Trace fossils from Bhuban Formation, Surma Group (Lower to Middle Miocene) of Mizoram India and their palaeoenvironmental significance

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A detailed ichnological study performed on the Bhuban Formation, Surma Group (Lower to Middle Miocene) of Mizoram, India reveals the occurrence of rich and diverse trace fossils. These have been collected from the two localities in Aizawl, i.e., Bawngkawn and Ropaiabawk, where sandstone–shale sequence is well exposed. Total 20 ichnospecies of 14 ichnogenera have been identified which include *Arenicolites* isp., *Cochlichnus anguineus*, *Helminthopsis abeli*, *Laevicyclus mongraensis*, *Ophiomorpha borneensis*, *Palaeophycus tubularis*, *Palaeophycus heberti*, *Palaeophycus sulcatus*, *Palaeophycus alternatus*, *Pholeus abomasoformis*, *Pholeus bifurcatus*, *Planolites beverleyensis*, *Planolites annularis*, *Polykladichnus irregularis*, *Rhizocorallium* isp., *Skolithos linearis*, *Taenidium satanassi*, *Teichichnus rectus*, *Thalassinoides horizontalis* and *Thalassinoides paradoxicus*. Ethologically these ichnogenera display dwelling and feeding activities of the infaunal organisms. *Arenicolites*, *Ophiomorpha*, *Polykladichnus* and *Skolithos* are the members of the *Skolithos* ichnofacies while *Palaeophycus*, *Planolites*, *Rhizocorallium* and *Thalassinoides* are the members of the *Cruziana* ichnofacies. The presence of *Skolithos* ichnofacies indicates sandy shifting substrate and high energy conditions in foreshore zone while the *Cruziana* ichnofacies indicate unconsolidated, poorly sorted soft substrate and low energy condition in the shoreface/offshore zone. These ichnogenera indicate foreshore to shoreface-offshore zone of shallow marine environment for the deposition of the rocks of the Bhuban Formation of Mizoram.

1. Introduction

In recent years, the ichnological studies in the Cenozoic successions have been carried out in many parts of India. These studies are mainly concerned with the western (Patel and Shringarpure 1990, 1992; Sudan *et al* 2002; Kundal and Dharashivkar 2006; Kundal and Mude 2008; Desai and Patel 2008), north-eastern India region (Reddy *et al* 1992; Bandopadhyay *et al* 2009; Singh *et al* 2008, 2010) other than the Mizoram and South India (Malarkodi *et al* 2009). However, rich and diverse ichnofossil assemblage of the Cenozoic succession of Mizoram is not yet explored and the

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previous studies are meagre. Mehrotra *et al* (2001) for the first time reported *Teredolites clavatus* from the Upper Bhuban unit of Bhuban Formation, Ramrikawn area about 10 km west of Aizawl city, Mizoram. This ichnospecies was found in association with other shallow marine taxa mainly tellinid bivalves and fishes. Subsequently Mehrotra *et al* (2002) described ichnogenus *Palaeophycus* from the Barail Group succession exposed at about 8.7 km from Champhai (a border town in the eastern part of the state) on the Champhai–Aizawl road. This was considered the first record of *Palaeophycus* from the Tertiary succession of north-east India.

This paper is an attempt to record and describe the trace fossil assemblage from the Bhuban succession of Mizoram. The Middle and Upper Bhuban units of Bhuban Formation (Surma Group) have yielded 20 ichnospecies shared among 14 ichnogenera and have been used for deducing the depositional environments.

2. Geological setting

Geologically, Mizoram is a part of Tripura–Mizoram depositional basin, and it has been considered as the southern extension of Surma Basin. The entire sedimentary column of the area is a repetitive succession of arenaceous and argillaceous rocks of Palaeogene to Neogene ages. It consists of sandstone, silty-sandstone, siltstone, shale, mudstone and their admixture of varying proportions along with a few pockets of shell-limestone, calcareous sandstone and intraformational conglomerates. This succession constitutes a series of approximately N–S trending and longitudinally plunging anticlines and synclines (Ganju 1975; Ganguly 1975, 1983). General strike direction of the rock successions is N–S with dip amount varying from 20°–50° either towards east or west. Tertiary succession of Mizoram has been grouped into the Barail (Oligocene), the Surma (Lower to Middle Miocene) and the Tipam Groups (Upper Miocene to early Pliocene) in the ascending order. Surma Group has been subdivided into Bhuban and Bokabil Formations. Bhuban Formation is the main lithostratigraphic unit in the state and it attains a thickness of about 5000 m. This formation is further divisible into Lower, Middle and Upper Bhuban units. The stratigraphic succession of the state and the lithological characteristics of each litho-unit as worked out by Karunakaran (1974) and Ganju (1975) with slight modification is given in table 1. The modification pertains to assigning

Table 1. *Lithostratigraphic classification of the Tertiary rocks of the Mizoram (modified after Karunakaran 1974 and Ganju 1975).*

Age	Group	Formation	Unit	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 Upper 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	Upper Bhuban (+1100 m)	Arenaceous predominating with sandstone, shale and siltstone
			Conformable and transitional contact	
			Middle Bhuban (+3000 m)	Argillaceous predominating with shale, siltstone-shale alternations and sandstone
			Conformable and transitional contact	
			Lower Bhuban (+900 m)	Arenaceous predominating with sandstone and silty-shale
Unconformity obliterated by faults				
Oligocene	Barail (+3000 m)			Shale, siltstone and sandstone
Lower contact not seen				

formation status to the Bhuban and Bokabil which were earlier assigned to subgroup and also unit status to the erstwhile Lower, Middle and Upper Bhuban Formations.

3. Depositional settings

Detailed sedimentological study of three units of Bhuban Formation is yet to be carried out. However, these units have been described based on field observations. Lower Bhuban unit (900 m) comprises alternations of sandstone and shale, the former being predominant. The shales are bluish grey to greenish grey, laminated with lenticular beddings. Sandstones are grey, fine-grained, silty with medium scale cross-stratification. Middle Bhuban unit (3000 m) is predominantly an argillaceous sequence with subordinate sandstones that occur as intercalations. Shales are grey to dark grey in colour and contain numerous calcareous concretions. Sandstones are thin bedded to massive, ill sorted, silty and are fine-grained. Wave ripple laminations, lenticular and flaser beddings are commonly observed in the sandstones. Siltstones are characterized by small scale cross-stratification and wave ripples. Upper Bhuban unit (1100 m) is an alternating sequence of arenaceous and argillaceous clastics with former being predominant. Sandstones are thin bedded to massive, grey, fine-grained, silty and ill sorted and are characterized by mega ripples along with small to medium scale cross-stratification with tidal bundles. The shales are bluish grey, thinly laminated, splintery, fissile, micaceous with lenticular beddings. Siltstones are massive bedded (Rao 1983).

