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Trace Fossils of the Upper Eocene–Lower Oligocene Transition of the Manipur, Indo-Myanmar Ranges (Northeast India)

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Abstract: A detailed ichnological analysis, for the first time, has been preformed on Upper Eocene–Lower Oligocene Transition of Manipur, Indo-Myanmar Ranges (Northeast India). Previous trace fossil analyses in India are scarce and usually poorly detailed, especially with respect to Cenozoic materials. Sediments from the Disang and Barail groups contain a relatively abundant and moderately diverse trace fossil assemblage that has been characterized at the ichnogenus and ichnospecies level. *?Arenicolites* Salter 1857, *Helminthopsis tenuis* Książkiewicz 1968, *Ophiomorpha nodosa* Lundgren 1891, *Phycodes palmatus* (Hall 1852), *Planolites montanus* Richter 1937, *Rhizocorallium jenense* Zenker 1836, *Thalassinoides paradoxicus* (Woodward 1830) and *Skolithos linearis* (Haldeman 1840) have been described therein in detail, most of them for the first time in the Manipur state. This ichno-assemblage represents the record of classical *Skolithos* and/or *Cruziana* ichnofacies, being characteristic of a shallow-marine environment, with occasional high-energy conditions.

Key Words: ichnological analysis, Upper Eocene–Lower Oligocene, Disang and Barail groups, Manipur, India

Manipur Üst Miyosen–Alt Oligosen Geçişinin İz Fosilleri, Indo-Myanmar Bölgesi (Kuzeydoğu Hindistan)

Özet: Manipur Üst Miyosen–Alt Oligosen Geçişini konu edinen ayrıntılı bir iknolojik analiz ilk kez Indo-Myanmar Bölgesinde (Kuzeydoğu Hindistan) gerçekleştirilmiştir. Hindistan'da yürütülen ve özellikle Senozoyik kaya topluluklarını konu edinen iz fosili analizlerinin sayısı oldukça sınırlı olup, var olan çalışmaların ayrıntıları ise zayıf kalmıştır. Disang ve Barail gruplarını oluşturan sedimanlarda iz fosili topluluklar nisbeten daha zengin ve çeşitlidir; fosil toplulukları ikno-cins ve ikno-tür düzeyinde tanımlanabilmiştir. *?Arenicolites* Salter 1857, *Helminthopsis tenuis* Książkiewicz 1968, *Ophiomorpha nodosa* Lundgren 1891, *Phycodes palmatus* (Hall 1852), *Planolites montanus* Richter 1937, *Rhizocorallium jenense* Zenker 1836, *Thalassinoides paradoxicus* (Woodward 1830) ve *Skolithos linearis* (Haldeman 1840) gibi türler, büyük bölümü Manipur eyaletinde ilk olmak üzere, ayrıntılı olarak tanımlanmıştır. Bu ikno-toplulukları klasik *Skolithos* ve/veya *Cruziana* iknofasiyeslerinin kayıtlarını temsil ederken geçici yüksek enerji koşullarının hakim olduğu sığ deniz ortamlarını karakterize ederler.

Anahtar Sözcükler: iknolojik analiz, Üst Eosen–Alt Oligosen, Disang ve Barail grupları, Manipur, Hindistan

Introduction

Ichnological analysis has become a valuable tool in basin research, being of special interest for ichnostratigraphy, palaeoenvironmental analysis or sequence stratigraphy (McIlroy 2004; Miller 2007 for recent up-date). However, trace fossil studies are, in many cases, relatively underestimated with respect to other palaeontological and sedimentological disciplines.

Detailed ichnological analyses in India outcrops/cores are relatively scarce. Most of the ichnological research focused on the use of the trace fossils in earliest Cambrian stratigraphy, as well as in the interpretation of the Proterozoic–Phanerozoic transition and the 'Cambrian explosion' (i.e. Sarkar *et al*. 1996; Seilacher *et al.* 1998; Shah *et al*. 1998; Sudan *et al*. 2000; Tiwari & Parcha 2006, and references therein).

Apart from those two major ichnological researches, performed on the Proterozoic–Phanerozoic transition rocks, ichnological analysis in the rest of Phanerozoic sediments as well as other ichnological applications (basin analysis, palaeoenvironmental interpretations, etc.), are relatively poorly characterized. In Palaeozoic sediments, trace fossils have been presented for the Devonian (Kumar *et al*. 1977; Srivastava & Kumar 1992; Draganits *et al*.

1998, 2001) and more in detail for the Permo–Carboniferous successions (Guha *et al*. 1994; Chakraborty & Bhattacharya 2005). Mesozoic occurrences were referred in general terms for Triassic sediments (Makhalouf 2000), and with more detail for Jurassic (Fürsich *et al*. 1992; Fürsich 1998; Borkar & Kulkarni 2006) and Cretaceous (Borkar & Kulkarni 1992 and references therein) formations. Cenozoic references can be found for Paleocene to Miocene cores (Reddy *et al.* 1992), and Eocene to Miocene outcrops (Patel & Shringarpure 1990, 1992; Sudan *et al.* 2002).

At the study area of Manipur, ichnological research is near absent. Only Tripathi & Satsangi (1982) recorded crustacean burrows referable to *Ophiomorpha* (*O. nodosa* and others) from the Disang Group, and Hemanta Singh (2005) presented a preliminary ichnotaxa characterization from the Disang-Barail Transition Zone, with the recognition of *Chondrites*, *Skolithos* and *Thalassinoides* (*T. suevicus*). In both cases, trace fossils were useful to interpret depositional conditions of the studied sediments.

The aim of this contribution is a detailed description of trace fossils from the Upper Eocene–Lower Oligocene Transition of Manipur, Indo-Myanmar Ranges (Northeast India). Characterization of the trace fossil assemblage will be of special interest for future interpretations of the palaeoenvironmental conditions of the studied deposits.

