it now exhibits unconformable contacts with the overlying Quaternary Sediment (Figure 3(A), 9, 11).

Discussion

The following highlights the scientific problems and enigmas of the present study.

Ichnogenus *Chondrites* is the only reliable and representative trace fossil in interpreting the paleoecological setting and depositional environment of the formation. 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.

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 [14-16]. The content of trace fossils, consistent with characteristics of the *Zoophycos* Ichnofacies, is considered to correspond to pelagite/hemipelagite deposits [96]. 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, and bottom currents - determine sediment deposition; hence, a variety of facies including pelagites/hemipelagites, contourites, turbidites and hyperpycnites [99]. 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 [96-102].

Moreover, it is strongly constrained and challenging to conclude 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 deposition have been documented [103]. Collectively, these lithologies represent 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 deep-sea in origin [103]. 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 unique depositional site and is also quite different from the various depositional settings of the Sibumasu block of the Gondwana Supercontinent at the end of the Permian by previous authors.

Despite the study of trace fossils and a paucity of data analysis of lithological characteristics and their lithofacies variation due to ferruginous mineralization, the relationships among sea-level changes, ferruginous mineralization, *Thalassinoides*-producing organisms, and the taxonomy of root traces in the Kati Formation of the Permian basin remain controversial and enigmatic due to the limited information in the current research and the paucity of direct analogs in both recent and ancient sedimentary records at present.

On the other hand, no direct evidence of transgressive or regressive boundaries associated with sea-level changes (e.g., Carboniferous - Permian glaciation) is recorded in the formation. Instead, the paleoecological setting represents a relatively stable deep-marine environment inhabited by both burrowing and rooted organisms. The depositional environment appears to reflect a deep-marine pelagite/hemipelagite setting, where unusual root trace fossils and bioturbation structures co-occur. This suggests that the basin supported an atypical deep-sea ecosystem, potentially reliant on chemosynthesis rather than photosynthesis. Aphotic deep-sea

ecosystems are sustained by chemosynthesis, in which bacteria and archaea harness chemical energy from substances such as hydrogen sulphide (H_2S) and methane (CH_4) to produce biomass [104,105]. Chemosynthetic microorganisms form the base of biological communities at hydrothermal vents and cold seeps, where they exploit chemical energy from reduced compounds such as hydrogen sulphide and methane [103]. These chemosynthetic systems support diverse and highly specialized faunal assemblages, including shrimp, polychaetes, nematodes, tubeworms, flatworms, mollusks, and crustaceans, all of which thrive independently of sunlight [106]. Given these analogues, the deep-sea root systems and associated trace fossils of the Kati Formation may reflect ancient chemosynthetic ecosystems, in which plant-like organisms or root analogues adapted to deep-marine conditions through symbiotic relationships with chemosynthetic microorganisms. Although enigmatic, this interpretation provides a novel framework for exploring non-photosynthetic or hybridized plant strategies in deep-marine environments, representing an emerging frontier in ichnology and palaeoecology. Accordingly, the deep-marine system of the Kati Formation may have supported chemosynthetically adapted plants and burrowing organisms, including *Thalassinoides* producers, forming a distinctive deep-sea ecosystem.

The basic hypothesis of the common occurrence of wood/plants reflects an ancient continental environment. However, plants crossed the barrier between life in water to life in the atmosphere [107]. There are three types of wood/plant preservation: petrified wood/plant, coalified wood/plant and mummified wood/plant, known as Rhizoliths, that are found in a remarkable variety of locations around the world. Petrified wood/plant is the preservation of ancient trees in stone. The process of forming petrified wood, known as petrification, occurs when trees are rapidly buried under layers of sediment, preventing them from decaying. Over time, mineral-rich water flows through these sediments, gradually replacing the organic material in the wood/plant with minerals like silica, calcite, quartz or others. This transformation turns the wood into a three-dimensional fossil, retaining intricate details of the original tree, including its cellular structure and growth rings and retaining part of the shape of the original tree. Petrification of wood involves two processes: permineralization and replacement; instead, both processes may occur contemporaneously during diagenesis [108,109].