Composite litholog of Bhuban Formation as a whole along with depositional settings is yet to be worked out. Previous researchers have studied isolated sections of this formation at different stratigraphic levels based on palaeobiota (bivalves and gastropods) (Tiwari *et al* 1997; Tiwari and Kachhara 2000, 2003; Tiwari 2001, 2006), decapods (Tiwari and Satsangi 1988; Tiwari *et al* 1997; Ralte *et al* 2009), echinoids (Jauhri *et al* 2003; Srivastava *et al* 2008), foraminifers (Jauhari *et al* 2003; Lokho and Raju 2007; Lalmuankimi *et al* 2010), fish teeth and skeletons (Tiwari *et al* 1998; Tiwari and Bannikov 2001; Ralte *et al* 2011), mangrove palm (Mehrotra *et al* 2003) and leaf and seed/fruit impressions (Tiwari and Mehrotra 2002) and inferred changes in depositional environment

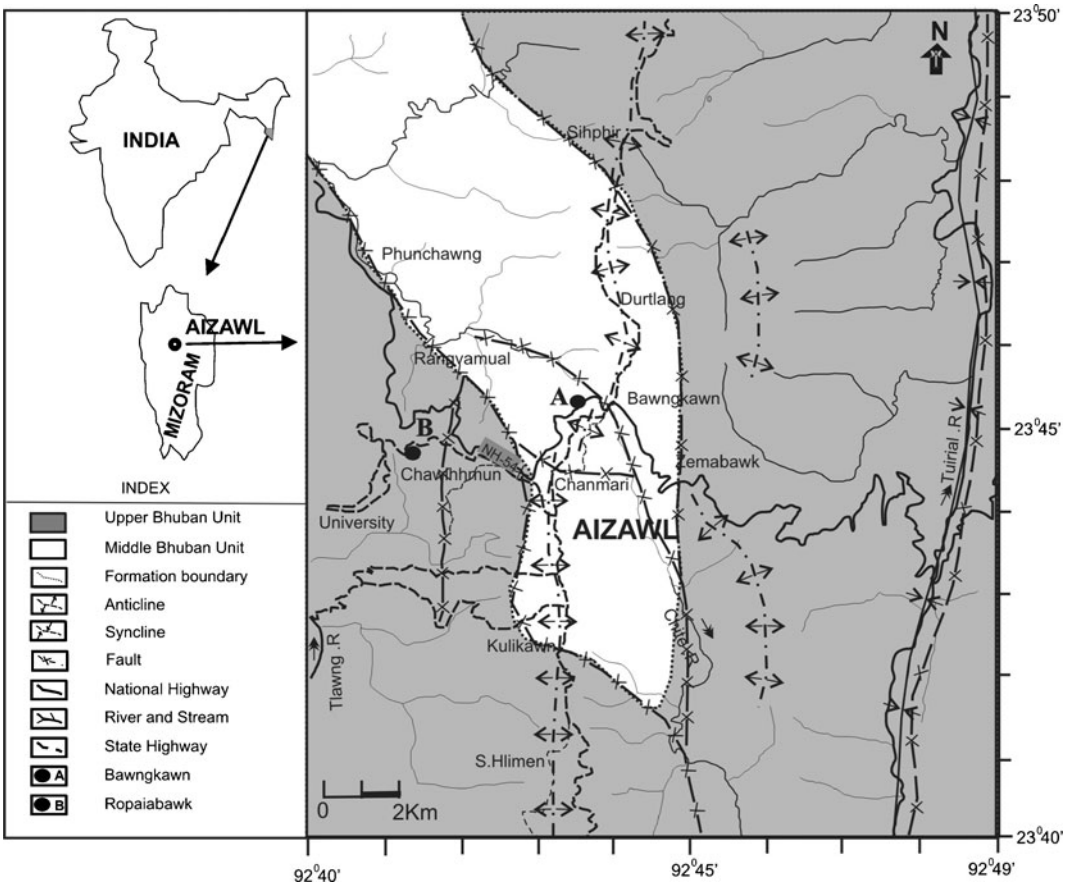

Figure 1. Geological map of Aizawl showing trace fossil localities.

throughout the stratigraphy with shallow marine, near shore, lagoonal through coastal to fluviatile (op. cit.).

Studied section in Bawngkawn locality (figure 1) belongs to lower part of Middle Bhuban unit of Bhuban Formation. 120 m thick succession exposed at this locality comprises sandstone, silty-sandstone, silty-shale, shale and sandstone–shale alternation. Sandstones are grey to buff coloured, thickly bedded, ill sorted, occasionally silty and

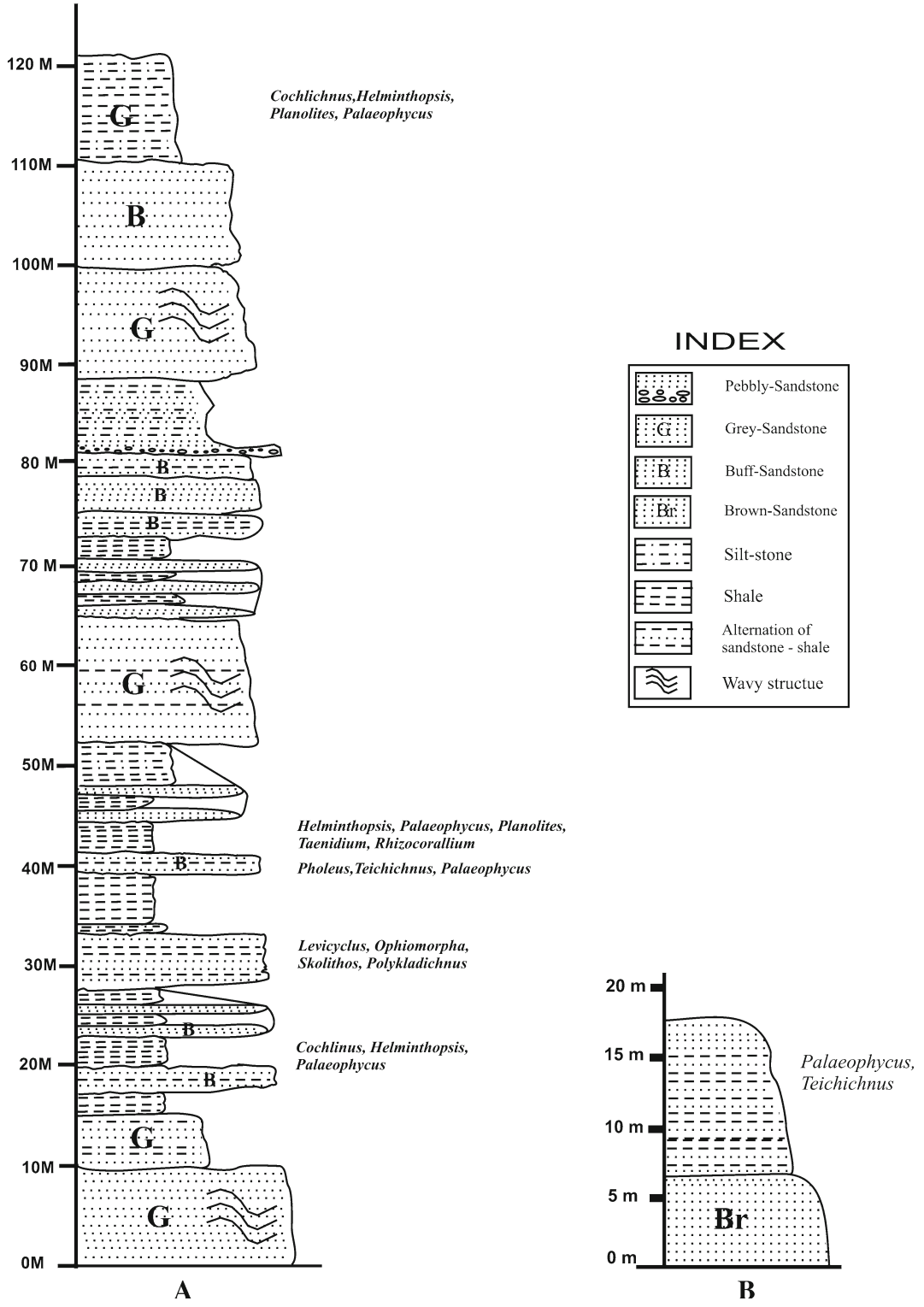

Figure 2. Lithocolumn at fossil localities. (**A**) Bawngkawn–Sairang Road (NH 54) and (**B**) Ropaiabawk (Tanhril–Mizoram University Road).