Geological Setting

The studied area belongs to the Imphal Valley (latitudes between 24º14´–25º00´ N and longitudes of 93º48´–93º07´ E), located in the central part of the Manipur State, Northeast India (Figure 1). The hills of Manipur form an integral part of the Indo-Myanmar Ranges (IMR). The IMR in general and the Manipur Hills in particular evolved as a result of dextral shear coupling between Indian and Myanmar plates, when the former subducts bellow the latter (Soibam 1998, 2001). During the subduction (island arc type), the sediments between the two plates have been thrown into a mountain range as an accretionary prism when the obducted part of the oceanic crust is found embedded within the sediments. Thus, most of the lithounits in the region represent the form of an imbricate thrust system where older lithounits lie above the younger ones (Soibam 1998, 2001).

The outcrops at the state of Manipur mainly consist of Tertiary and Cretaceous sediments with only minor igneous and metamorphic rocks. The sedimentary rocks are mostly composed of sediments deposited by currents that belong to the Disang and Barail Groups, (Figure 1).

The Disang Group is Late Cretaceous to Late Eocene in age, and forms the principal lithounit of the eastern part of the state of Manipur as well as of Imphal Valley and its peripherial areas. This group consists of a monotonous sequence of dark grey to black splintery shales, and occasional rythmites of shales and siltstones/fine-grained sandstones in the upper part (the Upper Disang). The Barail Group is Late Eocene to Early Oligocene in age, forming major part of the western half of the state. This group is made up of arenaceous sediments with local thick intercalations of argillaceous materials. The contact between the two groups is gradational and locally tectonic (Soibam 2006). This gradational contact is related with a gradual change from dominantly argillaceous deep marine to a mainly arenaceous shallow marine depositional environment (Guleria *et al.* 2005).

Trace fossils were recovered from several outcrops in the Imphal Valley (Figure 1), with the two most important localities belonging to the Thongjaorok Stream section in the Bishnupur area (latitude 24º37˝41 N and longitude 93º44˝48 E) and the Hawalok Stream section in the Gopibung area (latitude 25º07˝32 and longitude 93º54˝02), respectively. The lithological succession in the studied outcrops belongs to the Laishong Formation, which is the lowermost division of the Barail Group. This formation is characterized by alternations of shales and fine to medium grained sandstones (Figures 2 & 3).

Systematic Ichnology

The collected specimens are housed in the Geological Museum of Imphal College at Imphal labelled as IVTF (Imphal Valley Trace Fossil). Ichnological determinations in the laboratory were compared with field observations.

?*Arenicolites* isp. Salter 1857 (Figure 4a)

Arenicolites consists of vertical U-tubes without spreite (after Fürsich 1974a).

Description. Numerous paired tubes in muddy siltstone, 3 mm in diameter, 30–40 mm long, 10–15 mm apart, and filled with fine-grained sandstone. Most of the specimens are found in the horizontal surface and only occasionally vertical sections have been recognized. In our case some

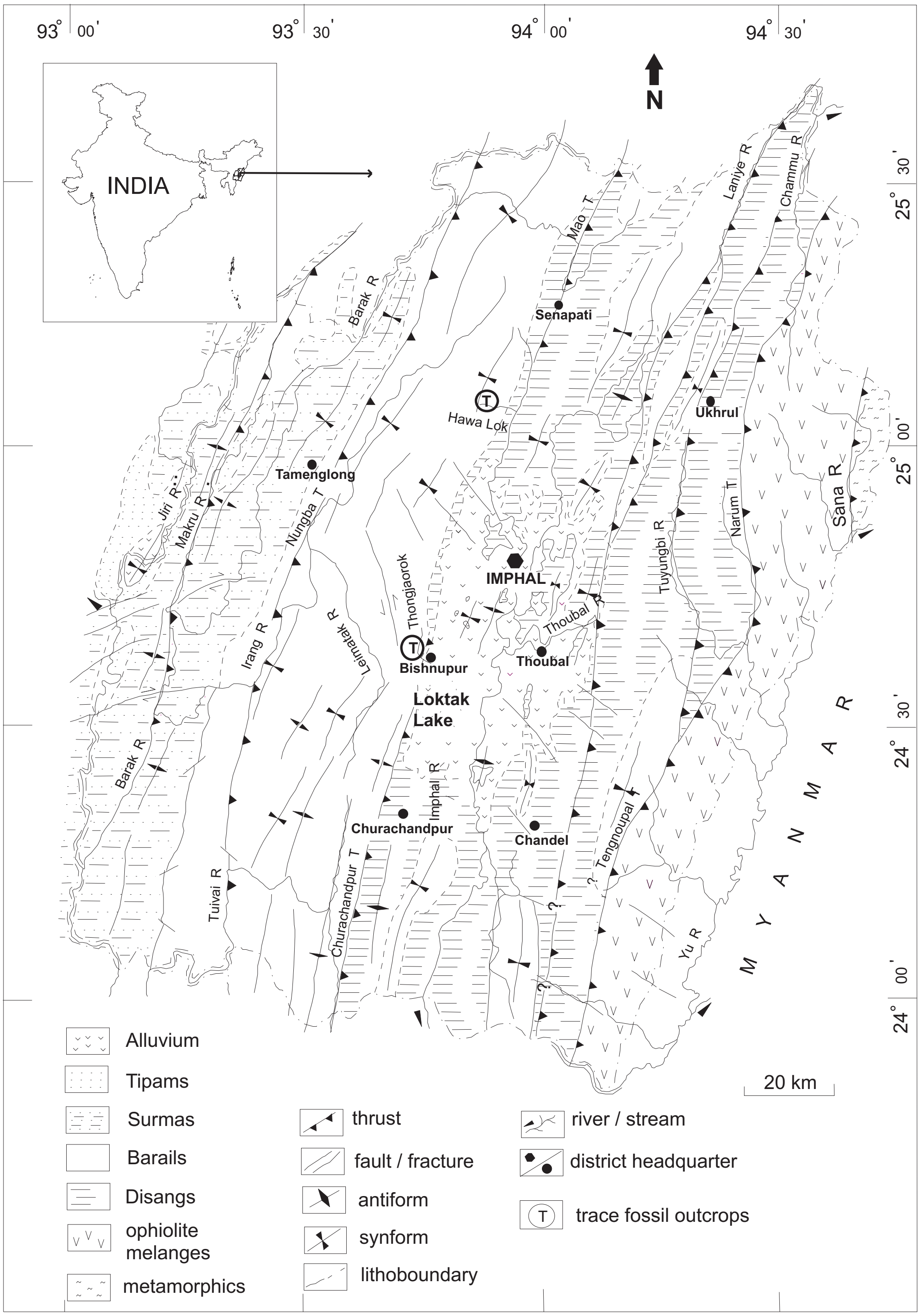

Figure 1. Location map showing the geological and structural features of the Manipur state (Soibam 2006). Note the location of the two ichnofossil localities (T encircled).

