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Ichnofabric variability and paleoenvironmental insights from the Middle Bhuban rocks of Aizawl, Mizoram, India

Chinmoy Rajkonwar[1,2*], Raghavendra Prasad Tiwari[3]

[1]CSIR-North East Institute of Science and Technology, Jorhat, India
[2]Academy of Scientific and Innovative Research, Ghaziabad, India
[3]Central University of Punjab, Bathinda, Punjab, India

*Corresponding author: chinmoyearth@gmail.com

Abstract - The Middle Bhuban succession of the Surma Group is extensively exposed in the Aizawl district of Mizoram, India; the study area predominantly features alternating intervals of shale, sandstone, and siltstone. The sediments exhibit significant bioturbation and host a diverse array of seventeen ichnofossils. Six ichnofabrics have been identified, including *Cochlichnus*, *Funalichnus*, *Palaeophycus*, *Psilonichnus*, *Teredolites,* and *Thalassinoides*. The bioturbational ichnofabrics are primarily composed of simple feeding traces (*Cochlichnus*, *Funalichnus*, *Psilonichnus*, and *Thalassinoides*) and the dwelling burrow (*Skolithos*) created by opportunistic organisms colonizing the foreshore/shoreface zone. In contrast, the bioerosional ichnofabric, characterized by the ichnogenera *Teredolites*, is confined to rippled sandstone deposits found in the foreshore/nearshore zone. The ichnofabrics display abrupt changes in colonization patterns (ichnofossils, ichnoassemblages, and tiering styles) throughout the succession, reflecting the benthic infaunal community responses to fluctuations in sedimentation rates and sea level dynamics. Sedimentological and ichnological analysis of the Middle Bhuban rocks in the study area suggests that the area was deposited under foreshore/shoreface environments, with a temporary sea-level rise indicated by the backshore environment marked by the *Teredolites* ichnofabric.
Key words: Aizawl, ichnofabric, Middle Bhuban, paleoenvironment, Surma Group.

Riassunto - Variabilità dell'icnofabric e implicazioni paleoambientali nelle rocce del Bhuban Medio di Aizawl, Mizoram, India.
La successione del Bhuban Medio del Surma Group affiora estesamente nel distretto di Aizawl, nello stato di Mizoram (India). L'area di studio è caratterizzata prevalentemente da intervalli alternati di argillite, arenaria e siltite. I sedimenti mostrano una bioturbazione significativa e ospitano una ricca associazione di diciassette icnofossili. Sono stati identificati sei icnofabric, tra cui *Cochlichnus*, *Funalichnus*, *Palaeophycus*, *Psilonichnus*, *Teredolites* e *Thalassinoides*.
Gli icnofabric bioturbazionali sono principalmente costituiti da semplici tracce di alimentazione (*Cochlichnus*, *Funalichnus*, *Psilonichnus* e *Thalassinoides*) e dalla tana di abitazione (*Skolithos*) creata da organismi opportunisti che colonizzavano la zona di foreshore/shoreface (battigia/litorale sommerso). Al contrario, l'icnofabric bioerosionale, caratterizzato dall'icnogenere *Teredolites*, è confinato ai depositi di arenaria ondulata rinvenuti nella zona di foreshore/nearshore (battigia/litorale prossimo alla costa).

Gli icnofabric mostrano cambiamenti repentini nei modelli di colonizzazione (icnofossili, icnoassociazioni e stili di tiering) lungo l'intera successione, riflettendo le risposte delle comunità bentoniche endobionti alle variazioni nei tassi di sedimentazione e nelle dinamiche del livello del mare.
Le analisi sedimentologiche e icnologiche delle rocce del Bhuban Medio nell'area di studio suggeriscono che i depositi si siano formati in ambienti di foreshore/shoreface, con una temporanea risalita del livello marino indicata dall'ambiente di retrospiaggia (backshore), contraddistinto dall'icnofabric a *Teredolites*.
Parole chiave: Aizawl, Bhuban Medio, icnofabric, paleoambiente, Surma Group.

Introduction

Ichnofossils are widely used as a valuable tool for interpreting paleoenvironmental conditions prevailing during deposition and establishing stratigraphic frameworks, especially in successions where body fossils are scarce (Mcllroy, 2004; Miller, 2001; Kundal & Mude, 2008; Singh *et al*., 2010; Kundal & Dharashivkar, 2006). Although the Surma succession in Mizoram exhibits a diverse and rich assemblage of body fossils as documented by various researchers (Tiwari & Satsangi, 1988; Tiwari *et al*., 1997, 1998; Tiwari & Bannikov, 2001; Tiwari & Kachhara, 2000, 2003; Tiwari, 2001, 2006; Srivastava *et al*., 2008; Ralte *et al*., 2009), their occurrence is sporadic and the intervals between fossiliferous horizons are typically devoid of body fossils. As such, these are not very helpful in deciphering depositional set-up of the entire succession. Ichnofossils studies in Mizoram is however limited (Mehrotra *et al*., 2001, 2002; Tiwari *et al*., 2011, 2013; Rajkonwar *et al*., 2013, 2014; Lokho & Singh, 2013). Therefore, the paleoenvironmental framework of the Surma succession remains poorly understood.
Ichnological analysis of individual sedimentary units involves assessing the extent of bioturbation, which is valuable for interpreting colonization patterns. This allows for comparisons of ichnofossils on a bed-by-bed basis against established ichnofacies divisions (Moslow & Pemberton, 1988). The trace fossils observed in each sedimentary unit indicate the presence of highly specialized organisms capable of adapting to changing environmental conditions. Ichnofabric analysis is valuable for understanding the character of initial stages colonization by employing tiering principles under varying substrate conditions (Frey & Goldring, 1992). It may also help in deciphering the fine characterization of the foreshore-shoreface sedimentary sequence based on the traditional ichnofacies model (Seilacher, 1964; Pemberton & Wightman, 1992).
The present study focuses on a well-exposed section of the Bhuban Formation of Surma Group in Aizawl, Mizoram. This succession is characterized by highly bioturbated sandstones, shales, siltstones and their intercalations, hosting a remarkably diverse assemblage of trace fossils. Notably, this study represents the first detailed ichnofabric analysis of the Bhuban succession in Mizoram. The integration of ichnological data with lithofacies interpretation provides a significant advancement in the sedimentological and paleoenvironmental understanding of the region.

Materials and Methods

Trace fossils from the study area were systematically documented through field photography and, where feasible, collected for subsequent analysis. The specimens were examined in comparison with reference materials available in the repository of the Department of Geology, Mizoram University, as well as relevant published literature. Detailed lithological analysis was carried out for each rock unit, focusing on vertical and lateral continuity, sedimentary structures and biogenic features, which were synthesized into a lithostratigraphic column. Furthermore, the distribution patterns of trace fossils, including their orientation, preservation states and sedimentary associations, were meticulously recorded to support interpretations of the depositional environment.

Ichnogenera and ichnospecies were assigned following the binomial nomenclature system, in accordance with the guidelines of the International Code of Zoological Nomenclature (ICZN). The classification framework adopted follows the guidelines proposed by Simpson (1975) and Seilacher (1964, 1967). Field based stratigraphic observations were conducted to differentiate sedimentary beds within the study area, with particular emphasis on bedding planes and notable variations in grain size, sorting, color and sedimentary structures such as cross-bedding, ripple marks and mud cracks. These features provide critical insights into the prevailing depositional conditions.

Geological setting

The lithological succession of Mizoram primarily consists of sedimentary rocks which are categorized into three main groups i.e. the Barail Group (Oligocene), Surma Group (early to middle Miocene) and Tipam Group (late Miocene to early Pliocene). Among these, Surma Group is predominantly developed in the entire state, which is further subdivided into the Bhuban and Bokabil Formations. The Bhuban Formation is approximately 5000 m thick and consists of repetitive sequences of sandy and clayey rocks, predominantly sandstone, shale, siltstone and their intermixtures. Additionally, localized occurrences of calcareous sandstone, shell limestone and intraformational conglomerate are also present (Tiwari & Kachhara, 2003; Bharali *et al*., 2021). Based on the presence of sandy and clayey content and their alternation, the Bhuban Formation is subdivided into Lower, Middle and Upper Bhuban Units. Detailed stratigraphic and lithological characteristics of Mizoram are presented in Tab. 1 (Karunakaran, 1974; Ganju, 1975).

The study area is an ~ 46 m thick exposure of the Middle Bhuban sedimentary rocks along a road cut section situated towards the northern side of Aizawl city of Mizoram. The study area is located between 23°45′18.9″N to 23°46′21.36″N latitude and 92°44′53.15″E to 92°44′53.43″E longitude based on the Survey of India Topo-Sheet 84A/9 (Fig. 1).

