Attribute of trace fossils of Laisong flysch sediments, Manipur, India

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The depositional basin in which the Late Eocene–Early Oligocene Laisong flysch sediments Barail Group, Manipur region (Indo-Myanmar ranges) have been deposited is generally considered to be of deep marine environment. However, field observation indicates the presence of many shallow environment signature characteristics of marginal to sublittoral marine settings, in addition to the general occurrence of deep marine turbidites. To address this aspect, ichnological analyses of the Laisong Formation has been attempted for elucidating palaeoenvironmental setting prevalent during the deposition of these sediments. Presence of 36 ichnospecies belonging to 33 ichnogenera has so far been identified. The ichnospecies may be grouped into different ichnofacies such as *Skolithos*–*Cruziana* mixed ichnofacies, *Cruziana* ichnofacies, *Skolithos* ichnofacies, *Zoophycos* ichnofacies, *Nereites* ichnofacies and *Teredolites* ichnofacies which decrease in abundance in this order of sequence with *Skolithos*–*Cruziana* mixed ichnofacies being the most dominant. The above-mentioned ichnofacies are found associated with sedimentary structures such as large sole marks, parallel laminations, massive and structureless beds, rip-up clasts, etc., which are characteristics of submarine fan deposits below the storm wave base and current ripples, herringbone structures, hummocky cross stratifications, pot casts, rain prints, etc., that marked shallow marginal marine setting such as tidal flats, deltas and shoreface. With such observations it is very likely that the Laisong sediments were formed in a tectonically active basin with varied bathymetric ranges indicating alternate transgressive and regressive nature.

1. Introduction

The Palaeogene rocks of Manipur in the Indo-Myanmar Ranges comprise of the flysch and molasse sediments. The flysch sediments are represented by the Disang Group (Upper Cretaceous–Late Eocene) and the Barail Group (Late Eocene–Late Oligocene) whereas the molasse sediments are represented by the Surma Group (Late Oligocene–Miocene). Both the flysch and molasse sediments are characterized by moderately rich occurrence of trace fossils. It is a well established fact that trace fossils can be used in the interpretation of

paleoenvironment of depositional basin (McIlroy 2004; Miller 2007; Rodriguez-Tovar 2010). In the Indian context, a number of ichnological studies have been carried out recently on various stratigraphic horizons ranging in age from Cambrian to Miocene primarily from peninsular India, to understand their depositional environments (Patel *et al.* 2008, 2009, 2014; Malarkodi *et al.* 2009; Nagendra *et al.* 2010; Saha *et al.* 2010; Joseph *et al.* 2012; Srivastava and Mankar 2012; Chakraborty *et al.* 2013; Desai and Saklani 2014; Kulkarni and Borkar 2014; Pandey *et al.* 2014; Patel 2014). But ichnological research of the Palaeogene succession of

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Indo-Myanmar ranges is very scanty. Tripathi and Satsangi (1982) for the first time reported trace fossil *Ophiomorpha* isp. from the Palaeogene sediments of northeast India (Manipur). Rajkumar (2005) studied three ichnospecies, namely *Chondrites* isp., *Ophiomorpha* isp. and *Thalassinoides* isp. from the Disang–Barail transition, Manipur and indicated a neritic depositional zone. Later ichnological analysis of the above transitional sediments has been carried out on the basis of eight ichnospecies and designated a shallow marine environment with occasional high energy conditions (Rajkumar *et al.* 2008). Rajkumar and Klein (2014) suggested a marginal marine setting for certain horizons in the basal part of Laisong (Disang–Barail transition) based on the preservation of perissodactyl tracks and associated invertebrate trace fossils. The above-cited ichnological research of the Disang–Barail transition differs from the present research paper described herein, in that, the present paper deals with trace fossils from the Laisong Formation which is practically just above the Disang–Barail transition. Mairambam and Kushwaha (2008) have also reported trace fossils from the Eocene–Oligocene deposits between Bijang and Tupul, Manipur. Mairambam *et al.* (2010) presented the palaeoenvironmental importance of Bhuban and Boka Bil formations, Surma Group of Manipur and proposed a frequent fluctuating sea level, moderate to strong energy condition, subtidal to lower intertidal environment, rich in organic nutrients. In comparison to Manipur, ichnological studies of Neogene rocks have been more frequently undertaken in the adjoining state of Mizoram due to the availability of better exposures and relatively greater abundance of trace fossils. Tiwari *et al.* (2011) studied the palaeoenvironmental significance of Bhuban sediments of Mizoram and indicated a 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. Rajkumar *et al.* (2012) suggested a shallow marine depositional basin characterised by moderately high energy and well oxygenated conditions with a corresponding bathymetric position in the intertidal to subtidal zone for the middle Bhuban, Surma Group of Mizoram. Tiwari *et al.* (2013) reported *Funalicchnus bhubani* isp. nov. from Bhuban Formation, Surma Group (Lower–Middle Miocene) of Aizawl, Mizoram and inferred a shoreface and sheltered foreshore environment. Rajkonwar *et al.* (2013, 2014a, b) also worked on the relationship between ichnofauna and palaeodepositional environments of Bhuban Formation, Mizoram.