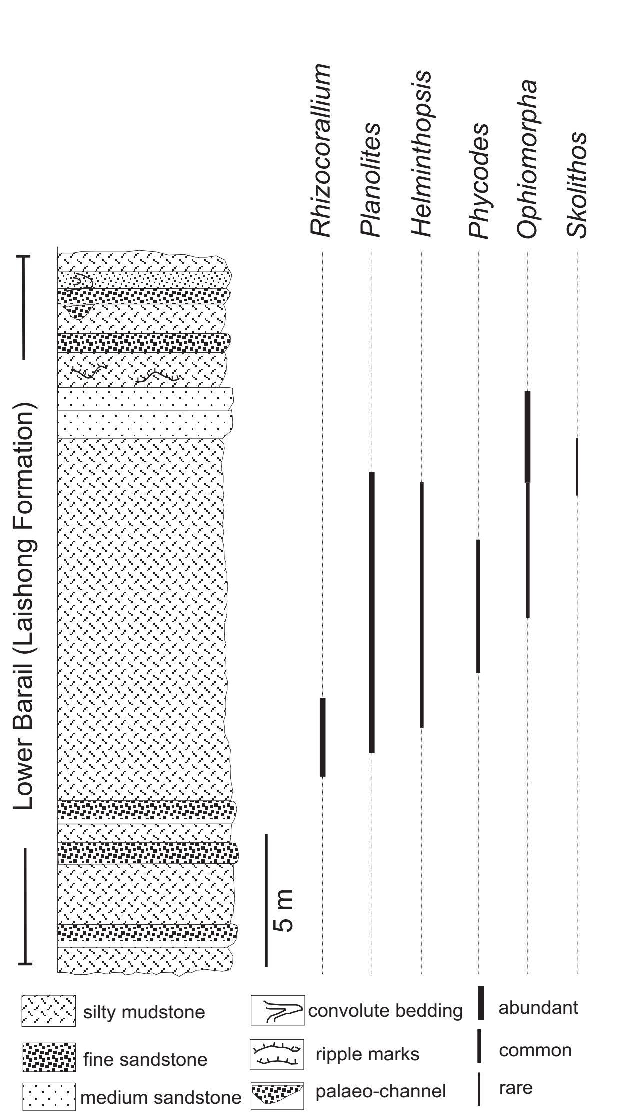

Figure 2. Lithological column of the trace fossil type section at Hawalok Stream section in Gopibung area, stratigraphical distribution and relative abundance of ichnotaxa.

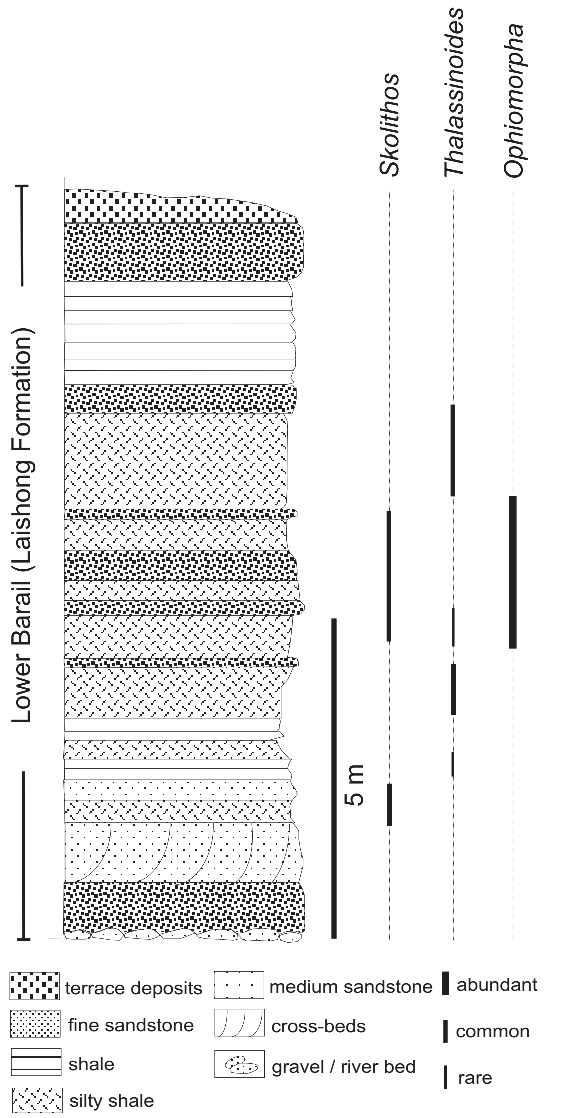

Figure 3. Lithological column of the Thongjaorok Stream section in the Bishnupur area, stratigraphical distribution and relative abundance of ichnotaxa.

of the tubes are oblique. Most of the specimens belong to the Tupul section.

Remarks. The assignation to the ichnogenus *Arenicolites* Salter 1857, is tentative because no U-shaped specimens have been found. However, this is not a conclusive feature, being *Arenicolites* occasionally differentiated as vertical to slightly oblique-paired burrows (Guillette *et al.* 2003).

Arenicolites is usually considered as a dwelling and feeding structure of suspension-feeding annelids (Hakes 1976) or crustacean-like organisms (Goldring 1962), but other interpretations as a domichnial structure have been also proposed (Bromley 1996). This structure occurs in diverse environments, including non-marine areas (Guillette *et al.* 2003), being typical of shallow-marine settings (Crimes 1977).