fine-grained. Wave ripple laminations, lenticular and flaser beddings are commonly observed in the sandstone beds. Siltstone show small scale cross-stratification and wave ripples. Shales are grey to dark grey in colour and are thinly laminated with lenticular beddings. Tidal bundles are common in cross bedded units. This indicates that succession at this locality was deposited in a deltaic set-up. Further, the exposed succession broadly shows coarsening upward trend referring to regression. About 17.5 m thick succession belonging to middle part of Upper Bhuban unit of Bhuban Formation is exposed at Ropaiabawk locality (figure 1). The succession comprises brown coloured, fine-grained sandstone and sandstone–shale intercalations. The succession is characterized wave-ripples indicating its deposition under the shoreface environment.

4. Locality description

Trace fossil assemblage described in this paper has been collected from the two localities in the western limb of Aizawl anticline in Mizoram. The geological description of the fossil localities is here under:

4.1 *Locality 1: Bawngkawn, Aizawl*

It lies at a distance of 0.75 km on Bawngkawn–Sairang road (NH 54) on the left road cutting (23°45′11″N–92°43′05″E). About 120 m thick succession belonging to lower part of Middle Bhuban unit of Bhuban Formation is exposed at this locality. Trace fossils from this locality have been collected from the sandstone, sandstone–shale intercalations, silty-sandstone, shale and silty-shale lithologies (figure 2A). This locality is highly rich in ichnospecies and bulk of the collection comes from it. The ichnospecies collected from this locality are *Arenicolites* isp., *Laevicyclus mongraensis, Palaeophycus heberti, Palaeophycus sulcatus, Palaeophycus alternates, Pholeus bifurcatus, Polykladichnus irregularis, Skolithos linearis, Taenidium satanassi* and *Thalassinoides paradoxicus* from sandstone bed; *Helminthopsis abeli, Ophiomorpha borneensis, Planolites beverleyensis* and *Skolithos* linearis from sandstone–shale intercalations; *Arenicolites* isp., *Cochlichnus anguineus, Pholeus abomasoformis, Planolites beverleyensis* and *Planolites annularis* from silty-sandstone; *Cochlichnus anguineus, Palaeophycus tubularis, Planolites annularis, Rhizocorallium* isp. and *Skolithos linearis* from shale; and *Palaeophycus alternatus* and *Thalassinoides horizontalis* from silty-shale.

4.2 *Locality 2: Ropaiabawk, Aizawl*

It lies at Ropaiabawk junction in Chawlhhmun area in the western outskirt of Aizawl city on the Aizawl–Mizoram University road (figure 1). About 17.5 m thick succession belonging to middle part of Upper Bhuban unit of Bhuban Formation is exposed at this locality. Sandstone–shale intercalations exposed at the left road cut section at this junction (23°44′46″N–92°41′39″E) contain trace fossils that include *Palaeophycus alternatus* and *Teichichnus rectus* (figure 2B).

5. Systematic descriptions

All the ichnospecies described and illustrated in this paper are archived in the Palaeontology Laboratory of the Department of Geology, Mizoram University, Aizawl, Mizoram. These include *Arenicolites* isp., *Cochlichnus anguineus*, *Helminthopsis abeli*, *Laevicyclus mongraensis*, *Ophiomorpha borneensis*, *Palaeophycus tubularis*, *Palaeophycus heberti*, *Palaeophycus sulcatus*, *Palaeophycus alternatus*, *Pholeus abomasoformis*, *Pholeus bifurcatus*, *Planolites beverleyensis*, *Planolites annularis*, *Polykladichnus irregularis*, *Rhizocorallium* isp., *Skolithos linearis*, *Taenidium satanassi*, *Teichichnus rectus*, *Thalassinoides horizontalis* and *Thalassinoides paradoxicus*. In the present study, ichnogenera and ichnospecies are named according to I.C.Z.N. rules, using the binomial system of nomenclature and described alphabetically.

Ichnogenus: *Arenicolites* Salter (1857)
Ichnospecies: *Arenicolites* isp.
(Plate 1a & b)

Description: Endichnial, full relief, vertical, slender, small, U-shaped burrow with no spreiten. Limbs closely spaced, circular in cross section and are parallel to each other. Depth of the burrow is 8 mm; diameter of the tube is 2 mm and distance between the limbs are 1 to 2 mm. Width of the burrow as well as diameter of the limb are uniform throughout the height of the burrow. A somewhat larger form occurs as paired burrow (Plate 1b) on the bedding surfaces; diameter of this burrow is 12 to 15 mm and distance between the limbs is 10 mm. Burrow fills are distinct and different than the host sediments.

Remarks: The burrows are U-shaped, small in dimension, slender and are without spreite.

Occurrence: Silty-sandstone and sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