Results

Lithology of the study area

The studied section in Aizawl district of Mizoram consists of alternating layers of sandstone, shale and silt of varying thickness (Fig. 2). The sandstone beds are typically medium to coarse grained and rich in quartz, exhibiting cross-bedding and ripple marks of varying scales. In contrast, the shale beds are predominantly clay-rich and display well-preserved laminations. A total of 13 distinct beds were identified in the study area based on their lithological variations, as shown in Fig. 3a. Their physical and ichnological characteristics of these beds were systematically documented. The beds are briefly described below in ascending order, from the lowermost exposed layer to the uppermost.

Bed no. 1: This bed is characterized by medium-grained, micaceous sandstone of grey color, spanning 1.5 m in thickness. It appears massive and lacks visible physical or biological structures, but significant for its fossil content, primarily comprising abundant species of the bivalve genus *Apolymetis* (Fig. 3b).

Bed no. 2: Comprising grey silty-shale, this layer extends 1.2 m in thickness. It is devoid of fossils and exhibits minimal physical and biological structures, except for thin silty partings.

Bed no. 3: This bed consists of grey, fissile shale, with a thickness of 1.4 m. Its fissile nature indicates its tendency to split easily along parallel planes.

Bed no. 4: Grey in color and massive, this medium-grained sandstone bed is 0.5 m thick. It typically lacks fossils and distinct bioturbation features, indicating minimal biological activity during deposition.

Bed no. 5: Grey, splintery shale characterizes this layer, which is 6 m thick. It does not contain body fossils but features a dominant structure known as *Thalassinoides*.

Bed no. 6: This bed displays alternations of sandstone and shale (Fig. 3c). The medium grained sandstone is brown in color and exhibits cross-lamination, whereas the shale contains interbedded sand layers showing ripple structures. Spanning 7 m, it hosts trace fossils like *Funalichnus bhubani*, indicating diverse sedimentary depositional conditions.

Bed no. 7: Grey and well-sorted, this medium-grained sandstone bed is massive, measures 1 m in thickness and displays ripple marks (Fig. 3d). It lacks other distinct physical and biological structures, suggesting a relatively uniform sedimentary environment during its formation.

Bed no. 8: This bed is composed of grey silty-shale, displaying small scale cross laminations. It spans 4.5 meters in thickness and contains abundant structures of *Psilonichnus upsilon* (Fig. 3e) and *Psilonichnus* isp.

Bed no. 9: The bed is mainly consisting of sandstone-shale intercalation and is approximately 9 m in thickness, highly bioturbated units and consisting of varieties of abundant trace fossils of *Cochlichnus anguineus* (Fig. 3f)*, Palaeophycus tubularis* (Fig. 4a)*, Rhizocorallium genense* (Fig. 4b)*, Skolithos* isp. (Fig. 4c)*, Thalassinoides suevicus* (Fig. 4d).

Bed no. 10: This layer consists of medium grained, brown micaceous sandstone, spanning 5 meters in thickness. It displays ripples at the top and contains mud clasts (Fig. 4e). Numerous specimens of *Pinna* shells were found within this bed (Fig. 4f). The sandstone shows high bioturbation and hosts a diverse array of trace fossils, including *Cochlichnus anguineus*, *Gordia marina* (Fig. 4g), *Palaeophycus striatus* (Fig. 4h), *Rhizocorallium* isp. and *Thalassinoides suevicus*.

Bed no. 11: This layer consists of brown silty sandstone, 2 m thick. Although it lacks distinct sedimentary structures, occasional biogenic laminae are present.

Bed no. 12: Brown colored medium grained sandstone, 4.5 m thick, contains mud clasts and frequently xylic substances. It shows frequent bioturbation, with evident boring structures of *Teredolites*.

Bed no. 13: This layer is composed of brown silty-sandstone, spanning 3 m in thickness. It lacks distinct physical and biogenic structures.

Ichnological analysis

A detailed ichnological investigation of the studied section has identified twelve distinct ichnospecies. This diverse assemblage of trace fossils exhibits a mixture of behavioral categories, including domichnia (dwelling structures include *Funalichnus bhubani*, *Psilonichnus upsilon*, *Skolithos* isp.), fodinichnia (feeding burrows of *Cochlichnus anguineus*, *Palaeophycus striatus*, *Palaeophycus tubularis*, *Rhizocorallium jenense*, *Teredolites clavatus*, *T. longissimus*, *Thalassinoides horizontalis* and *T. suevicus*.) and pascichnia (grazing trails like *Gordia marina*). The variety of ichnofossils reflect a dynamic paleoenvironment with multiple ecological niches and complex interaction between the organisms and their sedimentary habitat.

Ichnofacies analysis

The Middle Bhuban sedimentary succession of Mizoram (early to middle Miocene), is significant for its fossiliferous and bioturbated layers. This succession is characterized by a predominance of feeding traces (fodinichnia), which indicate the activity of organisms searching for food within the sediment. These traces are more common than dwelling traces (domichnia), which represent the permanent or semi-permanent burrows of organisms and grazing traces (pascichnia), which are indicative of surface feeding or grazing activities. The trace fossil assemblages are influenced by factors such as substrate type, hydrodynamic conditions and bathymetry. Based on these factors, they are grouped into four ichnofacies, *Skolithos*, *Cruziana*, *Teredolites* and a mixed *Skolithos*-*Cruziana* ichnofacies (Seilacher, 1967; Bromley, 1996). The ichnological features have been further classified based on their ethological and topological characteristics and are presented in Tab. 2.

The *Skolithos* ichnofacies is represented by ichnogenera such as *Funalichnus* and *Psilonichnus*, which develop in the sandstone-shale alternations and cross-laminated silty shales, respectively. These suspension-feeding burrows suggest an unconsolidated, shifting substrate and indicate moderate to high energy wave and current environments typical of a tide dominated shoreface to foreshore environment. The *Cruziana* ichnofacies is observed in soft-ground environments with moderate to high diversity. It is characterized by the predominance of suspension feeding and deposit feeding activities as well as grazing trails, that includes *Cochlichnus anguineus*, *Gordia marina*, *Palaeophycus striatus*, *Palaeophycus tubularis* and *Rhizocorallium jenense*. These ichnofossils suggest a low to moderate energy conditions and fluctuating sea level in shallow marine depositional environment (Gilbert & Benner, 2002; Singh *et al*., 2010). The *Skolithos-Cruziana* mixed ichnofacies is identified by the presence of common ichnospecies such as *Cochlichnus anguineus*, *Palaeophycus tubularis*, *Skolithos* isp. and *Thalassinoides suevicus*. This ichnofacies indicates fluctuating energy conditions in a stressful environment with variable substrate consistency (Joseph *et al*., 2012). The *Teredolites* ichnofacies, found in hardgrounds with low diversity, is characterized by *Trypanites* borings (Bromley *et al*., 1984). This ichnofacies features *Teredolites longissimus* and *T. clavatus*, typically associated with woody or xylic substrates. *Teredolites* infested wood logs are found across a wide range of marine facies and have often been described in deposits linked to relative sea level rise, particularly within transgressive system tracts (Savrda, 1991; Savrda & King 1993; Tewari *et al*., 1998; Desai, 2013). Savrda (1991) also suggested that low sedimentation rates contributed to the concentration of these logs.

Ichnofabrics analysis

Ichnofabrics represent the total modification of internal structure and texture of the host sediment resulting from bioturbation and bioerosion at various intensities (Bromley & Ekdale, 1986). In marginal marine environments, organisms typically responded rapidly to even minor changes in environmental conditions. The ichnofossil assemblage preserved within the Bhuban Formation of the study area ranges from monodominant to moderately diverse. Within the four identified ichnofacies, six distinct ichnofabrics have been recognized in the vertical profile (Fig. 5), each designated according to the most representative ichnotaxon. These ichnofabrics are characterized based on their trace fossil composition, tiering patterns, degree of bioturbation and their relationship to primary sedimentary structures.

Cochlichnus *ichnofabric*

This ichnofabric occurs within brown-coloured, medium-grained, micaceous sandstone, which is highly bioturbated and hosts a diverse assemblage of trace fossils, with *Cochlichnus* being the most dominant ichnotaxon. The sandstone unit is characterized by the presence of mud clasts, ripple marks on the upper bedding surfaces and is notably fossiliferous, containing abundant and well-preserved specimens of *Pinna*. Lithofacies analysis indicates that this medium-grained, micaceous sandstone was deposited under moderate energy conditions typical of shoreface to offshore transition zones, influenced by episodic turbidity currents and continuous background sedimentation (Reading, 2009; Howard & Reineck, 1981; Bayet-Goll, 2022). The presence of mud clasts suggests episodic high-energy turbidity currents delivering sediments from distal sources, while the small, low-amplitude ripple marks suggest the action of slowly shifting currents. The ichnofossil assemblage, comprising *Cochlichnus anguineus*, *Gordia marina*, *Palaeophycus striatus* and *Thalassinoides suevicus*, exhibit a wide range of behavioural patterns. *Rhizocorallium* occurs at the surface tier, *Cochlichnus* and *Gordia* at shallow depths just below the surface, *Palaeophycus* at intermediate levels and *Thalassinoides* at the deepest tier, collectively indicating a well-oxygenated substrate with active water circulation. The dominance of horizontal traces and soft, unconsolidated substrate characteristics are indicative of a typical *Cruziana* ichnofacies. The abundant occurrence of both shallow and deep-tier trace fossils of deposit feeders further indicates organic-rich sediment accumulation under predominantly low-energy conditions within a shoreface setting (Bayet-Goll, 2022; Yang *et al*., 2024).