Helminthopsis Heer 1877

According Fillion & Pickerill (1990) *Helminthopsis* is an unbranched, irregularly winding or meandering, horizontal burrow or trail that does not touch or cross itself. Only

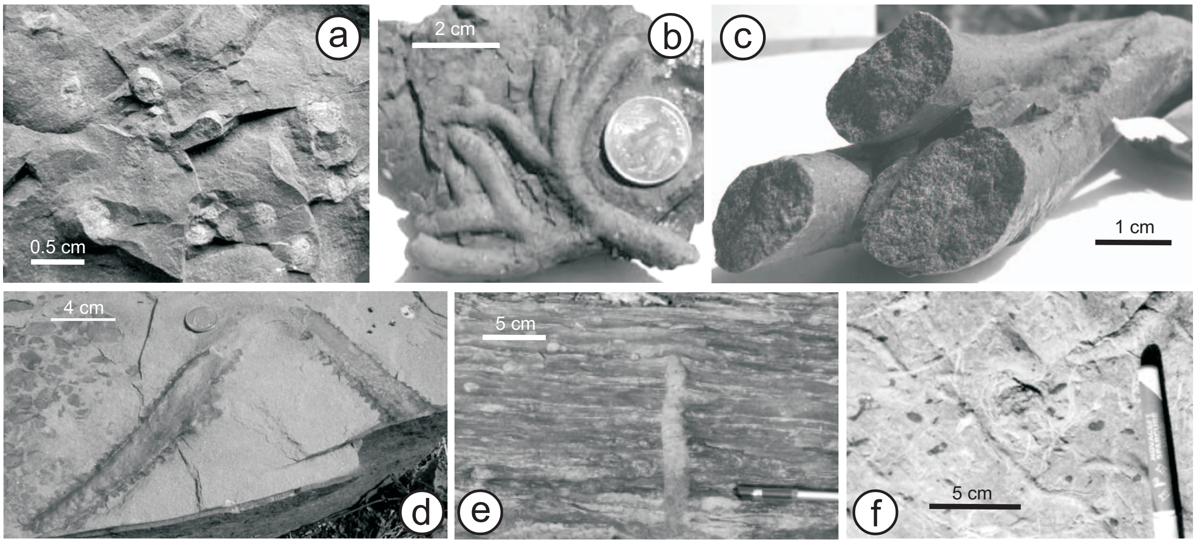

Figure 4. **(a)** Pairs of tubes without spreiten determined as ?*Arenicolites* isp., from the Tupul section; **(b–c)** *Phycodes palmatus* (Hall 1852) from the Hawalok section, showing the branches that originate in a palmate or digitate form in b and the cross-section of branches in c; **(d–e)** *Ophiomorpha nodosa* Lundgren 1891 from the Hawalok section, in horizontal and vertical sections, d and e respectively; **(f)** *Planolites montanus* Richter, 1937, as hypichnial, slightly sinuous structures, from the Hawalok section.

one order of meandering may be present. Burrow fill is massive.

Helminthopsis tenuis Książkiewicz 1968 (Figure 5e)

Helminthopsis tenuis Książkiewicz 1968 presents irregular, high-amplitude windings but only with U-turns, without horseshoe-like turns (Wetzel & Bromley 1996).

Description. Irregularly meandering convex, hypichnial unlined, smooth ridges, which are about 8 mm wide and up to 300 mm long. They are filled with mudstone with some proportions of fine silts, similar to the host rock. The specimens were collected at the Hawalok section.

Similar forms of *H. tenuis* are illustrated in Pickerill *et al.* (1992, *Figure 3a* as epirelief) and Buatois & Mángano (2003, *Figure 2d*).

Remarks. Only some species of *Helminthopsis* have been considered valid; *H. abeli* and *H. hieroglyphica* were accepted in both re-evaluations (Han & Pickerill 1995; Wetzel & Bromley 1996), while *H. granulata* is only considered valid by Han & Pickerill (1995) and *H. tenuis* by Wetzel & Bromley (1996). These ichnospecies are essentially differentiated on the analysis of their course and their diameter. From those, *H. abeli* shows horseshoe-like turns, and the most characteristic feature of *H. hieroglyphica* is the presence of straight element with often windy curves giving a box-shaped fold appearance (Wetzel & Bromley 1996). *H. granulata* is characterized by an external ornament of warts and ridges (Blissett & Pickerill 2004).

A detailed review of *Helminthopsis* behaviour, tracemaker and record is presented in Buatois *et al.* (1998). *Helminthopsis* is interpreted as pascichnial grazing trails, produced by deposit feeders (Buatois *et al.* 1998). Various tracemakers can be considered; polychaete annelids in brackish to fully marine environments, different types of arthropods, nematodes and insect larvae in freshwater settings, and larvae of Diptera in modern ponds. *Helminthopsis* is common in deep-marine deposits, but is also in shallow-marine and non-marine environments (Buatois *et al.* 1998); thus, this ichnogenus can be considered as a “facies-crossing” occurring in a variety of ichnofacies (Kim *et al.* 2002).

Ophiomorpha Lundgren 1891

Ophiomorpha is a simple to complex burrow systems distinctly lined with agglutinated pelletoidal sediment. Burrow lining more or less smooth interiorly, densely to