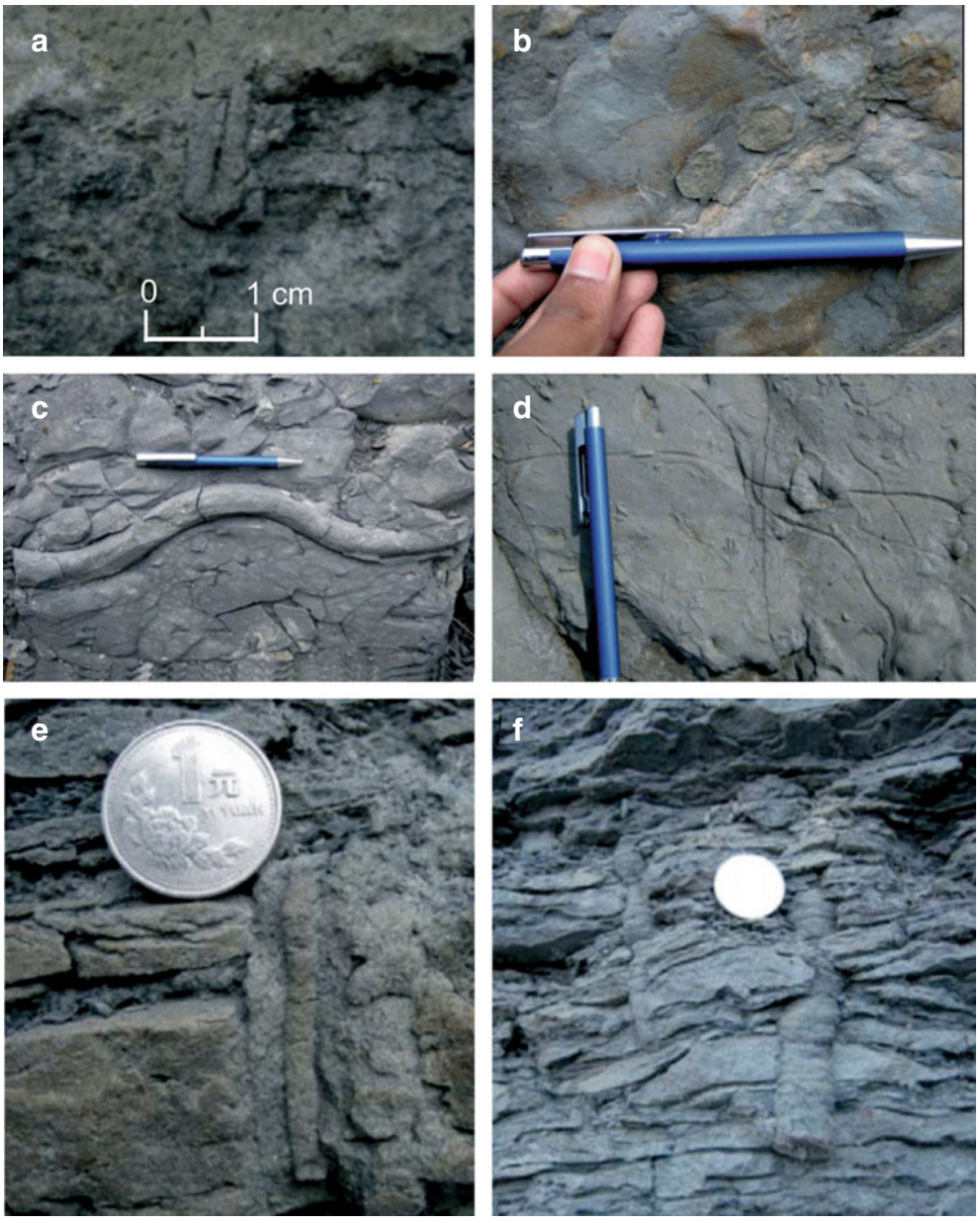

Plate 1. (**a** and **b**) *Arenicolites* isp. Salter (1857); field photograph. (**c**) *Cochlichnus anguineus* Hitchcock; c= field photograph. (**d**) *Helminthopsis abeli* Ksiazkiewics; specimen no. Ich/29. (**e**) *Laevicyclus mongraensis* Chiplonkar and Badve; field photograph. (**f**) *Ophiomorpha borneensis* Keij; field photograph.

Ichnogenus: *Cochlichnus* Hitchcock (1858)
Ichnospecies: *Cochlichnus anguineus* Hitchcock (1858) (Plate 1c)

Description: Smooth, sinusoidal, horizontal, unlined and unbranched feeding trails, preserved as convex epirelief and consisting of identical filled sediments to the surroundings. Regular meanders resemble sine curves and without any ornamentation. The length of the larger trail is 40 cm and diameter is 5 cm whereas smaller trail has length of 8 cm and diameter of 4.5 cm.

Remarks: Differentiation among the hitherto known species of *Cochlichnus* namely *C. anguineus* Hitchcock 1858, *C. kochi* Ludwig 1869 and *C. serpens* Webby 1970 in the available literature is confusing and these can at best be regarded as conspecific. Present specimen shows regular sinuosity in structures which is identical to *C. anguineus* Hitchcock. According to Eager *et al* (1985), *Cochlichnus* are the crawling traces and probably are the feeding structures of small worms or worm-like animals. *Cochlichnus* has been reported in sediments of supposedly low salinity palaeoenvironment (Hakes 1976).

Occurrence: Silty-sandstone and shale, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Helminthopsis* Heer (1877)
Ichnospecies: *Helminthopsis abeli* Ksiazkiewicz (1977) (Plate 1d)

Description: Smooth, unbranched and horizontal traces preserved on silty-sand stone. Burrow diameter is constant throughout, typically alternating between winding straight course. Maximum observed length of the burrow is 200 mm and diameter is 10 mm. Burrow fill is massive.

Remarks: On account of its unbranched and winding or meandering nature, this horizontal trace is placed under inchnogenus *Helminthopsis*. This ichnospecies closely resembles *Helminthoida* illustrated by Chamberlain (1974). Though it is gently meandering or irregularly winding burrow with typically alternating winding and straight course, it is lacking the regular tight meandering pattern of *Helminthoida*.

Occurrence: Sandstone–shale intercalation, Middle Bhuban unit of Surma Group (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Laevicyclus* Quenstedt (1879)
Ichnospecies: *Laevicyclus mongraensis* Chiplonkar and Badve (1970) (Plate 1e)

Description: Endichinal full burrow; vertical cylindrical body consists of central shaft surrounded by scrapping circles and right angle to the bedding plane. Maximum outer diameter is about 20 mm; shaft diameter is 5 mm and depth of the burrow is 70 mm. The outer ring sediments are coarser than the inner shaft which reflect the distinct relief and fill as well. The diameter of the burrow is constant throughout and infill material is different from the surrounding.

Remarks: The diameter of central shaft and scrapping circle in present burrows are similar with *Laevicyclus mongraensis* originally described from Bagh bed, Gujarat (Chiplonkar and Badve 1970). Subsequently, Badve and Ghare (1980) and Kundal and Sanganwar (1998) reported this species from other exposures of Bagh and Patel *et al* (2008) from the Jurassic of the Habo dome, Gujarat. Kundal and Dharashivkar (2006) also reported this species from Neogene and Quaternary deposits of Dwarka–Okha area of Gujarat. However, *L. mongraensis* is also reported from the deep water flysch deposits and is considered to be a circular trace of the suspension feeding animals (Uchman 1998).

Occurrence: Sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Ophiomorpha* Lundgren (1891)
Ichnospecies: *Ophiomorpha borneensis* Keij (1965) (Plate 1f)

Description: Full relief and endichnial burrows with long straight vertical shafts; lined, packed with the bilobate pellets. Rare to scattered ovoid or single pellets are also found. Depth of the burrow is about 15.0 cm and diameter is 2.8 mm. Burrow tubes have thick wall formed of ferruginous and argillaceous material with smooth interior surfaces and distinctly irregular rugose exterior surface. The burrow fill is different from the surrounding sediment.

Remarks: According to Frey *et al* (1978), the morphology of this form is like *O. nodosa* and *O. irregularie* which could be genetically related. Fursich (1973) regarded *O. borneensis* to be synonym of *Spongiliomorpha saxonica* but failed to consider the bilobate pellets. Kundal and Dharashivkar (2006) reported this species from Neogene and Quaternary deposits of Dwarka–Okha area of Gujarat, India.

Occurrence: Sandstone–shale intercalation of Middle Bhuban unit of Surma Group (Miocene), Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Palaeophycus* Hall (1847)
Ichnospecies: *Palaeophycus tubularis* Hall (1852) (Plate 2a)

Description: Endichnial, full relief, long, horizontal, smooth, straight and cylindrical, unbranched, unornamented and lined burrow. Length of the burrow is 100 mm and diameter is 20 to 25 mm; burrow is compressed, appears as elliptical in cross section and filled with the same sediment as the host rock.

Remarks: The distinction between *Palaeophycus*, *Planolites* and *Macaronichnus* is partially controversial (Pemberton and Frey 1982; Fillion 1989; Fillion and Pickerill 1990). *Palaeophycus* is a eurybenthic facies-crossing form produced probably by polychaetes or annelids (Pemberton and Frey 1982). Present form is classified as *P. tubularis* on account of the horizontal smooth, straight, long and unbranched burrows with distinct lining. Badve (1987) and Kundal and Sangawar (1998) reported this species from the Bagh Group of M.P. *P. tubularis* is also known to occur in the Miocene sediments of Dwarka–Okha area (Kundal and Dharashivkar 2006), Middle Jurassic of Kachchh (Patel *et al* 2008) and Surma Group of Manipur (Singh *et al* 2010).