Besides, palaeoenvironmental aspects of the Palaeogene sediments of Manipur and adjoining states have also been studied by various researchers

through a non-ichnological approach. Guleria *et al.* (2005) studied the Palaeogene plant materials of Upper Disang and Lower Barail sediments of Manipur and indicated the existence of a moist tropical environment at the time of deposition; Dasgupta and Biswas (2000) indicated a shallow water inner neritic zone for the Disang sediments during Late Eocene and shallow brackish water condition for the Barail sediments during Oligocene on the basis of microfaunal assemblages; Biswas and Mukhopadhyay (2011) described the Palaeogene submarine fan from the Jenam Formation, Barail Group of Jenamghat, Assam as to have been formed in deep-water proximal- to mid-fan depositional setting based on lithofacies analysis. Yengkhom *et al.* (2013) studied pollen and spores and suggested a warm, shallow marine environment similar to modern tidal flats for the Uppermost Disang sediments transitional to basal part of Laisong Formation.

The present paper attempts to analyse the palaeoenvironmental aspects of the basin in which the Laisong sediments were deposited using the moderately diverse trace fossils and the associated sedimentary features. This will certainly help us to fill up the gap in our knowledge with respect to the trace fossil assemblages of Laisong succession and their palaeoenvironmental significance. The 33 ichnogenera and 36 ichnospecies, so far studied and identified in the present work are named according to the rules of International Code of Zoological Nomenclature and described alphabetically. The ichnospecies are archived in the Mantrimayum Ichnological Museum (MIM) of United College Lambung Chandel, Manipur. Figure 1 represents the geological map of Manipur showing the different study sites.

2. Geological setting and location

The Barail Group of sediments belong to the Central Naga Hill Palaeogene flysch sediments (Acharyya *et al.* 1986). The principal Palaeogene and Neogene lithounits of Manipur comprise of flysch sediments of the Disang and Barail Groups and molasse sediments of the Surma and Tipam Groups, respectively (table 1). The Disang Group consists of a monotonous sequence of dark grey to black splintery shales, and occasional rhythmites of shales and siltstones/fine-grained sandstones, especially in the upper horizon, forming the principal lithounits of the eastern half of the state of Manipur. The Barail Group, mainly of Oligocene age with some possible extension towards the Upper Eocene, consists of ~3000-m thick arenaceous beds intercalated with shales, carbonaceous shale, silty shales and siltstones which rest over the

Figure 1. Geological map of Manipur indicating studied locations.

Disang Group. The basal part of the Barail Group has a gradational (as well as tectonic) contact with the Disang Group (Soibam 1998), which is related with a gradual change from a dominantly argillaceous deep marine (cf. Mathur and Evans 1964) to a mainly arenaceous shallow marine depositional environment (Rao 1983; Rajkumar *et al.* 2008; Yengkhom *et al.* 2010). The Barail Group has been divided into three formations namely the Laisong, Jenam and Renji (Evans 1932). The Laisong Formation, approximately 1200-m thick, is characterized by intercalations of shales, silty

shales, siltstones and fine-to-medium grained sandstones. These sediments are characterized by two groups of sedimentary structures. One kind represents shallow marine environment such as straight crested ripples, linguinal ripple, cross beddings, cross laminations, gutter casts, pot casts, herringbone structures, hummocky cross stratifications, imbricate structures, rain prints, etc., indicating wave and current influence and deposition above the storm wave base. The second group of sedimentary structures are characteristics of turbidites. Examples are massive and structureless beds, parallel

Table 1. Generalized stratigraphic succession of Manipur (modified from Soibam 1998; Rajkumar and Klein 2014).