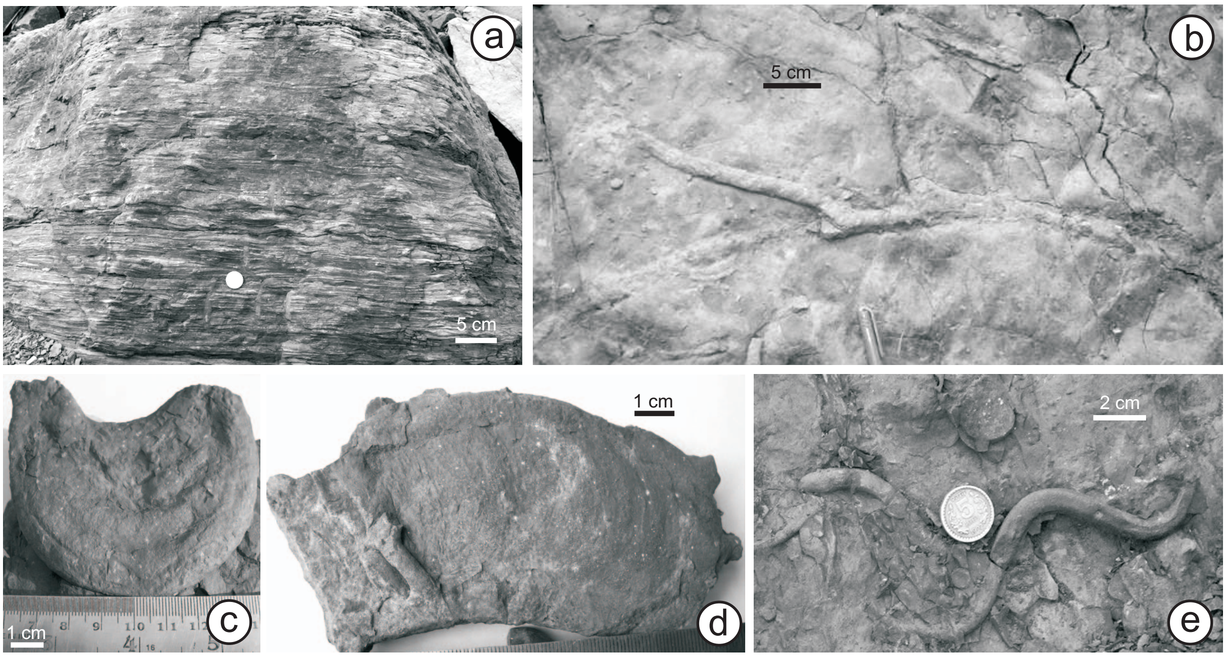

Figure 5. (a) *Skolithos linearis* (Haldeman 1840), as densely distributed straight, vertical burrows from the Hawalok section; (b) *Thalassinoides paradoxicus* (Woodward 1830), showing horizontal structures with irregular T and Y-shaped intersections from the Thongjaorok section; (c–d) *Rhizocorallium jenense* Zenker 1836 from the Hawalok section, showing slightly sinuous form in D and concentric disposition of the spreiten with a variable number of ridges and grooves in c and d; (e) Helminthopsis tenuis Książkiewicz 1968 from at the Hawalok section as irregular, meandering structure, preserved in convex hyporelief.

sparsely mammilated or nodose exteriorly. Individual pellets or pelletal masses may be discoid, ovoid, mastoid, bilobate, or irregular in shape.

Characteristics of the lining may vary within a single specimen (after Frey *et al*. 1978). The diagnosis is not completely satisfactory for some authors (Bromley & Ekdale 1998). Uchman (1998) refers as simple to complex burrow system lined at least partially with agglutinated pelletoidal sediment (modified from Howard & Frey 1984).

Ophiomorpha nodosa Lundgren 1891 (Figures 4d, e)

Ophiomorpha nodosa Lundgren 1891 presents burrow walls consisting predominantly of dense regularly distributed discoid, ovoid, or irregular polygonal pellets (Frey *et al*. 1978).

Description. Horizontal and vertical, mainly straight tubes and occasionally branched burrow systems showing Y-shaped branchings. Individual cylindrical tubes are 10–30 mm in diameter, with oval cross-sections, and around 100 mm long. The tubes possess smooth interior and very distinct exterior surfaces densely covered by muddy ovoid pellets, 1–4 mm in diameter. The tubes are filled with fine and medium sand, similar to the host rock. Occasionally, geometry of the systems is a meander maze having smoothly curved internodal tunnels. Studied specimens were collected in both major sections at Thongjaorok and Hawalok.

Remarks. Ichnospecies of *Ophiomorpha* (*O. annulata*, *O. borneensis*, *O. irregulaire*, *O. nodosa*, *O. puerilis* and *O. rudis*) are differentiated on the basis of variations in burrow configuration, and the nature of burrow linings, especially the shape and distribution of the pellets (Frey *et al*. 1978; Howard & Frey 1984; Uchman 2001; de Gibert *et al*. 2006). Although *O. borneensis* shows regularly distributed bilobate pellets (Frey *et al*. 1978), sometimes differentiation between *O. borneensis* and *O. nodosa* is difficult due to poor preservation; in this case the former tends to be dominantly horizontal, with smaller dimensions, whereas the later displays both vertical and horizontal components and tends to be larger (Pemberton & Jones 1988). *O. irregulaire* shows irregular conical pellets, distinctive from the regular lining of rounded pellets on *O. nodosa*, as well as a typical sinuous, branched maze extending in a horizontal plane (Pedersen & Bromley 2006). We can not discard that some meandering structures, in which the differentiation of pellets morphology is difficult, could be assigned to *O. irregulaire*.

This is one of the most common post-Palaeozoic trace fossils known in both siliceous and calcareous sedimentary rocks, mainly from shallow-marine environments (Pemberton & Jones 1988; Uchman & Gaździcki 2006). Pellets are usually interpreted as supporting the structure to prevent collapse of unconsolidated sediment during and after burrow construction (Ekdale *et al.* 1984; Bromley 1996; Bromley & Ekdale 1998). In modern environments, this trace fossil is produced by callianassid crustaceans (e.g., Uchman & Gaździcki 2006). The ethology of the *Ophiomorpha* tracemaker is complex and may be a variable combination of deposit and/or suspension feeding behaviours (e.g., Ekdale 1992; Uchman & Gaździcki 2006).

At the ichnogenus level, *Ophiomorpha* is registered in a wide environmental range, from shallow-water deposits represented mainly by *O. nodosa* to deep-sea environments represented mainly by *O. rudis* (Książkiewicz 1977; Tchoumatchenco & Uchman 2001). *O. nodosa* is most typical of the *Skolithos* ichnofacies (Frey & Seilacher 1980; Pemberton *et al.* 2001) but also occurs in deeper shelf tempestites (Frey 1990; Frey & Goldring 1992; Uchman & Gaździcki 2006).

Phycodes Richter 1850

Phycodes is a horizontally bundle burrow preserved outwardly as convex hyporeliefs. The overall pattern is reniform, fasciculate, flabellate, broom-like, ungulate, linear, falcate or circular. Most forms consist of a single or a few main branches showing a spreite-like structure that give rise distally to numerous free branches. In other forms the spreiten are lacking and branching tends to be second or more random. Individual branches are terete and finely annulate or smooth (Osgood 1970; Fillion & Pickerill 1990; Han & Pickerill 1994).