Occurrence: Shale, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnospecies: *Palaeophycus heberti* Saporta (1872) (Plate 2b)

Description: Smooth, thickly lined, unornamented, gently curved, endichnial burrows. Length of the burrow is 55 mm in broken specimen (Plate 2b) whereas diameter is constant in a given specimen and is of 12 mm. Burrow fill is structureless and identical to the host rock. Thick wall of the burrow can be seen along with smooth burrow fill inside exposed due to differential weathering.

Remarks: *Palaeophycus heberti* is distinguished from other species of *Palaeophycus* by its thick wall lining (Pemberton and Frey 1982).

Occurrence: Sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnospecies: *Palaeophycus sulcatus* Miller and Dye (1878) (Plate 2c)

Description: Endichnial, horizontal, straight to gently sinuous, cylindrical, lined burrow. Often the burrow enlarges at some distance and shows variation in diameter. The observed length of the burrow is 220 mm and diameter is 18–20 mm.

Plate 2. (**a**) *Palaeophycus tubularis* Hall; field photograph. (**b**) *Palaeophycus heberti* Saporta; specimen no. Ich/23. (**c**) *Palaeophycus sulcatus* Miller and Dyer; field photograph. (**d**) *Palaeophycus alternatus* Badve; d= field photograph. (**e**) *Pholeus abomasoformis* Fiege; specimen no. Ich/44. (**f** and **g**) *Pholeus bifurcatus* Knaust; f= specimen no. Ich/1; g= specimen no. Ich/6.

Nature of the burrow fill is similar to that of the host rock.

Remarks: Pemberton and Frey (1982) and Keighley and Pickerill (1995) reviewed the controversies between *Planolites*, *Palaeophycus* and *Macaronichnus* and suggested *Palaeophycus* to be lined burrows. *Palaeophycus sulcatus* differs from *P. striatus* by anastomosing rather than longitudinal striations and from *P. alternatus* in having consistent rather than alternating striations (Crimes and McCall 1995).

Occurrence: Sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnospecies: *Palaeophycus alternatus* Pemberton and Frey (1982) (Plate 2d)

Description: Hypichnial, full relief, slightly curved, thinly lined burrows encircled by thin ring-like structures or distinctly placed annulations arranged serially on the burrows. The diameter of the burrow is constant being of 12 mm and length of the burrow is 60 mm. The burrow fill is structureless and identical to the surrounding materials.

Remarks: The trace fossil is named as *P. alternatus* though Buckman (1995) considered the ichnospecies as *Nomia dubia* and doubted its taxonomic position. The characteristic annulations occurring on the tubes support its recognition as *P. alternatus* (Badve 1987).

Occurrence: Silty-shale and sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram; sandstone–shale intercalation of Upper Bhuban unit (Miocene) of Ropaiabawk area, Aizawl, Mizoram.

Ichnogenus: *Pholeus* Fiege (1944) Ichnospecies: *Pholeus abomasoformis* Fiege (1944) (Plate 2e)

Description: Endichnial, full relief, thinly lined, U-shaped, cylindrical burrow circular in cross-section. The burrow consists of gently curved, thick horizontal arm accompanied by a smaller upward oriented shaft at the opposite side of the burrow opening. The horizontal arm consists of faint scratch mark. The length of the burrow in horizontal arm is 55 mm and diameter varies from 8 to 12 mm.

Remarks: *Pholeus abomasoformis* is the simplest and smallest form with no branching and is elliptical in cross-section (Knaust 2007). The general structure of *Pholeus* in combination with the smaller vertical shaft burrow lining and scratch ornament are clear fingerprints indicating crustaceans as its producer (Knaust 2002).

Occurrence: Silty-sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnospecies: *Pholeus bifurcatus* Knaust (2002) (Plate 2f & g)

Description: Endichnial, full relief, thinly lined three dimensional branched burrow systems. It consists of a vertical shaft which bifurcates at lower end into two horizontal to inclined shafts which show quasi-cylindrical cross-section. The diameter of burrow is constant and being of 25 mm and length of each arms are variable. The burrow swells at junctions and shows rugged exterior surfaces.

Remarks: *Pholeus bifurcatus* is a large size burrow that bifurcates at the lower end. On these counts, this ichnospecies can be differentiated from the *Pholeus abomasoformis* (Knaust 2002). Wall lining and rugged exterior surface of the structure indicate that the burrow producers were most probably decapod crustaceans. Compound burrow systems and retrusive burrow parts with spreiten-like structures are common and point to an upward shifting of the burrows related to certain sediment input in relation to tidal currents.

Occurrence: Sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Planolites* Nicholson (1873) Ichnospecies: *Planolites beverleyensis* Billings (1862) (Plate 3a)

Description: Simple, horizontal, long, cylindrical, smooth-walled, unlined, straight to gently curved, unbranched burrow and oriented more or less parallel to bedding plane and preserved as epichnial ridges. Burrow occurs as a single isolated specimen with small nondescript feeding trail. The maximum observed length is 160 mm and diameter is constant and being of 8 mm. The other figured specimen (Plate 2b) is undulated and showing somewhat larger dimension. The burrow fill is surrounding the host sediments.

Remarks: *Planolites beverleyensis* is essentially unbranched and oriented more or less parallel to bedding (Pemberton and Frey 1982). The observed burrows are exceptionally long and usually lack in burrow wall or burrow lining. *Planolites* is

generally regarded as belonging to Fodinichnia/ Pascichnia ethological group and has been considered as a product of vermiform deposit feeder actively back-filling its burrow (Uchman 1998). This ichnospecies has previously been reported from the Wadhwan Formation of Gujarat (Borkar and Kulkarni 1992), Bagh Group of M.P. (Kundal and Sanganwar 1998, 2000), Neogene-Quaternary sediments of Dwarka Formation, Gujarat (Kundal and Dharashivkar 2006) and Surma Group of Manipur (Singh *et al* 2010).

Occurrence: Silty sandstone and sandstone–shale intercalation of Upper Bhuban unit, Surma Group (Miocene), Ropaiabawk area, Aizawl, Mizoram.

Ichnospecies: *Planolites annularis* Walcott (1890) (Plate 3b)

Description: Endichnial, full relief, horizontal, large, straight to gently curved, semicircular burrows exhibiting faint transverse annulations which are preserved on right side of the burrow. The burrow is exceptionally large and attains length more than 400 mm and diameter of 25 to 30 mm. Burrow lack lining and fill material is identical to the host rock.

Remarks: The distinct annulations distinguish this species from *P. beverleyensis*. Annulations possibly reflect the peristaltic movements of the trace maker.

Occurrence: Silty-sandstone and shale, Middle Bhuban unit, Surma Group (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Polykladichnus* Fursich (1981) Ichnospecies: *Polykladichnus irregularis* Fursich (1981) (Plate 3c)

Description: Endichnial, full relief, Y-shaped, cylindrical to subcylindrical, vertical to steeply inclined burrows with a smooth, thinly lined to unlined. Very often collapsed structures of the burrows were also observed. Observed burrow depth of up to 15 cm and diameter is constant and being of 7 mm. Structureless fills consisting of fine to medium-grained sand size particles which is similar to surrounding.