Group	Formation	Age	Lithological and palaeontological features
Alluviums	Younger	Recent	Dark grey to black clay, silt and sandy deposits of fluvio-lacustrine origin of the Imphal Valley. Fluvial alluviums in the Barak Valley area of western plains.
	Older	Pleistocene	Clay, sand, gravel, pebbles, boulder deposits of the foothills and old river terraces. Skeleton remains of horse about 40 Ka old reported from Kangla.
----- Unconformity -----			
Surma	Girujan Clays	Late Miocene	(Likely exposure in the foothills of Jiribam)
	Tipam sandstone		Greenish to blue, moderate to coarse ferruginous sandstone with sandy shale, clay. Often brown to orange due to weathering. Molasse type of deposits (total lack of palaeontological report).
	Boka Bil (~1400 m)	Late Miocene	Shale, sandy shale, siltstone, ferruginous sandstone, massive to false-bedded ferruginous sandstone. Mainly <i>Cruziana</i> ichnofacies.
	Bhuban (~1400 m)	Late Oligocene ↕ Early Miocene	Alternations of sandstone and shale with more argillaceous horizons in the middle and minor conglomerates. Mainly <i>Cruziana</i> ichnofacies. Transitional characters from flysch to molasse sediments.
----- Unconformity -----			
Barail	Renji (~800 m)	Late Oligocene	Massive to thickly bedded sandstones. Ichnotaxa are similar with those of Jenam. Mainly <i>Cruziana</i> ichnofacies. Flysch sediments.
	Jenam (~1200 m)	↕	Massive to thickly bedded sandstones with carbonaceous shale horizons. Ichnotaxa are similar with those of Laisong Formation but size of <i>Thalassinoides</i> is found to increase comparatively. Mainly <i>Cruziana</i> ichnofacies. Flysch sediments.
	Laisong (~1200 m)	Late Eocene/Early Oligocene	Intercalation of bedded sandstones with relatively thin siltstones and shales. Conglomerate horizon in upper part. Characterized by abundant trace fossils with relatively less invertebrate fossils, plant/leaf fossils and very little vertebrate and invertebrate body fossils. <i>Thalassinoides</i> , <i>Ophiomorpha</i> and <i>Skolithos</i> are dominant ichnotaxa. Mainly <i>Skolithos-Cruziana</i> mixed ichnofacies. Flysch sediments.
Disang	Upper Disang (~2000 m)	Late Eocene	Intercalations of shales with relatively thin siltstones and sandstones showing rhythmites. Characterized by presence of certain pelecypods, gastropods, microfossils, and few trace fossils like <i>Thalassinoides</i> and some other trails. Flysch sediments.
	Lower Disang (~2000 m)	Late Cretaceous	Dark grey to black, splintery shales with virtually no vertebrate and trace fossil evidence. Flysch sediments.
----- Unconformity -----			
Ophiolite Mélange Zone	Ukhrul limestone	Late Cretaceous	Limestones, cherts, conglomerates characterized by abundant microfossils – foraminifers and radiolarians.
			Unconformity
		Late Cretaceous/ (?) Older	Mafic and ultramafic rocks: Ultramafic Harzburgite, Lherzolite; diabasic dykes and silts; volcanic pillows, etc.
----- Unconformity -----			
Metamorphic Complex		Pre-Mesozoic	
----- Unconformity -----			
Basement Complex		Pre-Mesozoic/Older	

laminations, convolute laminations, load casts with characteristic squeezed and lineated downward protrusions, etc. The various important localities where detailed trace fossil analyses have been carried out are: (i) Tentha ($24^{\circ}34'12.34''\text{N}$ and 93°

$58^{\circ}56.43''\text{E}$; 788 m), (ii) Thongjaorok ($24^{\circ}37'36.88''$ – $24^{\circ}38'08.99''\text{N}$ and $93^{\circ}44'40.42''$ – $93^{\circ}44'28.71''\text{E}$; 860–920 m), (iii) Gelmon ($24^{\circ}20'36.28''\text{N}$ and $93^{\circ}39'43.89''\text{E}$; 986 m), (iv) Keithelmanbi ($24^{\circ}46'37.91''\text{N}$ and $93^{\circ}46'46.03''\text{E}$; 958 m), (v) Leimatak

Figure 2. Generalized Laisong lithocolumn showing the vertical distribution of the various trace fossils.