Phycodes palmatus (Hall 1852) (Figure 4b, c)

Phycodes palmatus (Hall 1852) consists of a few thick and rounded branches that originate in a palmate or digitate form from nearly the same point (Fillion & Pickerill 1990), and can be therefore distinguished from similar but smaller *P. curvipalmatum* (Pollard 1981; Knaust 2004). *Phycodes palmatus* is presented in figure 5.12 of Han & Pickerill (1994). Absence of a knobby wall, covered with small irregular mounds, allows differentiation with *P. bilix* (Uchman 1998).

Description. Horizontal hypichnial structures, consisting of three or four branches originated from nearly the same point of a thick, slightly curved single stem. Oval-cross sections (compaction?) of the branches, with burrow diameters of 10–13 mm in the horizontal and 15–20 mm in the vertical axes, while the main tube is 15 mm and 22 mm in diameter. Burrows filled with very fine-grained sand while the host rock is a mudstone with fine silts. All the specimens come from the Hawalok section.

Remarks. According to Han & Pickerill (1994) *Phycodes* reflects a variety of behavioural activities by the tracemaker, but two basic interpretations are: (i) a fodinichnion produced by an organism that systematically mining a nutrient-rich layer along a silt-mud surface (Seilacher 1955), or (ii) a structure performed by an organism that burrowed outwards from a single point and then withdrew to a 'home-case' only to re-burrow outwards again in part the previously excavated tunnel (Marintsch & Finks 1982). Mángano *et al.* (2005) pointed that the bauplan of *Phycodes* consists of two main strategies to exploit the rich fine-grained sediment: (i) one or a few proximal tunnels that tend to fan out distally, or (ii) proximal splitting forming bundles of subparallel tunnels. *Thalassinoides*-*Phycodes* (*P.* cf. *palmatus*) compound burrow systems have been recognized and interpreted as probable combination dwelling-deposit feeding structures produced by endobenthic crustaceans occupying and operating the systems for relatively long time intervals (Miller 2001).

Numerous variable producers are taken into account, being considered a sediment-feeding vermiform annelid, a Pennatulacean, or an anthoptiloid sea pen. The trace is mainly related with shallow water environments, being characteristic trace fossil of the *Cruziana* ichnofacies. It is also less frequently found in deep-marine and non-marine conditions (see Han & Pickerill 1994 for review). *Phycodes* is commonly present at the base of centimetre-thick siltstone or silty sandtone beds within shales (Seilacher 2000; Mángano *et al.* 2005).

Planolites Nicholson 1873

Planolites refers to straight to tortuous burrows, unlined or rarely lined, smooth to irregularly walled or annulated, rarely branched, circular to elliptical in cross-section, and with variable dimensions and configurations (Pemberton & Frey 1982; Fillion & Pickerill 1984). Fill differs in lithology from the host rock, being essentially structureless.

Planolites montanus Richter 1937 (Figure 4f)

Description. Cylindrical to sub-cylindrical, sinuous to slightly straight horizontal structures preserved in full relief, 3–7 mm in diameter. The burrow fill is structureless, being different in colour (brownish) and composition (silt and sand size) to the host sediment (greyish and muddy silt). The specimens were collected at the Hawalok section.

Remarks. Several taxonomic revisions reveal that *Planolites* can be distinguished from *Palaeophycus* by the existence of an unlined wall and a fill different from the host rock in the former, that is a consequence of an actively against a passively backfilled burrow (Pemberton & Frey 1982; Fillion & Pickerill 1990; Keighley & Pickerill 1995).

We do not discard that some of the studied specimens could be assigned to *Planolites beverleyensis* (Billings). *Planolites montanus* is very similar to *Planolites beverleyensis*, the former being smaller in size and more tortuous (Pemberton & Frey 1982). In this sense, Keighley & Pickerill (1997) analyzed the problems of differentiating between the two ichnospecies. Other species of *Planolites* are well distinguished, as *P. annularius* (with annulations), and *P. terranovae* (with striations) (Pemberton & Frey 1982; Fillion & Pickerill 1990).

Planolites is interpreted as a feeding structure of deposit feeder, mainly worms (Pemberton & Frey 1982), or possibly larval insects in continental deposits (Buatois & Mángano 1993; Kim *et al*. 2002).

Rhizocorallium Zenker 1836

Rhizocorallium refers to U-shaped spreiten-burrows, parallel or oblique to bedding planes. Limbs more or less parallel and distinct, with tube diameter: diameter of spreite usually > 1:5 (after Fürsich 1974b). Variations in morphology are significant, from straight short structures to long sinuous, planispiral or trochospiral ones. Moreover, at times limbs slightly diverge in the distal part (away from the apertures), with increasing burrow diameter, and showing a pear or fan-shaped structure (Fürsich & Mayr 1981; Uchman *et al*. 2000).

Rhizocorallium jenense Zenker 1836 (Figure 5c, d)

Rhizocorallium jenense Zenker 1836, consists of more or less straight, short U-shaped spreiten-burrows, commonly oblique to bedding plane and rarely vertically retrusive (after Fürsich 1974b). When oblique to bedding, the angle of burrowing can vary considerably (Worsley & Mork 2001). Different kinds of scratchmarks (simple, paired) were distinguished on the surfaces of the marginal tunnels and in the spreiten (Fürsich *et al*. 1981; Uchman *et al*. 2000; Rodríguez-Tovar & Pérez-Valera 2008).

Description. Two incomplete specimens have been found. They are straight, or slightly sinuous, comparatively short U-shaped protrusive spreiten-burrows, with parallel limbs at least 20 and 110 mm long and 20 and 65 mm in width. The limbs are 4 and 9 mm in diameter. Horizontal orientation, parallel to bedding planes is exclusive, but taphonomic absence of an oblique part is not discarded. Well-developed scratchmarks have been found in the spreiten. Sediment composition of marginal tubes and spreiten is fine sand while host sediment is silty shale. All the specimens were collected in the Hawalok section.

Remarks. From the great variety in forms and the numerous ichnospecies of *Rhizocorallium*, three ichnospecies are now differentiated: *R. jenense* Zenker 1836, *R. irregulare* Mayer 1954, and *R. uliarense* Firtion 1958, although this classification is still under some debate (Jensen 1997 in Worsley & Mork 2001). Although assigned to *R. jenense*, we do not discard the possibility that the larger specimen could be classified as *R. irregulare* on the basis of its slightly sinuous and comparatively long size and the presence of possible burrows branches. The third U-shaped specimen, showing increasing burrow width toward the distal part could be assigned to *R. jenense*, but the absence of spreite impede a conclusive classification. The assignation to U-shaped forms without spreite, as *Arenicolites* is discarded due to the horizontal orientation of the studied structure.