Remarks: *Polykladichnus irregularis* is Y-shaped burrow made by the suspension/deposit feeder polychaetes (Fursich 1981). Mucus bound tubes/ burrows constructed by *Nereis costoe*, *N. unifasciata*, *N. diversicolour*, *Lycastis indica*, *Lumbriconereis pseudobifilaris* and *Heteromastus filiformis* described from the Mandvi coast (Patel and Desai 2009) are identical to the ichnogenus *Polykladichnus irregularis*.

Occurrence: Sandstone, Middle Bhuban unit of Surma Group (Miocene), Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Rhizocorallium* Zenker (1836) Ichnospecies: *Rhizocorallium* isp. Zenker (1836) (Plate 3d)

Description: The burrows are simple, horizontal, sinuous (curved), U-shaped anddisposed parallel to the bedding plane, circular incross-section and preserved as positive epirelief. The burrow is poorly preserved and shows two marginal tubes which are 10 to 15 mm apart; tube-diameter 10 mm and length of the burrowis 110 mm. The spreiten structure is poorly preserved and dim. The burrow preserves some veryfaint scratch-marks.

Remarks: The present burrow is identified as *Rhizocorallium* isp. since its morphological features agree with the digonastic characters such as long, sinous, U-shape and parallel to the bedding. Since spreitens of the burrow are not well preserved, species level identification has not been attempted.

Occurrence: Shale of Middle Bhuban unit (Miocene) exposed in Bawngkawn area of Aizawl, Mizoram.

Ichnogenus: *Skolithos* Haldemann (1840) Ichnogenus: *Skolithos linearis* Haldemann (1840) (Plate 3e–h)

Description: Vertical or steeply inclined, unbranched, cylindrical or subcylindrical, lined or unlined burrow perpendicular to the bedding plane with a structureless fill. It occurs as closely spaced or isolated tubes on bedding planes. The depths of burrows vary in different burrow populations and maximum depth (Plate 3g) observed is 35 mm with diameter of 10 to 12 mm. It is also appearing as circular to subcircular outlines (Plate h and i) on bedding plane and standout as high relief burrow, infill material is different from the surrounding matrix and mostly seen as light colour.

Remarks: Morphologically, this specimen clearly falls within the range of *Skolithos linearis* as

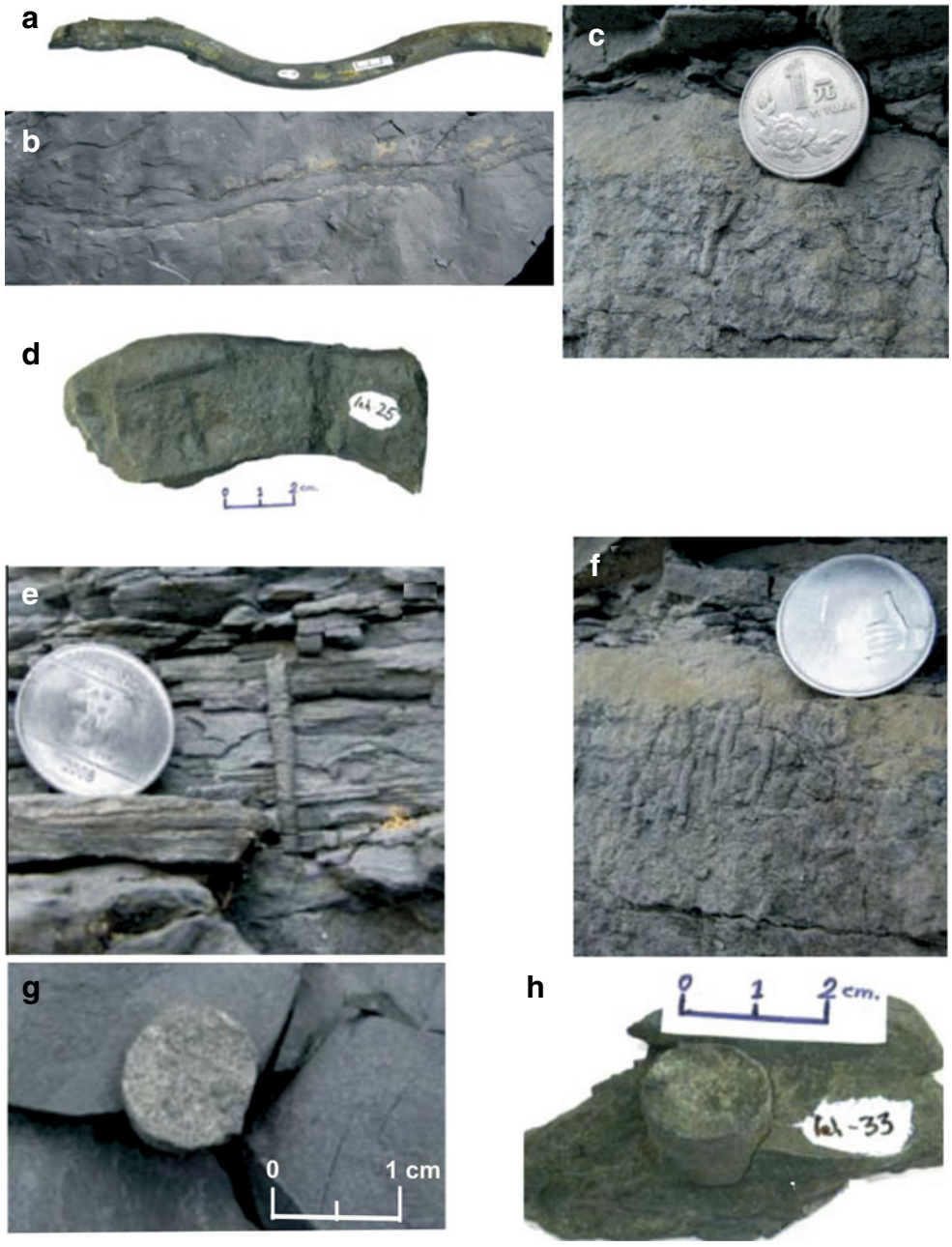

Plate 3. (**a**) *Planolites beverleyensis* Billings; a= specimen no. Ich/9. (**b**) *Planolites annularis* Walcott; field photograph. (**c**) *Polykladichnus irregularis* Fursich; field photograph. (**d**) *Rhizocorallium* isp. Zenker; specimen no. Ich/25. (**e**–**h**) *Skolithos linearis* Halddemann; e, f and g= field photographs; h= specimen no. Ich/33.

described by Alpert (1974), Curran and Frey (1977) and Curran (1985). Alpert (1974) and Pemberton and Frey (1982) suggested that *Skolithos* may have been dwelling burrows of suspension feeding polychaetes.