Figure 3. Lithocolumns at (a) Thongjaorok section, (b) Gelmon section, and (c) Leimatak section.

Table 2. Sedimentology and ichnological details of the studied locations.

Locality	Sedimentological characters	Ichnological details
Tentha	The rock exposure comprises of thin- to thick-bedded sandstone intercalated with thin-bedded siltstone beds, light grey weathered shales. Due to the exposure nature, preparation of litholog is not convenient.	<i>Teredolites longissimus</i> and <i>Ophiomorpha nodosa</i> .
Thongjaorok	The lithocolumn (figure 2a) at the locality represents a coarsening upward sequence. Grey shale, silty shales with inclusion of fine sandstone pebbles, siltstone, fine sandstone, medium sandstone, greenish colour (?glauconitic sandstone), coal streaks, etc., are the main lithologies.	<i>Acanthorhapha</i> isp., <i>Ancorichnus ancorichnus</i> , <i>Archaeonassa</i> isp., <i>Aulichnites parkerensis</i> , <i>Chondrites targionii</i> , <i>Furculosus</i> isp., <i>Gordia marina</i> , <i>Gyrochorte comosa</i> , <i>Halopoa imbricata</i> , <i>Megagraption</i> isp., <i>Ophiomorpha nodosa</i> , <i>Parahaentzschelinia surlyki</i> , <i>Skolithos linearis</i> , <i>Thalassinoides paradoxicus</i> and <i>Zoophycos</i> isp.
Gelmon	Geologically the sediments at the section belong to the basal part of Laisong Formation which is at a gradational transition with the Upper Disang Formation. The exposed rocks consist of turbidites and tempestites comprising of shales, silty shales, siltstones and thinly bedded to massive fine sandstones. The (figure 2b) section more likely represents deep marine setting in general as indicated by structures such as parallel laminations, huge load casts, massive and structureless sandstone bodies, etc., in addition to the deep water related ichnoassemblages. However, sedimentary features such as current ripples and rain prints are also present in some horizons indicating shallow sub-aerial depositional environment as well.	<i>Aulichnites parkerensis</i> , <i>Chondrites targionii</i> , <i>Circulichnus</i> isp., <i>Desmograption alternatum</i> , <i>Gordia marina</i> , <i>Gyrochorte comosa</i> , <i>Gyrophyllites kwassizensis</i> , <i>Helminthorhapha flexuosa</i> , <i>Helminthopsis tenuis</i> , <i>Helminthoidichnites</i> isp., <i>Ophiomorpha nodosa</i> , <i>Palaeodictyon maximum</i> , <i>Palaeodictyon strozzi</i> , <i>Paleophycus striatus</i> , <i>Phycodes palmatus</i> , <i>Scolicia</i> isp., <i>Skolithos linearis</i> , <i>Taphrhelminthopsis auricularis</i> , <i>Teichichnus</i> isp., <i>Thalassinoides horizontalis</i> , <i>Thalassinoides paradoxicus</i> and <i>Zoophycos</i> isp.
Keithelmanbi	The sediments belong to the Lower Laisong Formation and consist of rhythmic successions of light grey laminated shales, silty shales, siltstones and thinly bedded to massive fine grained sandstones; however, the component of laminated shale is more as the location is closer to Upper Disang.	<i>Palaeophycus tubularis</i> , <i>Skolithos linearis</i> , <i>Thalassinoides paradoxicus</i> and <i>Spongiomorpha</i> isp.
Leimatak	The section represents the middle part of Laisong Formation (figure 2c). The exposed rocks consist of rhythmites of shales, silty shales and thickly bedded to massive fine sandstones.	<i>Ophiomorpha nodosa</i> , <i>Skolithos linearis</i> , <i>Protovirgularia</i> isp., <i>Thalassinoides paradoxicus</i> , <i>Phycodes palmatus</i> , <i>Paleophycus tubularis</i> , <i>Scolicia</i> isp. and <i>Taphrhelminthopsis auricularis</i> .
Gopibung	The sediments belong to the middle upper part of Laisong Formation. The exposed rocks consist of rhythmites of laminated carbonaceous shales, silty shales, siltstones and thinly bedded to massive fine sandstones.	<i>Ophiomorpha nodosa</i> , <i>Paleophycus striatus</i> , <i>Paleophycus tubularis</i> , <i>Rhizocorallium jenense</i> , <i>Skolithos linearis</i> and <i>Thalassinoides paradoxicus</i> .
Atuyang	The section represents the upper part of Laisong Formation. The exposed rocks consist mainly of thinly laminated carbonaceous shales which are intercalated with thin bed of siltstones.	<i>Bergaueria hemispherica</i> , <i>Thalassinoides paradoxicus</i> , <i>Nereites missouriensis</i> and some trails.