Funalichnus *ichnofabric*

This ichnofabric is developed within a sandstone-shale alternation unit, prominently expressed in medium-grained, brown-coloured sandstone exhibiting cross-lamination and ripple marks. These sedimentary structures reflect wave or current-dominated conditions under moderate to high hydrodynamic energy, typical of shoreface environments (Leckie & Duke 1986; van Cappelle *et al*., 2016; Levell *et al*., 2020). Within this lithofacies, *Funalichnus bhubani* (Fig. 6a) occurs as a monospecific ichnofabric, forming deep-tier endichnial burrows within the shifting substrate. The trace-making organisms were likely suspension feeders inhabiting high-energy, well-oxygenated settings. The vertical, cylindrical burrows of *Funalichnus* are diagnostic of the *Skolithos* ichnofacies, which is characteristic of environments with high sedimentation rates and physically reworked substrates (Seilacher 1967; MacEachern and Pemberton 1992). The combination of lithological features such as, cross-lamination, ripple marks and the dominance of *Funalichnus* indicates deposition under persistent wave or current activity, typical of high-energy settings in the lower foreshore to upper shoreface zone. These dynamic conditions, acting on unconsolidated and shifting sediments, support the interpretation of a sheltered yet energetic shoreface environment for the development of this ichnofabric (Tiwari *et al*., 2013).

Palaeophycus *ichnofabric*

The *Palaeophycus* ichnofabric is developed within a highly bioturbated sandstone-shale alternation unit measuring approximately 9 m in thickness. The sandstone beds are fine-grained and range from massive to weakly laminated, with planar laminations often obscured due to intense bioturbation and textural reworking. This lithofacies assemblage reflects deposition under low to moderate energy conditions in a shallow marine setting, particularly within the offshore to offshore transition zone of a shoreface system (Davies & Ethridge, 1975; Mode *et al*., 2017; Hou *et al*., 2024).

The ichnofabric hosts a diverse suite of trace fossils, including *Cochlichnus anguineus*, *Palaeophycus tubularis*, *Skolithos* isp. and *Thalassinoides suevicus* (Fig. 6b), representing a broad spectrum of behavioural strategies such as grazing, feeding, and dwelling. These traces show a wide vertical tiering, from shallow to deep levels, where *Skolithos* is interpreted as a pre-depositional structure, while the remaining ichnotaxa belong to post-depositional suites. The coexistence of vertical and horizontal structures, along with the behavioural diversity, indicates a mixed *Skolithos-Cruziana* ichnofacies, typical of soft, unconsolidated substrates with moderate sedimentation rates and adequate bottom-water oxygenation. The integration of ichnological and lithological evidence strongly supports deposition in a low to moderate energy offshore to shoreface transition environment, consistent with a gradually shifting sedimentary regime under persistent but non-turbulent hydrodynamic conditions (Joseph *et al*., 2012; Patel *et al*., 2012).

Psilonichnus *ichnofabric*

The *Psilonichnus* ichnofabric is developed in silty shales characterized by small scale cross-lamination and horizontal lamination, indicative of alternating flow regimes, likely driven by tidal or wave influence in a shallow coastal setting with shifting, unconsolidated sediments (Carey & Roy, 1985; Clarke & Parnell, 1999). The ichnofabric is dominated by *Psilonichnus upsilon*, which occurs as simple, straight to slightly curved vertical burrows that penetrate multiple silt-shale layers. These structures are distinct from the host sediment in terms of colour and infill material, and they are not associated with burrow mottling or disrupted laminae, suggesting minimal post-depositional mixing. The ichnological assemblage is poorly diverse, with low to moderate bioturbation intensity, yet the high density of *Psilonichnus* indicates a stressed but productive environment. The preservation of physical sedimentary structures alongside ichnofossils suggests episodes of sedimentation and erosion under fluctuating energy conditions (Djouder *et al*., 2018). These conditions, combined with the textural variability from silt to clay, point to a shoreface environment affected by variable sediment supply and salinity changes (Taylor *et al*., 2003). The dominance of a single ichnotaxon within laminated silty-shales highlights an environment with episodic energy fluctuations, where organisms adapted to shifting substrates and periodic stress thrived under low diversity but high abundance colonization.

Thalassinoides *ichnofabric*

This ichnofabric is developed within grey, fine grained, splintery shale (bed no. 5), which reflects quiet water conditions with minimal wave or current action and slow sedimentation, typical of offshore transition to lower shoreface environments (Ali *et al*., 2024; Mout & Sarmah, 2022). The shale hosts a monospecific assemblage consisting solely of *Thalassinoides horizontalis* (Fig. 6c). These burrows are filled with surrounding sediment and their margins are distinguished by a contrasting dark colour relative to the host shale, facilitating clear identification. Although generally sparse, localized concentrations of burrows are observed.

The absence of primary lamination or additional trace fossils in this fine-grained, cohesive substrate suggests complete bioturbation by shallow-tier burrowers. The *Thalassinoides* structures represent the activity of suspension and deposit feeders, likely formed by crustaceans or polychaetes inhabiting well oxygenated, soft-ground settings (Bromley & Frey, 1974; Kern & Warme, 1974). The characteristics of both the sediment and ichnofabric indicate a low-energy, oxygenated shallow marine environment, most likely within the lower shoreface to offshore transition zone, where slow accumulation of fine-grained sediments provided a stable substrate for colonization. The relatively low diversity but presence of well-developed *Thalassinoides* systems suggests opportunistic colonization in soft, stable and moderately cohesive substrates under conditions of reduced physical disturbance (Ekdale *et al*., 1984; Joseph *et al*., 2012).

Teredolites *ichnofabric*

The *Teredolites* ichnofabric is developed on xylic substrates, primarily fossilized wood logs, within a 4.5 m thick unit of medium grained, brown sandstone containing abundant mud clasts. The presence of these mud clasts within medium grained sandstone suggests episodic high-energy depositional events, such as storm-induced or tidal currents capable of entraining and depositing both sand and mud rip-up clasts in a dynamic nearshore setting (Scholle & Spearing, 1982; Ogbahon & Opeloye, 2018; Ningthoujam *et al*., 2022). These energy fluctuations likely created favourable conditions for the transport and temporary exposure of wood debris prior to its rapid burial. The embedded wood logs are consistently bored by bivalves, producing a *Teredolites* ichnofabric characterized by two distinct ichnospecies: *T. clavatus* (Fig. 6d-f) and *T. longissimus* (Fig. 6g-h). These borings reflect intense bioerosion of organic substrates in marine settings, and the presence of such bored xylic material is indicative of wood-grounds, laterally continuous wood rich substrates commonly formed in coastal swamp environments. Colonization of these substrates is typically linked to post-lowstand marine transgressions, wherein previously exposed terrestrial material becomes available for marine biotic activity following flooding events (Hasiotis *et al*., 2013).

The occurrence of the ichnofabric within a transgressive sandstone unit further supports its stratigraphic significance as a transgressive system tract (TST) indicator (Savrda 1991). This interpretation is consistent with earlier studies reporting *Teredolites* infested wood from transgressive marine deposits in a variety of settings, including the Ukra Hill Member of the Western Kachchh region (Desai, 2013), the Cauvery Basin (Tewari *et al*., 1998), early Eocene deposits of India (Kumar *et al*., 2011), and the early to middle Miocene Bhuban Formation of Mizoram (Rajkonwar *et al*., 2014). In such contexts, increase in accommodation space and relatively high sedimentation rates during transgression enhance the preservation potential of xylic substrates and their associated borings. Integrating the sedimentological features and the *Teredolites* ichnofabric provide strong evidence for deposition in a nearshore, high-energy, transgressive marine environment, where storm activity and tidal currents transported woody debris and mud clasts, enabling opportunistic colonization and preservation during subsequent phases of marine flooding.

Discussion

The Middle Bhuban rocks exposed in the study area exhibit bioturbational (*Cochlichnus, Funalichnus*, *Palaeophycus, Psilonichnus* and *Thalassinoides*) and bioerosional (*Teredolites*) ichnofabrics. Bioturbational ichnofabrics are mainly developed in sandstone, silty-sandstone and shales and represent low to moderate bioturbation. The succession shows great variability from monospecific to diverse assemblages and characterized by wide range of tiering structures (such as shallow, medium and deep). The trace fossil assemblages reflect fully marine to marginal marine environmental elements of soft and unconsolidated ground.