There is no consensus on the *Rhizocorallium* producers. Most authors agree that this tracemaker probably pertains to crustaceans (the scratchmarks, usually registered on the limbs of the U-tube, are consistent with this interpretation). The lifestyle proposed for the

Rhizocorallium producer varies according to the morphological features of the burrows. *Rhizocorallium jenense* is interpreted as a suspension-feeding structure (Fürsich 1974b), but also as produced by scavenging organisms (Worsley & Mork 2001). Usually a domichnial behaviour has been proposed (Fürsich 1998; Worsley & Mork 2001). *R.jenense* occurs in greatly variable settings; usually related to unstable sedimentary environments, i.e. foreshore, high-energy regimes (Fürsich 1975), it is also related to more intermediate shoreface depths (Worsley & Mork 2001), in the middle ramp setting (Knaust 1998), or in deep waters (Uchman 1992). This structure also occurs in fresh water environments (Fürsich & Mayr 1981). *R. jenense* is generally related to transgressive surfaces, produced during a period of non-deposition, before and at the beginning of the subsequent deposition (Uchman *et al.* 2000; Rodríguez-Tovar *et al.* 2007).

Skolithos Haldeman 1840

Skolithos corresponds to structures unbranched, vertical to steeply inclined, straight to slightly curved, cylindrical to sub-cylindrical, lined or unlined with or without funnel-shaped top. Burrow wall distinct or indistinct, smooth to rough, some specimens annulated. Fill massive and burrow diameter in some individuals is slightly inconstant (Schlirf 2000; Schlirf & Uchman 2005). Detailed diagnosis, classifications at the ichnospecies level, and revision and relationship of the ichnogenus *Skolithos* can be found in several papers (Alpert 1974; Fillion & Pickerill 1990; Schlirf 2000; Schlirf & Uchman 2005).

Skolithos linearis (Haldeman 1840) (Figure 5a)

Skolithos linearis (Haldeman 1840) refers to cylindrical to sub-cylindrical, perfectly straight and vertical to slightly curved or inclined burrows. Burrow wall distinct to indistinct, may be annulated (Alpert 1974; Schirf 2000).

Description. Vertical to sub-vertical, straight, simple, cylindrical structures showing more or less uniform diameter, ranging from 3 to 20 mm. It is 40–270 mm, mostly about 120 mm long. It is filled with structureless, medium sand, similar to the host rock. More or less isolated burrows occur, but also dense occurrences were recognized. *Skolithos linearis* has been found in the Thongjaorok and Hawalok sections.

Remarks. Numerous ichnospecies of *Skolithos* have been differentiated, but only six can be considered valid (Alpert 1974, 1975); *S. annulatus*, *S. bulbus*, *S. ingens*, *S. linearis*, *S. magnus* and *S. verticalis*. However, as is claimed, *Skolithos* needs a detailed ichnospecific revision (Guillette *et al.* 2003; Schlirf & Uchman 2005; Gregory *et al.* 2006; Melchor *et al*. 2006).

Skolithos occurs in shallow-marine environments (Fillion & Pickerill 1990), but also rarely in non-marine environments (Bromley & Asgaard 1979; Schlirf *et al.* 2001; Gregory *et al.* 2006; Melchor *et al.* 2006). Dense occurrences of *Skolithos* are referred to 'pipe-rock' ichnofabric (Droser 1991). Marine *Skolithos* is mainly interpreted as a domichnion structure made by phoroids or annelids, while non-marine forms are related to insects or spiders as dwellings or shelters (Schlirf & Uchman 2005) or even to plants (Gregory *et al.* 2006). Archetypal *Skolithos* ichnofacies are related to relatively high energy environments, shallow water conditions, in nearshore to marginal marine settings.

Thalassinoides Ehrenberg 1944

Thalassinoides consist of three-dimensional burrow systems predominantly smooth-walled, essentially cylindrical to elliptical burrows of variable diameter. Branches are Y- to T-shaped, usually enlarged at the bifurcations points (after Howard & Frey 1984). A horizontal branching polygonal network is dominant, with vertical shafts connected to surface. For further discussion of this ichnogenus and its ichnotaxonomic problems see Fürsich (1973), Ekdale (1992) and Schlirf (2000).

Thalassinoides paradoxicus (Woodward 1830) (Figure 5b)

Thalassinoides paradoxicus (Woodward 1830) refers to sparsely to densely but irregularly branched, sub-cylindrical to cylindrical burrows oriented at various angles with respect to bedding. Mainly T-shaped intersections, with offshoots not necessarily with the same diameter as the parent truck (after Howard & Frey 1984).

Description. Three dimensional structures forming horizontal networks, smooth-walled, irregularly branched; mainly Y-shaped. Burrow diameter varies from 3 mm to 50 mm (average of about 20 mm) (Hemanta Singh 2005), with occasional enlargements in the bifurcation points. Size of burrow fill can be similar or different than that of the host material. *Thalassinoides* structures are registered in the Thongjaorok and Hawalok sections.

Remarks. Systematic of the ichnogenus is complicate, as revealed in several papers (Kennedy 1967; Fürsich 1973; Bromley & Frey 1974; Frey & Howard 1985, 1990; Ekdale 1992; Myrow 1995). Usually five ichnospecies are recognized as valid and useful (Kim *et al.* 2002); *T. saxonicus* (Geinitz), *T. ornatus* (Kennedy), *T. paradoxicus* (Woodward), *T. suevicus* (Rieth) and *T. horizontalis* (Myrow). *T. saxonicus* (Geinitz) is a mamillated large form with tunnels 5–20 cm in diameter (Kennedy 1967); *T. ornatus* (Kennedy) refers to a smaller ovate (0.8 × 1.6 cm to 1 × 2.2 cm; Kennedy 1967) horizontal to gently inclined burrows with swellings; *T. paradoxicus* (Woodard), corresponds to branching, boxwork burrows highly irregular in size and geometry (Kennedy 1967; Bromley & Ekdale 1984; Frey & Howard 1985); *T. suevicus* (Rieth) is a predominantly horizontal structure that may contains enlargements at Y-shaped bifurcations (Kamola 1984; Bromley & Ekdale 1984; Frey & Howard 1985, 1990), and *T. horizontalis* (Myrow) is characterized by an extremely regular burrow diameter of small size, typically less than 0.5 cm, and a strictly horizontal orientation, as well as a diagenetically wall lining. We can not discard that some specimens could be assigned *T. suevicus* (Rieth).