Section (24°36.106'–24°35.544'N and 093°41.870'–093°40.017'E; 1151–454 m), (vi) Gopibung (25°07'36.03"N and 093°53'50.01"E; 1845 m), and (vii) Atuyang (24°48'06.17"N and 93°42'09.74"E; 851 m) (figure 1).

3. Rock types and occurrence of trace fossils

The Laisong Formation is represented by a transgressive–regressive succession. The succession is more or less exclusively siliciclastic and contains a

rich and diverse marine ichnofauna. The vertical distribution of the trace fossils are represented alongside the Laisong lithocolumn (figure 2). All the trace fossils discussed herein were collected recently and do not comprise of any specimen of earlier works; the present group of authors only worked on the presently described localities so far. As observed from the vertical distribution (figure 2), trace fossils are more concentrated near the basal part of the Laisong Formation. This is possibly due the lack of exposures in other parts of the succession. The Thongjaorok, Gelmon and Leimatak are the three best exposed sections and figure 3 (a, b and c) respectively represents the lithologs detailing trace fossils and sedimentological features at these three sections. The sedimentological and ichnological details of the different studied sections are also represented by table 2.

4. Systematic ichnology

Identification procedure of the herein described ichnofossils is followed after the Treatise on Invertebrate Paleontology (Häntzschel 1962, 1975) and for classification of the traces into two broad categories as pre- and post-depositional, the classification schemes of Seilacher (1962, 1977b) and Uchman and Wetzel (2011) are followed. Altogether 36 ichnospecies belonging to 33 ichnogenera have so far been identified (table 3).

4.1 Pre-depositional traces

The pre-depositional trace fossils are the result of successional colonization (Leszczyński 1993); this assemblage is rich in graphoglyptids and grazing trails, and feeding structures. The ichnodiversity,

ethology, and morphologic complexity of the pre-depositional association are indicative of the *Nereites* ichnofacies (Seilacher 1964). The trace fossils of pre-depositional origin were produced in the hemipelagic facies underlying the turbidite bed (Seilacher 1977b). Quiet, stable conditions prevailed during this period without the influence of turbidites and with only small changes in the environmental factors (Frey and Pemberton 1984). The organisms that lived in such an environment had enough time to rework the sediment (Wetzel 1991). They are common on the soles of turbiditic sandstones, but never abundant. They are preserved mostly as semi-reliefs resulting from scouring and casting of shallow burrow systems. Their tubes are mostly less than 2 mm wide (Uchman and Wetzel 2011).

Ichnogenus: *Bergaueria* Crimes, Legg, Marcos and Arboleya 1977

Ichnospecies: *Bergaueria hemispherica* Crimes, Legg, Marcos and Arboleya 1977 (figure 4a)

Materials: Three specimens preserved in fine sandstone were collected (MIMB – 1 to 3) and more field observations at 24°48'02"N and 93°42'18"E (an unnamed locality).

Description: Typically knob-shaped, hypichnial mound on lower surface of sandstone beds, with hemispherical terminations, vertically arranged, oval to circular in outline with 14–20 mm diameter and 4–7 mm height; the sandy fill is essentially structureless.