Thalassinoides ichnofabric developed in shale, is monospecific and interpreted as having formed in normal marine environment of shoreface zone and occur at deep tier. Monospecific nature also indicates highly specialized deposit feeder colonized in the relatively cohesive substrate. The ichnofabrics of *Funalichnus* and *Psilonichnus* are also characterized by monospecificity. These ichnofabrics are found in shale and silty-shale beds which are well exposed in the middle portion of the area. Tiwari *et al*. (2013) described that the occurrence of *Funalichnus bhubani* indicates a shift in the colonization of benthic community, while a marine environment of backshore marginal area is indicated by *Psilonichnus* (Frey *et al*., 1984). Being a member of *Skolithos* ichnofacies the ichonofossils *Funalichnus* and *Psilonichnus* also suggests rapid changes in sedimentation rates in high-energy environment and unconsolidated, shifting substrate due to surface sediments erosion

(Walker & James, 1992; Singh *et al*., 2010). Tiwari *et al*. (2013) also suggested an unconsolidated and shifting nature of substrate in sheltered foreshore and shoreface environments for these ichnofabric. The overlying sandstone-shale intercalation and micaceous sandstone bed are moderately bioturbated and shows complex-tier marking a change in hydrodynamic conditions. Ichnofabrics *Cochlichnus* and *Palaeophycus* show most diverse structure as compared to any other ichnofabrics and consist of abundant horizontal structures (*Cochlichnus*, *Palaeophycus*, *Rhizocorallium* and *Thalassinoides*) of low specialized deposit feeder of fully marine environment. It is characterized by shallow-tier with *Planolites* and *Rhizocorallium*, a mid-tier *Cochlichnus* and *Palaeophycus* and deep-tier *Skolithos* and *Thalassinoides*. The prevalence of horizontal deposit feeding traces suggests a very calm aquatic environment with minimal disturbances, where organic matter can be deposited alongside sediments (Joseph *et al*. 2012). These assemblages indicate a transitional zone towards a lower shoreface environment, possibly experiencing quieter offshore conditions, likely at the lowest energy levels (Fürsich & Heinberg, 1983). The presence of mid and deep-tier structures created by semi-vagile and vagile deposit feeders indicates oxygen-rich environments, which represent intermediate to equilibrium or climax states in terms of trace fossil activity (Bromley 1990). A 5 m thick sandstone bed is exposed above a shale bed, exhibiting grazing trails attributed to *Gordia* ichnogenus and feeding burrows such as *Palaeophycus*, *Rhizocorallium* and *Thalassinoides*. *Thalassinoides* is commonly associated with oxygen rich conditions and soft yet cohesive substrates (Bromley & Frey, 1974; Kern & Warme, 1974; Ekdale *et al*., 1984; Bromley, 1996). This assemblage predominantly exhibits prominent horizontal feeding structures, suggesting environmental conditions characterized by low to moderate energy and soft, unconsolidated substrate at shoreface environments.

The bioerosional ichnofabric observed in xylic substrates or woodgrounds is prominently found at the top of the succession within medium-grained, buff-colored sandstone. This substrate-controlled ichnofabric exhibits well-developed boring structures such as *Teredolites clavatus* and *Teredolites longissimus*. The *Teredolites* ichnofabric holds significant stratigraphic value, marking sea-level changes more effectively than bioturbational ichnofabrics (Savrda, 1991). The presence of planar laminated structures in the sandstone suggests deposition in a coastal, deltaic plain or estuarine environment characterized by shallow-water sand flats. Mud clasts within the sandstone are interpreted as the result of intensive bed disruption and the partial or complete erosion of underlying beds, likely caused by the passage of strongly erosive currents or by bank collapses into flowing water (Potter *et al*., 2005). The wood-derived material containing *Teredolites* indicates transport through shallow fluvial channels and subsequent deposition on adjacent sand flats.

Haq *et al*. (1987, 1988) interpreted Mesozoic and Cenozoic sea level fluctuations using an integrated approach combining chronostratigraphy, biostratigraphy and magnetostratigraphic data. Their global eustatic sea level curve records a short lived highstand during the Langhian to early Serravallian stages of the Miocene epoch (~16 to 10 Ma). In the present study, the occurrence of *Teredolites* dominated ichnofabrics in xylic substrates near the top of the succession along with planar-laminated sandstone and mud clasts indicates a shallow marine transgression over a coastal plain or estuarine environment. This transgressive setting can be regionally correlated with a third-order eustatic sea level rise during the Miocene, likely associated with cycles 2.3 to 2.6 of the TB2 second-order supercycle as defined by Haq *et al*. (1987, 1988). Such a correlation suggests that the observed ichnofabric and associated sedimentological features not only reflect local depositional dynamics but also broader global sea level fluctuations driven by climatic and glacio-eustatic processes.

Correlation with Regional Stratigraphic Frameworks

The ichnological and sedimentological features documented from the Middle Bhuban succession of Aizawl can be correlated with previous studies of Paleogene-Neogene successions across the Indo-Myanmar Ranges and the Bengal Basin. Singh *et al*. (2008) reported moderately diverse trace fossil assemblages including *Skolithos linearis*, *Ophiomorpha nodosa* and *Rhizocorallium jenense* from the Upper Eocene-Lower Oligocene transition in Manipur. These assemblages were interpreted to represent well-oxygenated shoreface to offshore settings, consistent with the *Rhizocorallium* and *Palaeophycus* ichnofabrics observed in the Middle Bhuban rocks, which also suggest oxygen-rich, low-energy, shallow to mid-tier colonization under equilibrium conditions (Bromley 1990; Fürsich & Heinberg 1983). Similarly, the Paleogene sediments of the inner fold belt in the Naga Hills, as described by Khalo & Pandey (2018), contain a diverse assemblage of 16 ichnospecies belonging to both *Skolithos* and *Cruziana* ichnofacies. These trace fossils are indicative of deposition across a range of energy conditions, from nearshore to offshore, influenced by tidal currents, storms, and varying sediment supply.

Lokho *et al*. (2017) interpreted the ichnofabric associations such as *Thalassinoides*, *Planolites* and *Ophiomorpha*, from the Laisong Formation (late Eocene-early Oligocene) of Nagaland, which reflect colonization during breaks in sedimentation within a delta-fed turbidite system influenced by hyperpycnal flows in a shallow marine setting. These interpretations closely resemble the sedimentological and ichnological data recorded in the Bhuban succession of Aizawl. Rajkumar *et al*. (2019) documented a clear ichnofacies transition from *Skolithos* to *Cruziana* and subsequently to *Nereites* across the Upper Disang-Lower Barail contact in Nagaland. This vertical and lateral progression was interpreted to represent a proximal-to-distal depositional gradient, extending from foreshore to deep-marine settings and primarily controlled by fluctuations in sediment supply, relative sea level changes and tectonic processes. Similar patterns can be observed within the Middle Bhuban Formation of aizawl, where the vertical distribution of ichnofossil tiers and associated facies heterogeneity similarly reflect dynamic shifts in depositional environments.

Beyond the Indo-Myanmar Ranges, insights from the Bengal Basin also corroborate the interpretations of the present study. Four trace fossil assemblage zones (TAZ I–IV) were identified by Bera (1996), ranging from the late Eocene to Holocene in the western Bengal Basin. TAZ II and III, which include *Thalassinoides callianassae*, *Bergaueria hemispherica* and *Oniscoidichnus communis*, reflect deposition in high to low-energy marginal marine and lagoonal environments. According to More *et al*. (2016), a diverse palynoassemblage dominated by angiosperms along with pteridophytes, fungal remains and mangrove elements suggests that the Mio-Pliocene strata of the Churanthi River section in the Darjeeling Himalayan foothills were deposited in a brackish, shallow marine environment influenced by both deltaic progradation and wave-dominated coastal processes. Associated trace fossils such as *Planolites*, *Palaeophycus*, *Skolithos*, *Rosselia*, *Ophiomorpha* and *Teichichnus*, preserved within rippled mudstone-siltstone facies, further support a shallow marine setting marked by strong brackish water influence and active wave agitation. This environmental interpretation closely resembles the Miocene depositional conditions of the Middle Bhuban succession in Aizawl, Mizoram, where similar transitional coastal dynamics and fluvio-marine interactions prevailed (Tiwari *et al*. 2011).