Occurrence: Sandstone, sandstone–shale intercalation and shale, Middle Bhuban unit of Surma Group (Miocene), Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Taenidium* Heer (1877)
Ichnospecies: *Taenidium satanassi* D'Alessandro and Bromley (1987)
(Plate 4a)

Description: Concave and convex, hyporelief, endichnial burrows horizontal to weakly inclined to bedding, straight to gently curved backfilled burrows and the fills consisting of meniscate packets. The meniscates are symmetrical and equally

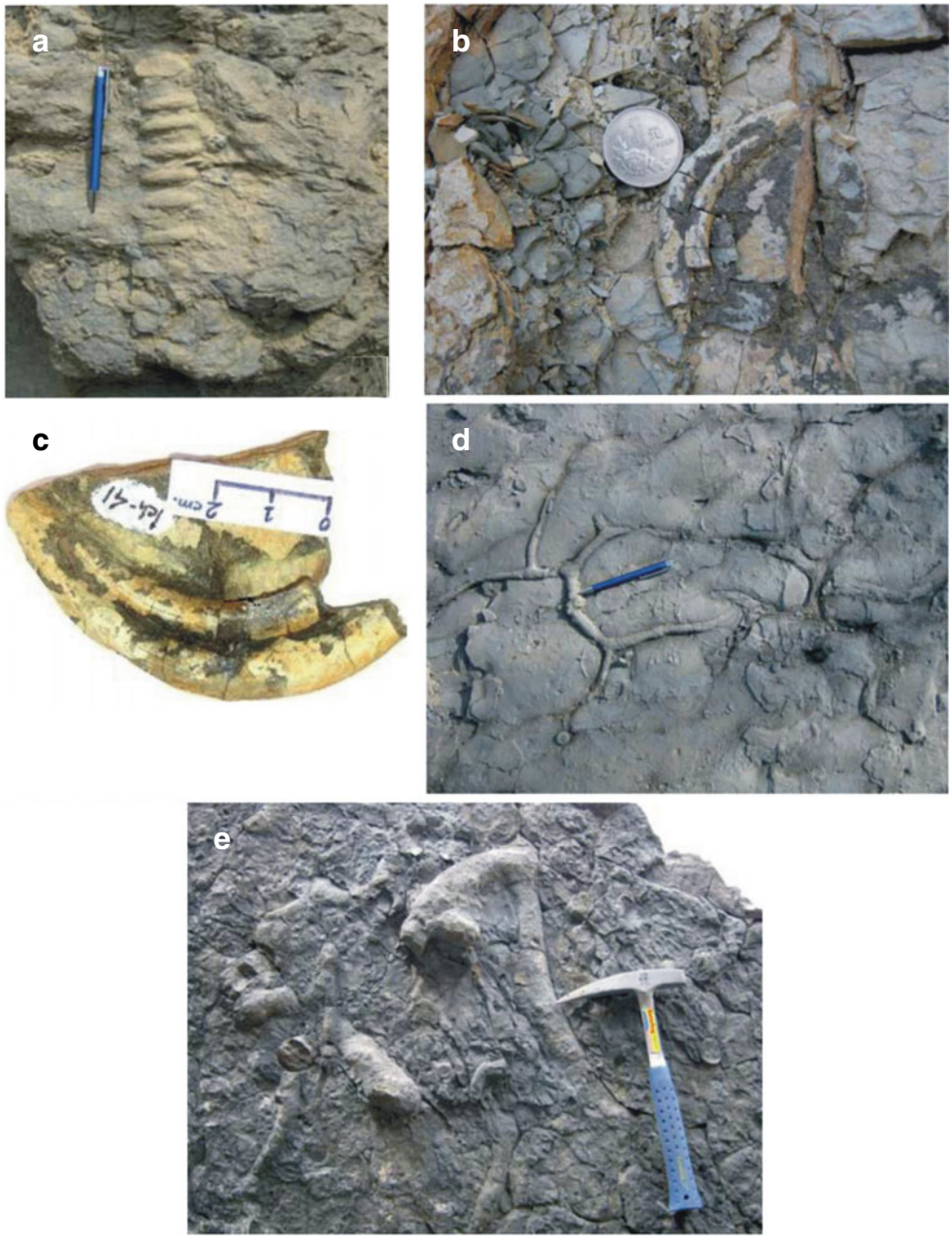

Plate 4. (**a**) *Taenidium satanassi* D'Alessandro and Bromley; field photograph. (**b** and **c**) *Teichichnus rectus* Seilacher; b= field photograph; c= specimen no. Ich/41. (**d**) *Thalassinoides horizontalis* Myrow; field photograph. (**e**) *Thalassinoides paradoxicus* Rieth; field photograph.

spaced and shows prominent relief. The width of the menisci is ∼10 mm and intraspace between the menisci is ∼8–10 mm. The burrow is 150 mm long and 40 mm wide.

Remarks: *Taenidium satanassi* differs from other ichnospecies in its arcuate menisci more or less equally sized packets of alternating sediment types (D'Alessandro and Bromley 1987). Few ichnospecies have also been encountered in marine settings (Keighley and Pickerill 1994). The cylindrical burrow exhibits typical periodic filling of tunnel in backward direction.

Occurrence: Sandstone, Middle Bhuban unit (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnogenus: *Teichichnus* Seilacher (1955)
Ichnospecies: *Teichichnus rectus* Seilacher (1955) (Plate 4b & c)

Description: The Bhuban Formation specimen of *T. rectus* consists of straight to sinuous

unbranched horizontal stacked circular U-shaped burrow. The stacked tubes are bend and shows oblong nature at its initial part and after that displays the uniform dimensions. The maximum observed length of the burrow is about 70 mm and width is 10 mm. Burrow filled is identical to host sediments.

Remark: Seilacher (1955) interpreted *Teichichnus* as the result of the vertical shift of horizontal burrow which might be U-shaped with pipe at the top. *T. rectus* has straight walled and generally having a higher width-depth ratio (approximately 1:1). Seilacher (1955) compared these forms to the modern structures made by the recent polycheate *Nereis diversicolor*.

Occurrence: Sandstone–shale intercalation, Upper Bhuban unit (Miocene) of Ropaiabawk area, Aizawl, Mizoram.

Ichnogenus: *Thalassinoides* Ehrenberg (1944) Ichnospecies: *Thalassinoides horizontalis* Myrow (1995) (Plate 4d)

Description: Smooth, unlined, three dimensional, horizontal burrow system showing Y/T shaped branching. The diagnostic features of this ichnospecies include bedding parallel oriented network, absence of vertical oriented offshoots from polygon framework and constant diameter of the individual tunnels. Tunnels are straight to curved; length varies from 100 to 250 mm and diameter varies from 42 to 60 mm. Burrows chiefly consist of horizontal tunnels that bifurcate at an angle of 80°–170°. Some of the burrow walls show scratch marks.

Remarks: The specimens differ from the type material of Myrow (1995) only in diameter. *T. horizontalis* resembles *T. bacae* but differs from it in lacking entirely of vertical shafts. *T. horizontalis* is robust and often occurs on the ripple marked silty-sandstone. Although the diameter of the burrow as suggested by Myrow (1995) is one of the prime factors in distinguishing the ichnospecies but in the present case overall morphological features are identical to ichnospecies *T. horizontalis*.

Occurrence: Silty-shale, Middle Bhuban unit, Surma Group (Miocene) of Bawngkawn area, Aizawl, Mizoram.

Ichnospecies: *Thalassinoides paradoxicus* Rieth (1932) (Plate 4e)

Description: Endichnial, full relief, horizontal to slightly oblique, three-dimensional irregular burrow system spread on the bedding plane. The burrow system comprises of vertical to inclined shaft connected to surface; bifurcations are commonly T-shaped and also show swelling at junction. Length of branch varies from 300 to 500 cm and diameter from 15 to 30 mm. The burrows fill is different from the surrounding.