Remarks: *Bergaueria hemispherica* is pre-depositional. It is either domichnia or cubichnia of shallow burrows or casts of upper part of deeper vertical burrows (Leszczyński 2004). Probably produced by suspension-feeders such as sea-anemones; also indicative of normal marine conditions on a wave- or tide-dominated shoreface and in flysch

Table 3. *Toponomic classification of Laisong traces.*

Forms	Ichnospecies
Endichnia	<i>Ancorichnus ancorichnus</i> , <i>Chondrites targionii</i> , <i>Ophiomorpha nodosa</i> , <i>Palaeophycus tubularis</i> , <i>P. striatus</i> , <i>Parahaentzschelinia surlyki</i> , <i>Phycodes palmatus</i> , <i>Rhizocorallium jenense</i> , <i>Skolithos linearis</i> , <i>Spongiomorpha</i> isp., <i>Teichichnus</i> isp., <i>Thalassinoides paradoxicus</i> , <i>T. Horizontalis</i> and <i>Zoophycos</i> isp.
Epichnia	<i>Archaeonassa</i> isp., <i>Aulichnites</i> isp., <i>Circulichnus</i> isp., <i>Gyrochorte comosa</i> , <i>Gyrophyllites kwassizensis</i> , <i>Helminthopsis tenuis</i> , <i>Proto-virgularia rugosa</i> and <i>Nereites missourensis</i> .
Hypichnia	<i>Acanthorhapha</i> isp., <i>Bergaueria hemispherica</i> , <i>Desmograption alternatum</i> , <i>Furculosus</i> isp., <i>Gordia marina</i> , <i>Halopoa imbricata</i> <i>Helminthoidichnites</i> isp., <i>Helminthorhapha flexuosa</i> , <i>Megagraption</i> isp., <i>Palaeodictyon maximum</i> , <i>P. strozzi</i> , <i>Scolicia strozzi</i> and <i>Taphrohelminthopsis auricularis</i> .

Figure 4. (a) *Bergaueria hemispherica*, in fine sandstone at 24°48'02"N and 93°42'18"E (an unnamed locality). (b) *Desmograption alternatum*, in the sole of thin fine sandstone from Gelmon. (c and d) *Halopoa imbricata*, in thick-bedded fine sandstone, Thongjaorok locality. (e) *Helminthoidichnites* isp. in sole of thin bedded fine sandstone, Gelmon. (f) *Helminthopsis tenuis*, in sole of very fine sandstone, Gelmon. (g) *Helminthorhaphe flexuosa*, in sole of thin-bedded shale, Gelmon.

deposits; common element of the *Skolithos* ichnofacies in brackish water environments, but greatly reduced in size (Uchman 1995).

Ichnogenus: *Desmograption* Fuchs 1895

Ichnospecies: *Desmograption alternatum* Książkiewicz 1977 (figure 4b)

Materials: Three specimens collected from Gelmon (MIMD – 1 to 3), which were found preserved on the sole of thin fine sandstone.

Description: Hypichnial double rows of meandered strings shaped like U or J and of moderate width, elevated in the curved portions. The connecting bars are obliquely oriented to the trace fossil axis and form a zig-zag pattern (cf. Uchman 1995).

Remarks: *Desmograption* isp. is interpreted as three-dimensional graphoglyptid trace fossils (Seilacher 1977a). It occurs in flysch deposits from the Silurian (McCann 1989, 1993) to the Miocene (D'Alessandro 1980; Uchman 1995). *Desmograption alternatum*

indicates the development of the traces immediately before the turbiditic event (Monaco and Cecconi 2010).

Ichnogenus: *Halopoa* Torell 1870

Ichnospecies: *Halopoa imbricata* Torell 1870 (figure 4c and d)

Materials: Three specimens from a thick-bedded, fine sandstone were collected from Thongjaorok locality (MIMHalo – 1 to 3).

Description: Horizontal, straight, pre-depositional, hypichnial burrows that show more or less distinctive longitudinal, irregular, imperfectly overlapping wrinkles and furrows of different sizes. They are 6–8 mm in cross-section. The specimens have short and abrupt branches and the ridges are intercrossing and interpenetrating (Uchman 1998).

Remarks: The burrows are recorded on soles of sandstone turbidite beds that rest on shale/mudstone possibly produced by deposit-feeding organisms (worms). They have a long geological range, Cambrian–Recent.

Ichnogenus: *Helminthoidichnites* Fitch 1850

Ichnospecies: *Helminthoidichnites* isp. Fitch 1850 (figure 4e)

Materials: Two specimens collected from Gelmon (MIMHe – 1 and 2) and more than 40 specimens noted at Gelmon; three specimens observed at 24°48'02"N and 93°42'18"E. They are occurring in the sole of thin-bedded fine sandstone.