During Miocene, the Bengal Basin has experienced dynamic depositional conditions driven by intense tectonic activity associated with the upliftment of the eastern Himalayas and the Indo-Burman Ranges. According to Alam *et al*. (2003), this tectonism led to a significant increase in clastic sediment influx from the northeast and eastern Himalayas, resulting in the development of varied depositional settings across the basin. While the central parts of the basin were dominated by deep marine sedimentation, the eastern sector, proximal to the Indo-Burman Ranges, was characterized by shallow marine to marginal coastal environments with active deltaic progradation. The Middle Bhuban succession of Aizawl, situated near this eastern margin, reflects these conditions through its alternating sandstone and shale lithofacies, widespread bioturbation and the presence of tidal indicators. Shakik & Hossain (2020) investigated the facies association and paleo-depositional environment of the exposed Neogene succession in the Sitapahar anticline of the Rangamati area, Chittagong Tripura Folded Belt (CTFB) region of the Bengal Basin, the Miocene period was marked by a dynamic depositional regime influenced by multiple episodes of sea level transgression and regression. This led to a complex interplay of shallow marine, tidal, deltaic and deep marine environments within the Sitapahar structure. Facies such as wavy sandstone-siltstone beds and lenticular laminated silty-shale indicate deposition under shallow marine conditions, while flaser-bedded sandstone-siltstone reflects tidal influence, characterized by bidirectional flow typical of tidal flats or estuarine settings.

Collectively, these regional studies support the interpretation that the ichnofabrics of the Middle Bhuban rocks in Aizawl, Mizoram, developed within a marginal marine to lower shoreface environment, shaped by fluctuating hydrodynamic conditions and episodic sediment influx. A generalized schematic representation illustrating the depositional setup of the study area is shown in Fig. 7. This diagram summarizes the key features and depositional processes observed, providing a visual overview of the stratigraphic relationships and sedimentary environments in the study area.

Conclusions

The Middle Bhuban unit of Bhuban Formation in the study area exposes a sedimentary succession approximately 46 m thick, characterized by alternating bands of sandstone and shale. The formation exhibit bioturbation and contain trace fossils ranging from monodominant to moderately diverse groups. Ichnological analysis identifies six ichnofabrics comprise ichnogenera such as *Funalichnus*, *Psilonichnus*, *Teredolites*, *Thalassinoides*, *Cochlichnus* and *Palaeophycus*, reflecting both monodominant and diverse assemblages. The formations also reveal four ichnofacies: *Skolithos*, *Cruziana*, mixed *Skolithos-Cruziana* and *Teredolites*. The bioturbational and bioerosional ichnofabrics provide valuable insights into the vertical distribution of ichnogenera across different substrates. Ichnofabric analysis of the Middle Bhuban rocks in Aizawl area suggests highly variable hydrodynamic conditions, nutritional availability and substrate conditions in foreshore-shoreface environments with occasional sea level retreat, marking significant environmental changes during deposition.

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Tab. 1 – Sedimentary succession of Mizoram (Karunakaran, 1974; Ganju, 1975; modified by Tiwari and Kachhara, 2003). / Successione sedimentaria di Mizoram (Karunakaran, 1974; Ganju, 1975; modificata da Tiwari & Kachhara, 2003).

Age	*Group*	*Formation*	*Unit*	*Generalized Lithology*
Recent	Alluvium			Silt, clay and gravel
------Unconformity------				
Early Pliocene to Late Miocene	Tipam (+900 m)			Friable sandstone with occasional clay bands
------Conformable and transitional contact------				
Miocene to Late Oligocene	S U R M A (+5950 m)	Bokabil (+950 m)		Shale, siltstone and sandstone
		------Conformable and transitional contact------		
		B H U B A N (5000 m)	Upper Bhuban (1100m)	Arenaceous predominating with sandstone, shale and siltstone
			---Conformable and transitional contact--	
			Middle Bhuban (3000m)	Argillaceous predominating with shale, siltstone-shale alternations ans sandstone
			----Conformable and transitional contact-	
			Lower Bhuban (900m)	Arenaceous predominating with sandstone and silty-shale
------Unconformity obliterated by faults------				
Oligocene	Barail (+3000 m)			Shale, siltstone and sandstone
------Lower contact not seen------				

Tab. 2 – Ethological characterization and environmental distribution of the ichnofossils of the study area. / Caratterizzazione etologica e distribuzione ambientale degli icnofossili dell'area di studio.

Sr. No.	Ichnospecies	Morphological (Simpson,1975)	Ethological (Seilacher, 1964)	Ichnofacies (Seilacher, 1964, 1967)
1	*Cochlichnus anguineus*	Tunnel	Fodinichnia	*Cruziana*
2	*Funalichnus bhubani*	Shaft	Domichnia	*Skolithos*
3	*Gordiamarina*	Tunnel	Pascichnia	*Cruziana*
4	*Palaeophycus striatus*	Tunnel	Fodinichnia	*Cruziana*
5	*Palaeophycus tubularis*	Tunnel	Fodinichnia	*Cruziana*
6	*Psilonichnus upsilon*	Shaft	Domichnia	*Skolithos*
7	*Rhizocorallium jenense*	Tunnel	Fodinichnia	*Cruziana*
8	*Skolithos* isp.	Shaft	Domichnia	*Skolithos*
9	*Teredolites clavatus*	Shaft	Fodinichnia	*Teredolites*
10	*Teredolites longissimus*	Tunnel	Fodinichnia	*Teredolites*
11	*Thalassinoides horizontalis*	Branched	Fodinichnia/ Domichnia	*Skolithos/ Cruziana*
12	*Thalassinoides suevicus*	Branched	Fodinichnia/ Domichnia	*Skolithos/ Cruziana*

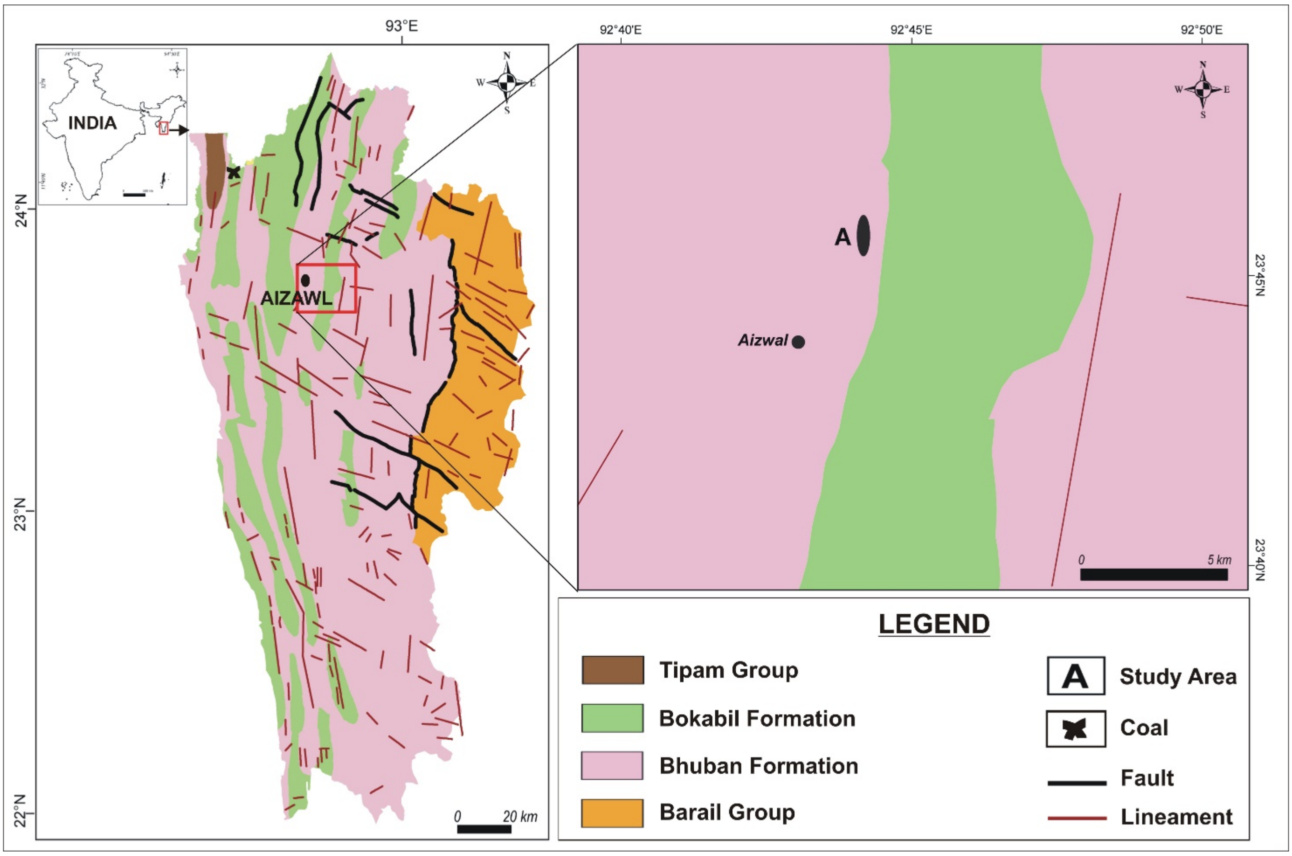

Fig. 1 – Geological map of Mizoram showing the ichnofossil locality (after Geological Survey of India). / Carta geologica del Mizoram che mostra la località con icnofossili.