Thalassinoides is a facies-crossing form, most typical of shallow-marine environments. Various tracemakers can be considered, but is mainly produced by crustaceans (Frey *et al.* 1984; Bromley 1996), or other type of arthropods, as deposit feeders (Ekdale 1992). *Thalassinoides* is usually interpreted as a fodinichnial/domichnial structure, passively filled, but occasionally an agrichnial behaviour has been interpreted for the tracemaker (Myrow 1995; Bromley 1996; Ekdale & Bromley 2003); frequently related to oxygenated situations and soft but fairly cohesive substrates (Bromley & Frey 1974; Kern & Warme 1974; Ekdale *et al.* 1984; Bromley 1990). The recognised association between *Thalassinoides* and firm-hardground substrates has been commonly used in sequence stratigraphy, especially in relation with the *Glossifungites* ichnofacies (Pemberton 1998; MacEachern *et al.* 1992; Pemberton & MacEachern 1995; Pemberton *et al.* 2001; Savrda *et al*. 2001).

Environmental Significance

The trace fossil assemblage from the Upper Eocene–Lower Oligocene Transition of Manipur, Indo-Myanmar Ranges (Northeast India), is mainly composed of *?Arenicolites* isp, *Helminthopsis tenuis*, *Ophiomorpha nodosa*, *Phycodes palmatus*, *Planolites montanus*, *Rhizocorallium jenense*, *Thalassinoides paradoxicus* and *Skolithos linearis*.

In the marine environment, some of the aforementioned ichnotaxa can be considered as facies-crossing forms, occurring in a variety of ichnofacies, and in diverse settings, as *Planolites*, *Helminthopsis* (in deep-marine, but also from shallow-marine deposits), or *Arenicolites*; even the latter is typical of shallow-marine settings (Crimes 1977). The remaining ichnotaxa occur in shallow-marine contexts: *Ophiomorpha* is typical of these environments (Pemberton & Jones 1988; Uchman & Gaździcki 2006), as well as *Thalassinoides*, frequently related to oxygenated environment in soft but fairly cohesive substrates (Bromley & Frey 1974; Kern & Warme 1974; Ekdale *et al.* 1984; Bromley 1990), and *Phycodes*, mainly in shallow water environments and less frequently registered in deep-marine conditions (Han & Pickerill 1994). Moreover, *Skolithos* is mainly recognized in shallow-marine environments (Fillion & Pickerill 1990), and the archetypal *Skolithos* ichnofacies in relatively high energy conditions, in nearshore to marginal settings. *Rhizocorallium jenense* is usually related to unstable, high-energy environments (Fürsich 1975). Thus, a shallow-marine environment, with occasional high-energy conditions can be interpreted based on the composition of the trace-fossil assemblage.

In shallow marine settings, two major ichnofacies have been traditionally differentiated; the *Skolithos* and *Cruziana* ichnofacies (see MacEachern *et al.* 2007 for an updated review). The *Skolithos* ichnofacies is characterized by trace fossils produced by suspension feeders, like *Skolithos*, *Ophiomorpha* and *Arenicolites* in the studied section, whereas the *Cruziana* ichnofacies contains *Planolites*, *Rhizocorallium*, *Thalassinoides*, *Phycodes*, *Helminthopsis*, *Ophiomorpha*, *Arenicolites* and *Skolithos* in the studied section. The ichnotaxa differentiated in the studied successions are typical for both the *Skolithos* and the *Cruziana* ichnofacies, and a more precise assignation must be based not only on a checklist of trace fossils, but also on the detailed analysis of the physical sedimentary structures and other facies evidences (research in progress), as well as relationships between the two ichnofacies.

The *Skolithos* ichnofacies is related to relatively high levels of wave or current energy, and is typically developed in clean, well-sorted, loose or shifting particulate substrates. Such conditions commonly occur on the shoreface and sheltered foreshores, but similar conditions occur also in a wide range of high-energy shallow-water environments (MacEachern *et al.* 2007). The *Cruziana* ichnofacies is most characteristic of permanently subtidal, poorly sorted, and unconsolidated (muddy) substrates in shallow marine settings typified by uniform salinity. Conditions typically range from moderate energy levels lying below fair-weather (minimum) wave base but above storm wave base, to lower energy levels in deeper, quieter waters. The most common settings correspond to the offshore extending to the very distal fringes of the lower shoreface (MacEachern *et al.* 2007). The *Skolithos* ichnofacies ordinarily grades seaward into the *Cruziana* ichnofacies, as was presented in some idealized shoreface models for ichnofacies (Frey *et al.* 1990; Pemberton & MacEachern 1995). Moreover, in a shallow environmental context, increased energy and allied parameters thus represent a temporary excursion of *Skolithos*-type conditions into an otherwise *Cruziana*-type setting.

Conclusions

Ichnological analysis of the Upper Eocene–Lower Oligocene Transition succession of Manipur, Indo-Myanmar Ranges (Northeast India), reveals a relatively abundant and moderately diverse trace fossil assemblage.

Biogenic structures registered in sediments from the Disang and Barail Groups have been described in detail and characterized taxonomically at the ichnospecies level for the first time in the Manipur state.

Trace fossil assemblage consists of ?*Arenicolites*, *Helminthopsis tenuis*, *Ophiomorpha nodosa*, *Phycodes palmatus*, *Planolites montanus*, *Rhizocorallium jenense*, *Thalassinoides paradoxicus* and *Skolithos linearis*.

This ichnoassemblage represents the record of classical *Skolithos* and/or *Cruziana* ichnofacies, allowing interpretation of a shallow-marine environment, with occasional high-energy conditions.

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