Moreover, mummified wood/plant retains a high proportion of the original cellulosic constituents, in contrast to coalified wood, where loss of cellulose and hemicellulose results in relative enrichment of lignin [110]. During coalification, wood and other plant remains are transformed into peat as a result of humification and gelification, which are biochemical processes. Humification involves the decomposition of original organic constituents to produce dark brown organic polymers [110]. In the present study of ferruginous mineralization, under conditions where wood/plant material, along with *Thalassinoides*, is unprotected from microbial degradation and exposure to harsh chemical environments, the tissues are mineralized completely without remaining original organic matter.

Conclusion

The concluding remarks of the present study are outlined below:

1. The Kati Formation comprises two new members: (i) Tronoh Member and (ii) Parit Member, and contains trace fossils such as *Chondrites*, *Planolites*, *Thalassinoides* and root traces. The Tronoh Member, as the parent rock and lower succession, comprises dark grey, bedded-to-massive shale intercalated with thin-bedded, fine-grained sandstone. The Parit Member, as a replacement origin and upper succession, contains hematite- and magnetite-beds. A gradual transition between the two members is observed, initially confined to bedding planes and later affecting entire beds.

2. The Kati Formation, lying unconformably on the Paleozoic metamorphic rocks, intruded by the Mesozoic granites, and underlain unconformably by the Quaternary Sediment corresponding to the Simpang Formation, is documented.

3. Two modes of burrow preservation are classified: (i) primary

preservation and (ii) diagenetic preservation. The primary preservation reflects the substrate tiered by bioturbators, and two styles are distinguished: (a) deep tiering, marked by *Chondrites* and *Thalassinoides*; and (b) shallow tiering, represented by *Planolites* and root traces.

4. Based on the diverse styles of diagenetic preservation of burrows, three stages of diagenetic events are examined:

- (a) Early-stage diagenesis marks the substrate of *Thalassinoides* and root traces replaced by hematite and magnetite, mediated by bacterial iron mineralization, leading to widespread ferruginous replacement of both bedding surfaces and entire beds with basin-wide scales at the end of the Permian. Mineralization of the *Thalassinoides* substrate indicates that it occurred after burrowing and colonization, but before primary infilling. Mineralization of both the primary position of root traces and the substrate is present. Additionally, mineralization of both the disintegrated roots marked on the bedding plane and the substrate is also present, indicating that these roots were redeposited and later transformed into hematite and magnetite.

- (b) Mid-stage diagenesis shows that the primary infill of *Thalassinoides* was eroded, and the secondary infill of yellowish-brown sandy siltstone derived from the overlying sediment was redeposited in the voids of eroded *Thalassinoides*. It exhibits a reshaping of *Thalassinoides*. Several hematite and magnetite boulders derived from the Parit Member were accumulated along the coastline. The features reflect evidence of region-wide unconformities between the Kati Formation and the overlying Sediment during Quaternary seafloor and coastline migration, accompanied by erosion, transportation and deposition of sediments.

- (c) Late-stage diagenesis exhibits red- and yellow-stained shale during the recent to subrecent weathering processes. Roots were altered to limonite and goethite. Voids (infill dissolution) are present because both primary and secondary infills have been removed. Centimetre-sized hematite- and magnetite-substrate fragments lie on the unconformity surface. Obscured burrow architectures on erosional surfaces, mottled textures, and surface weathering products such as paleosol are also noted.

5. Although the relationship between ferruginous mineralization (replacement of hematite and magnetite) and ichnological activity remains to be investigated on a regional scale in Southeast Asia, it may be linked to environmental perturbations associated with the End-Permian Mass Extinction (EPME). The origin of ferruginous mineralization is still debated; however, microbial mediation - especially bacterial iron mineralization - is considered a plausible mechanism. Although its importance in geochemical cycling is well recognized, the evolutionary history and environmental controls of this microbial process remain poorly understood. Future research activities are required.

6. Notably, the occurrence of root systems in a deep-marine depositional setting and their taxonomic classification remain to be investigated in further research. While root systems are well documented in continental environments from the Devonian onward, their preservation in the Permian deep-marine system is highly unusual. This is comparable to modern hydrothermal vents and cold-seep ecosystems. Further research is required to elucidate the interactions among deep-marine vegetation or root analogues, *Thalassinoides* burrowers, and ferruginous mineralization processes in the Permian basin of the Gondwana Supercontinent.

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.

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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, by permission. Data will be shared on request to the corresponding author.

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