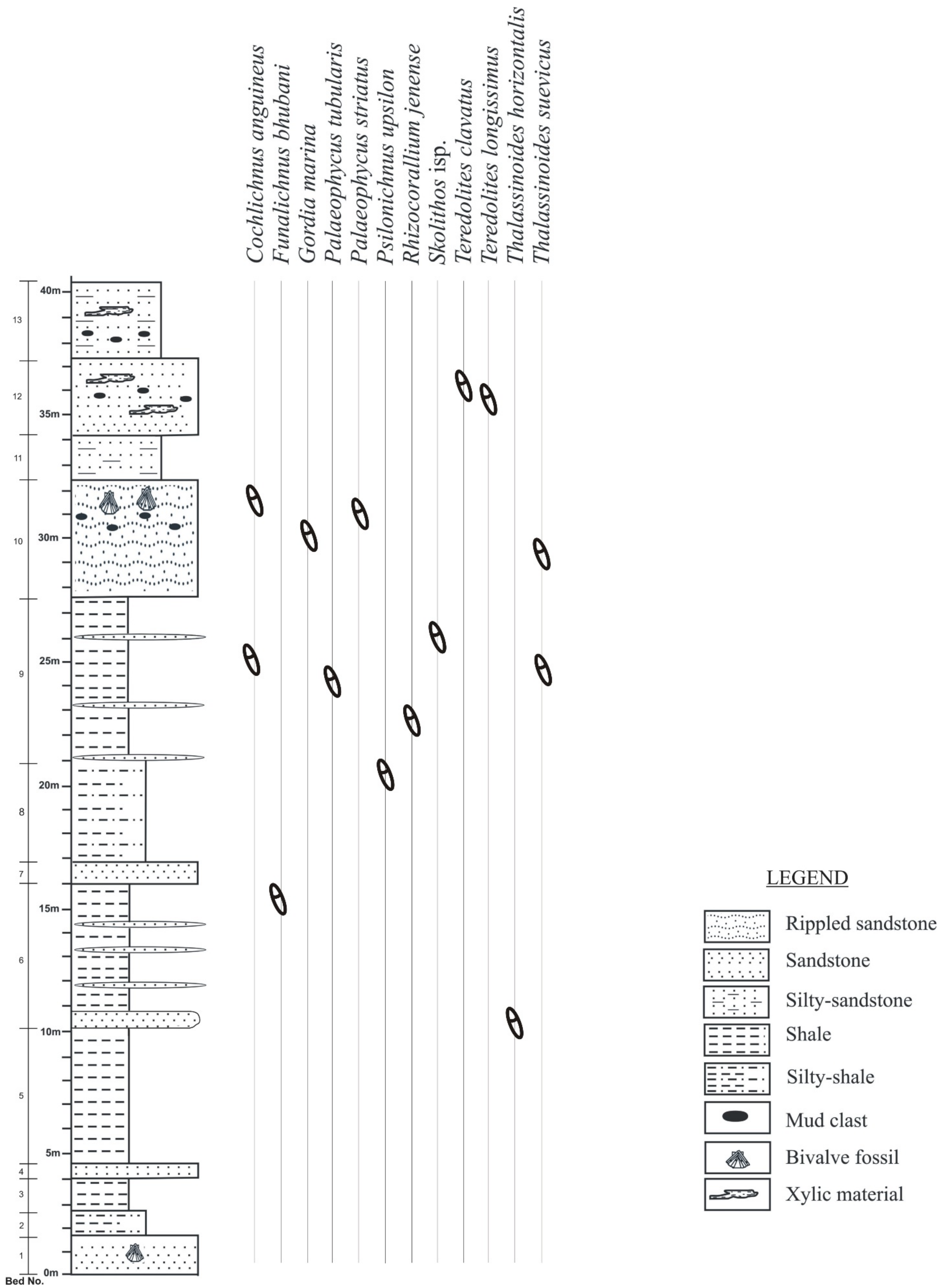

Fig. 2 – Distribution of lithological units and ichnofossils across the study area, as illustrated in a lithocolumn. / Distribuzione delle unità litologiche e degli icnofossili nell'area di studio illustrate in una colonna litostratigrafica.

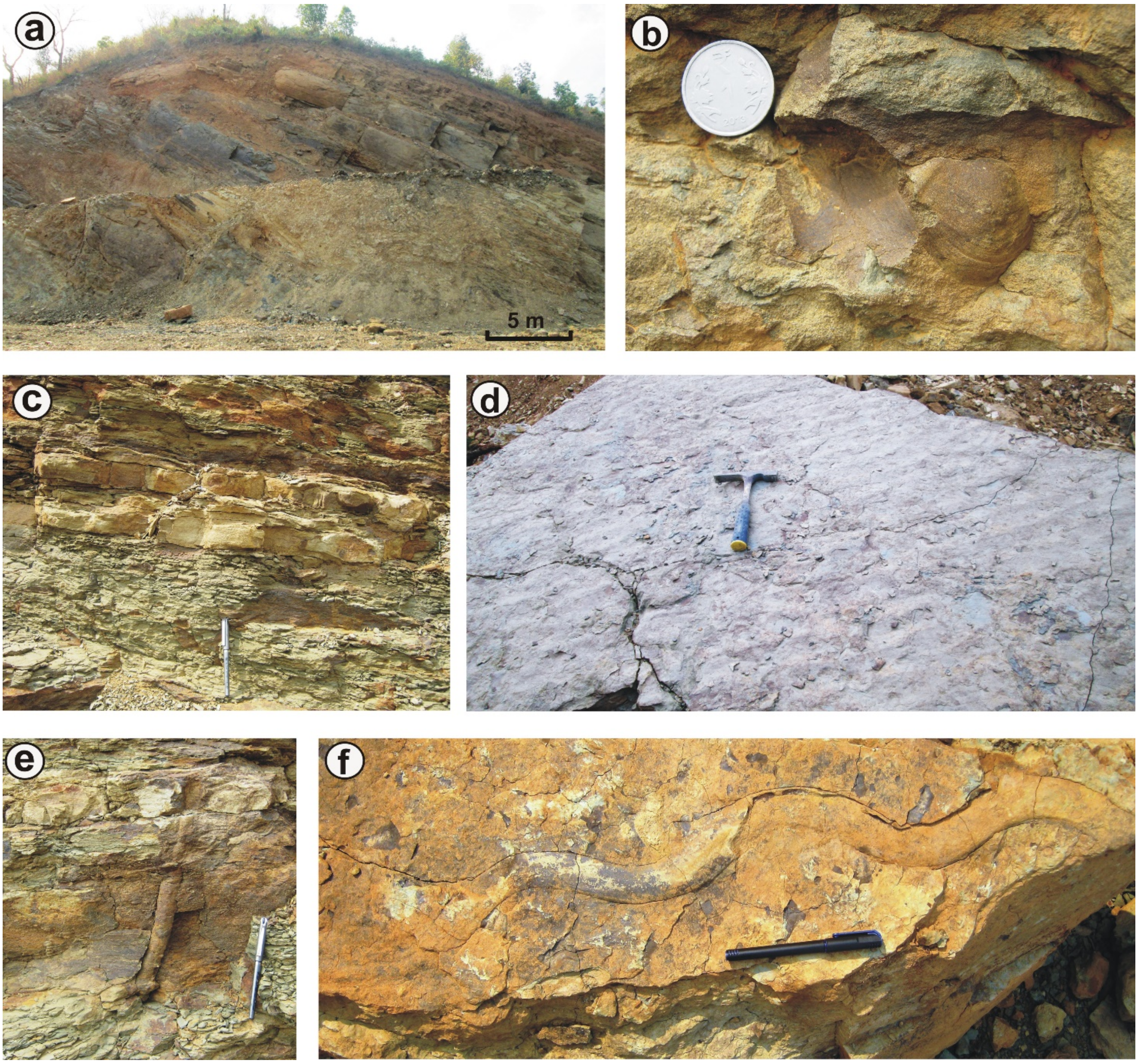

Fig. 3 – a) Field photograph showing the trace fossil locality in Aizawl. b) Bivalve cast (*Apolymetis* sp.). c) Shale dominated shale-sandstone alternation. d) Symmetrical wave ripples occur on the sandstone beds. e) *Psilonichnus upsilon*, steeply inclined to vertical burrow with L shaped terminal. f) *Cochlichnus anguineus*, large, sinuous structure. / a) Fotografia di campo che mostra la località degli icnofossili ad Aizawl. b) Calco di bivalve (*Apolymetis* sp.). c) Alternanza di argilliti e arenarie a prevalenza di argillite. d) Ondulazioni simmetriche da onda presenti sugli strati di arenaria. e) *Psilonichnus upsilon*, tana fortemente inclinata o verticale con terminale a forma di L. f) *Cochlichnus anguineus*, struttura grande, di forma sinuosa.