Remarks: *T. paradoxicus* is different from the *T. horizontalis* consisting of vertical shaft and branch dichotomous (Howard and Frey 1984). *Thalassinoides* is a facies-crossing form most typical of shallow-marine environment and is produced mainly by crustaceans (Frey *et al* 1984).

Occurrence: Sandstone, Middle Bhuban unit, Surma Group (Miocene) of Bawngkawn area, Aizawl, Mizoram.

6. Environmental significance

Rocks of the Bhuban Formation of the Surma Group are studied at two different localities, Bawngkawn and Ropaiabawk, Aizawl (figure 1) for their trace fossils content. The section at the Bawngkawn locality shows intercalated sequence of shale and sandstone, the proportion of the arenaceous sediments increases in the upward direction while the section at the Ropaiabawk locality comprises of mainly arenaceous sediments, is highly bioturbated and consists of ethologically diverse group of trace fossils. These largely constitute domichnia and fodinichnia associations and show existence of close affinity. Domichnia are the cylindrical dwelling burrows having strong wall lining of suspension feeders (Simpson 1975). The domichnia signatures are tangibly manifested from the recorded forms like *Arenicolites* isp., *Ophiomorpha borneensis*, *Laevicyclus mongraensis*, *Palaeophycus heberti*, *P. tubularis*, *P. sulcatus* and *Skolithos linearis* in sandstone of the Bawngkawn locality. Fodinichnia features are clearly evident in *Pholeus abomasoformis*, *P. bifurcatus*, *Taenidium satanassi*, *Teichichnus rectus*, *Thalassinoides horizontalis* and *T. Paradoxicus.* These trace fossils are found in silty-sandstone and silty-shale exposed at Bawngkawn locality.

The clastic sediments are characterized by the vertical 'U' 'I' and 'Y' shaped lined burrows like *Arenicolites, Laevicyclus*, *Ophiomorpha*, *Polykladichnus* and *Skolithos. Arenicolites* has been usually considered as a dwelling and feeding burrow believed to be emplaced by suspension feeding annelids or crustacean-like organisms (Goldring 1962; Hakes 1976; Fillion and Pickerill 1990); Y-shaped *Polykladichnus,* and *Skolithos* are also dwelling burrows of suspension feeding organisms

(Patel and Desai 2009). These three suspension-feeder structures comprise a pioneer community of opportunists commonly displaying low diversity and high density of trace fossils. These burrows were produced over a short period of time and the depositional environment was inhospitable to most life forms. This may be attributed to oxygen depletion, variable salinity, uneven rates of sediment accumulation or merely a newly-deposited biologically-unconditioned substrate. *Laevicyclus mongraensis* is a cylindrical dwelling burrow having strong wall of suspension feeder (Uchman 1998) having domichnion affinity and is known to occur in shallow marine set-up. *Ophiomorpha* is a deposit and/or suspension feeder (Ekdale 1992; Uchman and Gaździcki 2006) and its traces are found in the shallow water environment in siliceous and calcareous sedimentary facies of post-Paleozoic ages (Pemberton and Jones 1988; Uchman and Gaździcki 2006). In modern environment it is con sidered to be produced by crustaceans callianassid *Callianassa major* (Weimer and Hoyt 1964; Uchman and Gaździcki 2006) and Stomatopodean shrimp *Oratosquilla striata* (Patel and Desai 2009). *Pholeus abomasoformis* is a trace produced by crustaceans (Knaust 2002) whereas *Pholeus bifurcatus* most probably is produced by decapodean crustaceans. Both *Ophiomorpha* and *Skolithos* are associated with environments characterized by frequent high-energy events, drastic changes in the sedimentation rate and erosion of surface sediments (Walker and James 1992; Singh *et al* 2008).

Rocks of the Bhuban Formation also consists of horizontal, lined and unlined, branched and unbranched, dwelling and feeding burrows. *Palaeophycus* is a eurybenthic facies-crossing form produced probably by polychaetes or annelids (Pemberton and Frey 1982). It is a suspension/detritus feeder of domichnion affinity and points to well oxygenated environment with abundant subsurface food stuff. *Planolites* is interpreted as a feeding structure of deposit feeding worms (Pemberton and Frey 1982); *Rhizocorallium* is a feeding and dwelling burrow of active strip-mining by a deposit feeder and *Thalassinoides* burrows are mostly simple types of feeding and dwelling structures. These are normally considered typical of littoral environment with maximum water depth of ∼20 m.

Helminthopsis is considered as a 'facies-crossing' occurring in a variety of ichnofacies (Kim *et al* 2002), produced by deposit feeders and is interpreted as grazing trails (Buatois *et al* 1998) and probably made by polychaetes/annelids in brackish to fully marine environments. It is a common trace fossil in deep-marine deposits but is also known from the shallow-marine and non-marine environments (Buatois *et al* 1998). *Cochlichnus* is crawling traces and probably the feeding structures of small worms or worm-like animals (Eager *et al* 1985) and reported in sediments of low salinity paleoenvironment (Hakes 1976).

Trace fossils of the Bhuban Formation characteristically display the development of *Skolithos* and *Cruziana* ichnofacies typical of shallow marine settings (MacEachern *et al* 2007). *Arenicolites*, *Laevicyclus*, *Ophiomorpha*, *Polykladichnus* and *Skolithos* are typically the member of the *Skolithos* ichnofacies and are characterized by trace fossils produced by suspension feeders. The characteristic suits of biogenic structures and sediment types indicate relatively moderate to high energy conditions and shifting substrate have been exploited by the opportunistic animals in the shoreface/offshore environments. The *Skolithos* ichnofacies is associated with relatively high levels of wave or current energy and it is typically developed in clean well-sorted loose or shifting substrates. These 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; Singh *et al* 2008).

The fine-grained sediments of the Bhuban Formation consist of *Palaeophycus*, *Planolites*, *Rhizocorallium* and *Thalassinoides* which are the member of the *Cruziana* ichnofacies. This sedimentary sequence also comprises of some facies crossing trace fossils like *Cochlichnus* and *Helminthopsis*. The *Cruziana* ichnofacies mostly represents subtidal poorly sorted and unconsolidated muddy substrates in shallow marine settings with uniform salinity (Pemberton *et al* 1992). These 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 (Pemberton *et al* 1992; MacEachern *et al* 2007; Singh *et al* 2008). Therefore, it indicates prevalence of shoreface to offshore conditions where energy level is dropped and allows settling of fine-grained sediments. *Planolites* and *Palaeophycus* are essentially horizontal structures and occur few centimeters below the sediment–water interface suggesting unconsolidated substrate experiencing relatively moderate to low energy shoreface/offshore conditions. *Cochlichnus* and *Helminthopsis* are the essentially horizontal forms developed at the sediment–water interface and suggest very fine-grained unconsolidated substrate experiencing the low energy offshore condition.

7. Conclusions

A rich association of trace fossils in the Bhuban Formation of Mizoram are mainly found in

sandstone, silty-sandstone, silty-shale and shale lithologies. A total 20 ichnospecies of 14 ichogenera were identified which are dominated by feeding burrows and trails. Ethologically the association represents domichnia and fodinichnia groups. The development of *Skolithos* and *Cruziana* ichnofacies in Bhuban Formation rocks exposed at Bawngkawn and Ropaiabawk, Aizawl, indicate sandy shifting substrate and high energy conditions in foreshore zone and unconsolidated, poorly sorted soft substrate and low energy condition in the shoreface-offshore zone, respectively.

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