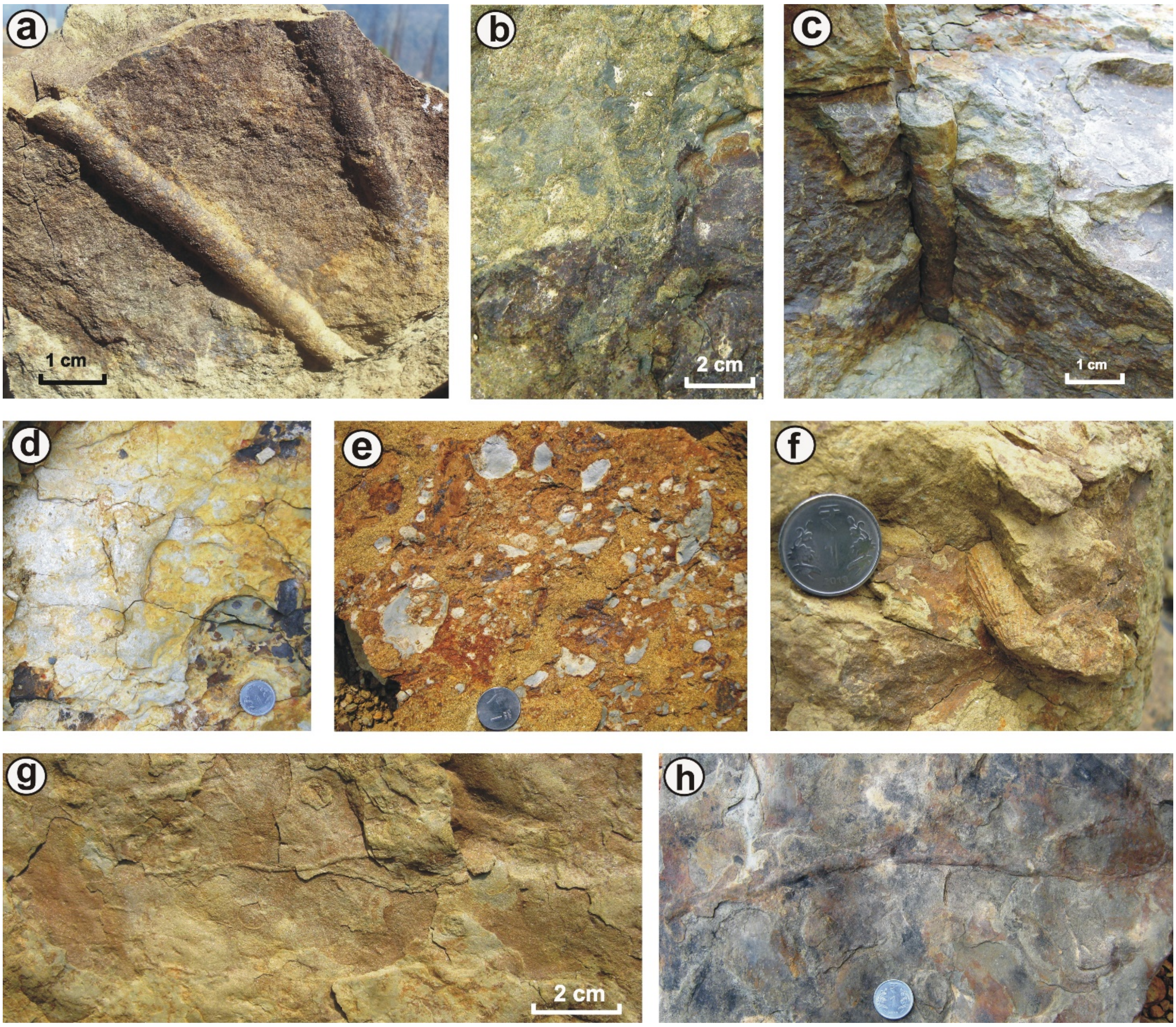

Fig. 4 – Fossiliferous Middle Bhuban rocks in Aizawl. a) *Palaeophycus tubularis,* horizontal borrow shows slightly variation in diameter along the burrow length due to compaction. b) *Rhizocorallium jenense,* horizontal, one arm and spreiten structure are well preserved but the other arm is collapsed. c) *Skolithos* isp., circular outline reflect the burrow opening. d) *Thalassinoides suevicus,* occur in sandstone layer of sandstone–shale intercalated sequence. e) Brown coloured sandstone consists of mud clasts. f) Bivalve *Pinna* preserved in grey sandstone. g) *Gordia marina*, long feeding trail shows the straight to undulated course. h) *Palaeophycus striatus,* striated burrow parallel to bedding plane. / Rocce fossilifere del Medio Bhuban di Aizawl. a) *Palaeophycus tubularis*, la tana orizzontale mostra una leggera variazione del diametro lungo tutta la sua lunghezza dovuta a compattazione. b) *Rhizocorallium jenense*, orizzontale; un braccio e la struttura a spreiten sono ben conservati, mentre l'altro braccio è collassato. c) *Skolithos* isp., profilo circolare che riflette l'apertura della tana. d) *Thalassinoides suevicus*, presente negli strati di arenaria di una sequenza intercalata arenaria–argillite. e) Arenaria di colore bruno contenente clasti di fango. f) Bivalve *Pinna* conservato in posizione vitale in arenaria grigia. g) *Gordia marina*, lunga traccia di alimentazione che mostra un percorso da rettilineo a ondulato. h) *Palaeophycus striatus*, tana striata parallela al piano di stratificazione.

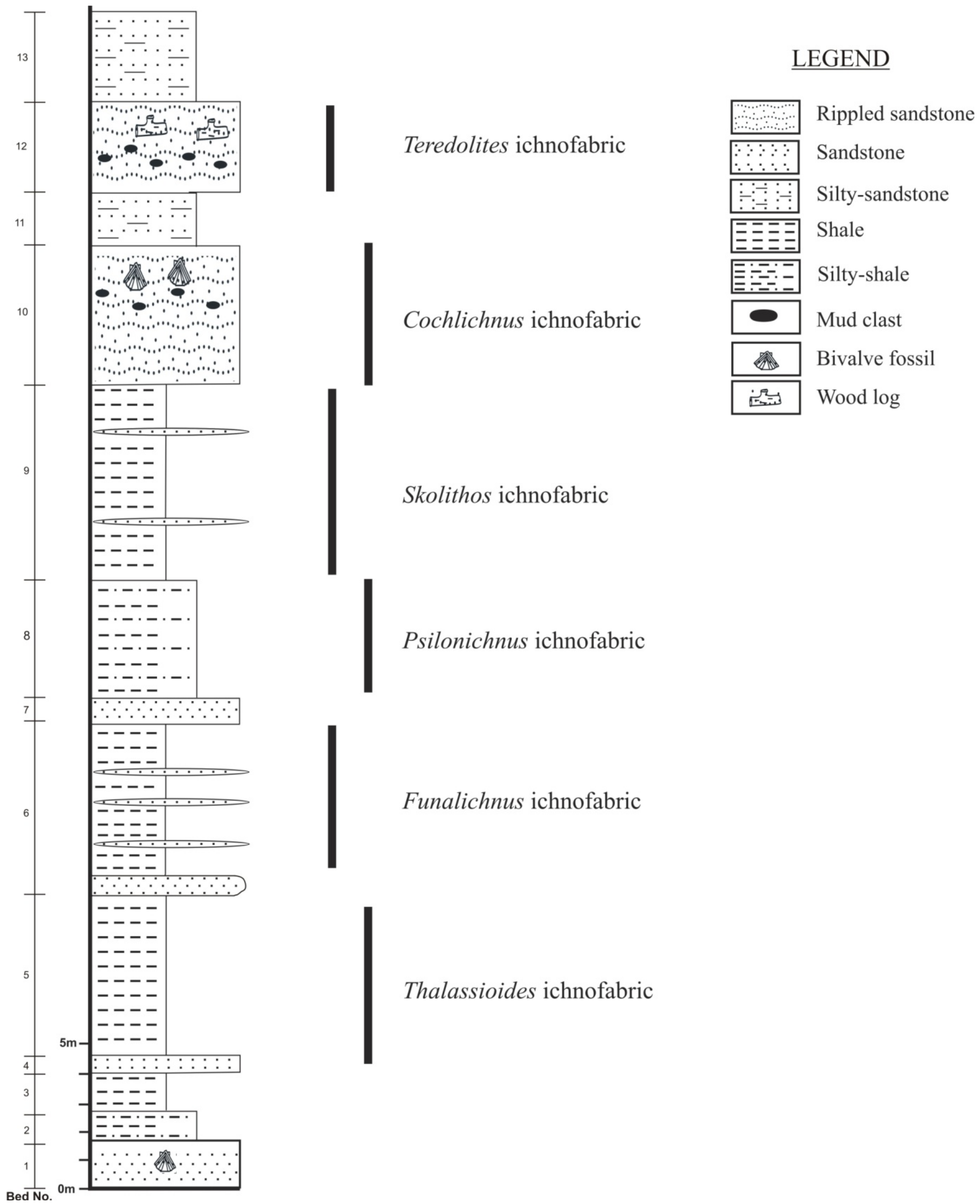

Fig. 5 – Spatial distribution of ichnofabrics within the lithocolumn of the study area. / Distribuzione spaziale degli icnofabric nella colonna litostratigrafica dell’area di studio.

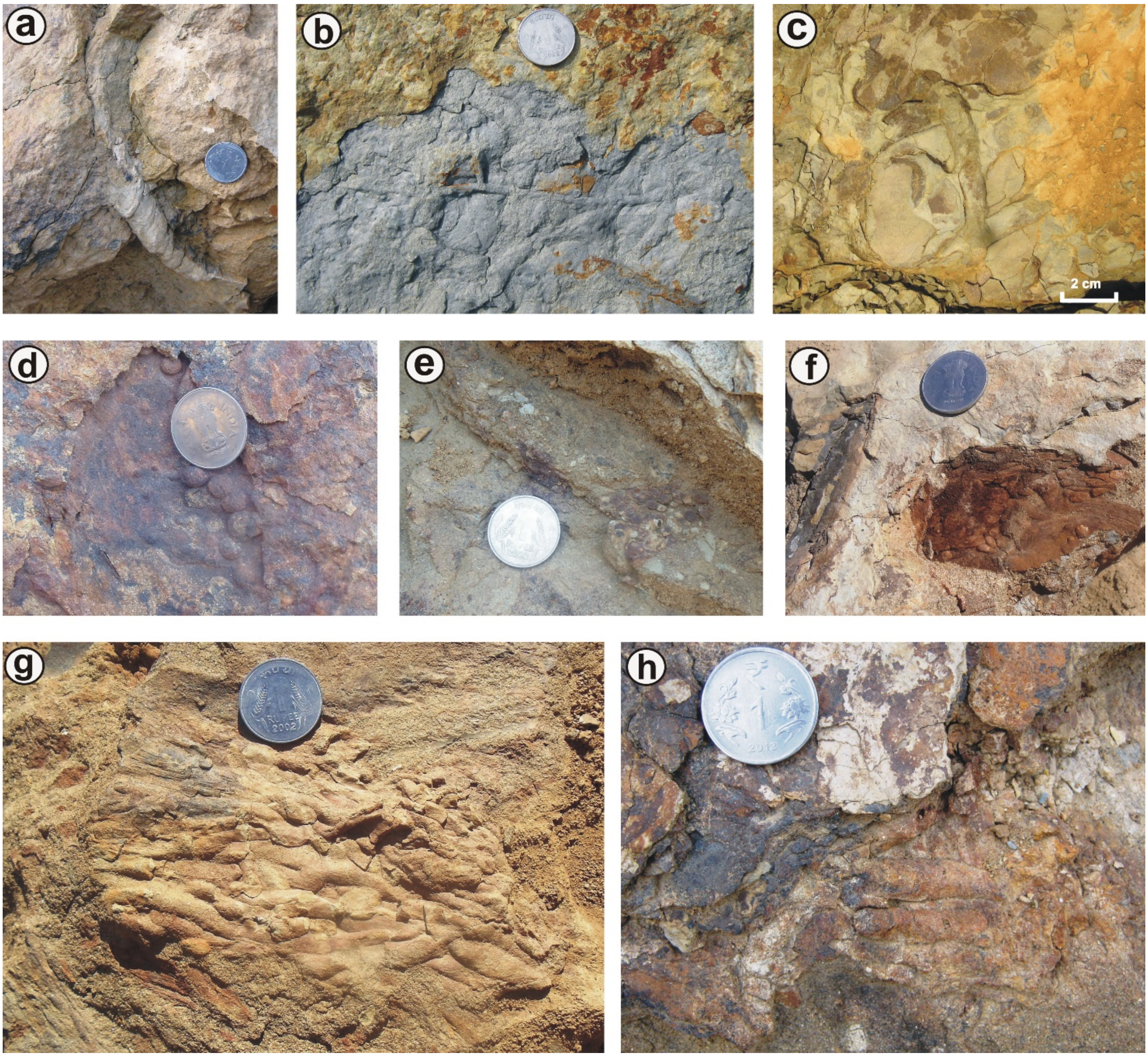

Fig. 6 – a) *Funalichnus bhubani*, vertical to steeply inclined burrow with different material, lower end gently curved and partly eroded. b) *Thalassinoides suevicus,* small and gently inclined acute branched burrow. c) *Thalassinoides horizontalis*, Y shaped, horizontal burrow and fill material is identical to surrounding. d - e) *Teredolites clavatus,* densely crowded, clavate shaped borings in woody substrates. f) Woody substrate shows development of boring like *T. clavatus* and *T. longissimus* (developed on periphery of xylic substrate). g - h) *Teredolites longissimus*, densely-packed, sinuous to contorted sand filled elongated tubes. / a) *Funalichnus bhubani*, tana verticale o fortemente inclinata con materiale differente; l'estremità inferiore è leggermente curva e parzialmente erosa. b) *Thalassinoides suevicus*, piccola tana con ramo acuto, leggermente inclinato. c) *Thalassinoides horizontalis*, tana orizzontale a forma di Y; il materiale di riempimento è identico a quello circostante. d - e) *Teredolites clavatus*, perforazioni fitte, a forma claviforme, in substrati lignei. f) Il substrato ligneo mostra lo sviluppo di perforazioni simili a *T. clavatus* e *T. longissimus* (sviluppate lungo la periferia del substrato xilico). g - h) *Teredolites longissimus*, tubi allungati, densamente concentrati, sinuosi o contorti, riempiti di sabbia.

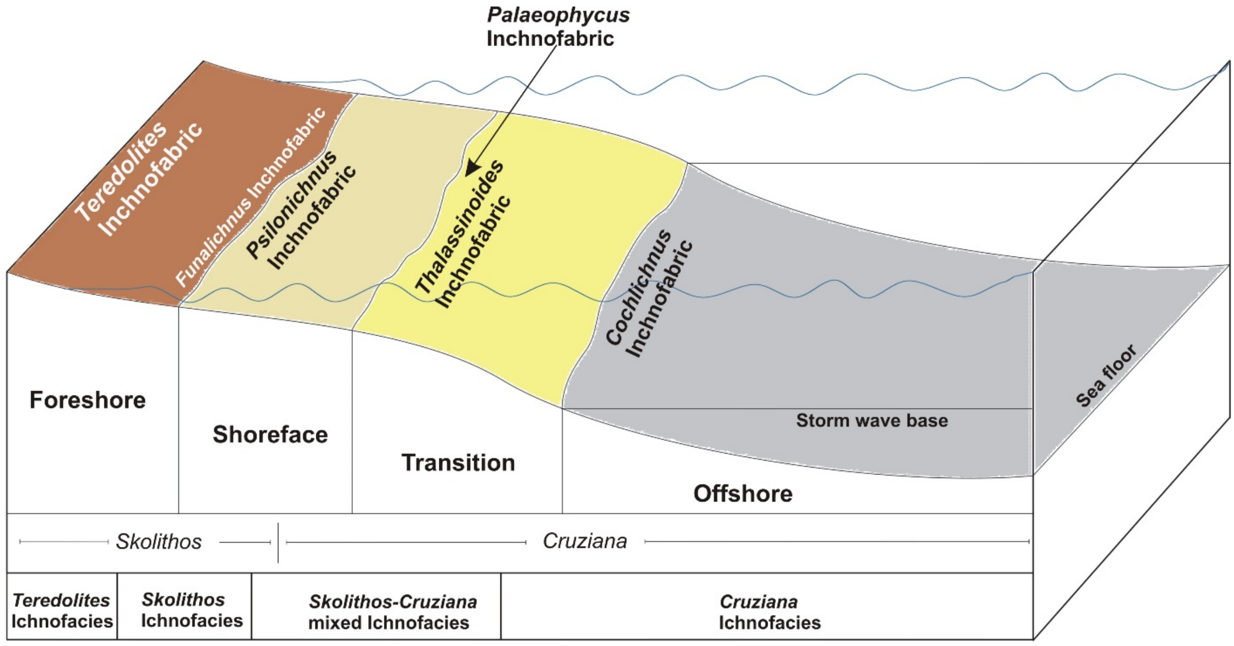

Fig. 7 – A schematic representation of the distribution of ichnofacies and their corresponding depositional environments in the study area. / Rappresentazione schematica della distribuzione delle icnofacies e dei corrispondenti ambienti di deposizione nell’area di studio.