Description: Small, simple and unbranched, winding traces preserved as positive hyporeliefs. The traces are about 1–3 mm wide with maximum length (as measured on the bedding plane) of about 15 mm. The structures are mainly horizontal and curvy with a few self-overcrossings.

Remarks: *Helminthoidichnites* differs from *Gordia* by lack of self-overcrossing (Kim et al. 2002). It is interpreted as a pascichnia produced in shallow tiers by vagile tracemakers. The ichnogenus has been reported from deep marine settings (Buatois and Mángano 2003).

Ichnogenus: *Helminthopsis* Książkiewicz 1968

Ichnospecies: *Helminthopsis tenuis* Książkiewicz 1968 (figure 4f)

Materials: Three specimens found in the sole of very fine sandstone were collected from Gelmon (MIMHelm – 1 to 3) and a few more field observations.

Description: Specimens display straight segment separated by irregular loose horizontal, smooth, unbranched, convex, unlined meandering trails or burrows. Diameter varies from 1.0 to 1.5 mm but is constant within each specimen; maximum length is 65 mm and width is about 4 mm; preserved in fine-grained turbidite sandstones.

Remarks: Irregular meander with greater sinuosity differentiates the specimens from *Helminthoidichnites* (Hofmann and Patel 1989) and from *Gordia* by its lack of self-overcrossing and the tendency to meander (Pickerill 1981). *Helminthopsis tenuis* is interpreted to represent a grazing trail produced by a deposit-feeding organism (Buatois et al. 1998); common in deep-marine deposits, but also observed in shallow-marine environments (Kim et al. 2005).

Ichnogenus: *Helminthorhaphe* Uchman 1995

Ichnospecies: *Helminthorhaphe flexuosa* Uchman 1995 (figure 4g)

Materials: Three specimens associated with thin bedded shale were collected from Gelmon (MIMHelm – 1 to 3).

Description: Convex hyporeliefs trails consisting of strings, which form narrow and high amplitude meanders which are numerous, regular to irregular and parallel to unparallel; closely spaced, with trail width of about 3–4 mm and meander length of 150 mm. The distance between the meanders is 2–3 times the diameter of the string. The surface of the string is smooth and no longitudinal striations or transverse riblets are seen. Bulges in the turning portion are very rare and poorly expressed.

Remarks: *Helminthorhaphe flexuosa* is known from the fan fringe deposits of the Eocene turbiditic Cingöz Formation (Uchman and Demircan 1999; Demircan and Toker 2004). The ichnospecies has also been described from the Eocene Kusuri Formation (Uchman et al. 2004).

Ichnogenus: *Megagraption* Książkiewicz 1968

Ichnospecies: *Megagraption irregulare* Książkiewicz 1968 (figure 5a)

Materials: Two specimens observed in thin-bedded very fine sandstone at Thongjaorok.

Description: Branching and winding strings with diameter of 5 mm and width of 0.5–1.4 mm. Angles of branching is commonly acute and to some extent right angles. The main ridges are up to 30 mm long. Burrow lining not detected.

Remarks: *Megagraption irregulare* is a distinctive graphoglyptid trace fossil (Seilacher 1977a), which is almost universally preserved as a positive feature in convex hyporeliefs on bedding plane soles. Irrespective of origin, the trace can be clearly assigned to *Megagraption irregulare*, which is characterized by its irregular shaped polygonal nets of different sizes and common right angle branches at irregular intervals (Książkiewicz 1977). The ichnogenus is typical deep-water form.

Ichnogenus: *Palaeodictyon* Meneghini 1850 in Savi and Meneghini 1850

Ichnospecies: *Paleodictyon* cf. *maximum* Eichwald 1868 (figure 5b)

Figure 5. (a) *Megagraption* isp. in thin-bedded very fine sandstone, Thongjaorok. (b) *Paleodictyon* cf. *maximum*, in sole of thin-bedded very fine sandstone, Gelmon. The traces are seen associated with *Thalassinoides* isp. (c) *Paleodictyon* *strozzi*, in the sole of thin, very fine sandstone, Gelmon. (d) *Acanthorhaphe* isp. in a 30-cm thick fine sandstone bed, Thongjaorok. (e) *Ancorichnus ancorichnus* in massive fine sandstone, Thongjaorok. (f) *Archaeonassa* isp. in thin-bedded fine sandstone, Thongjaorok.

Materials: Two specimens found preserved on sole of thin-bedded, very fine sandstone were collected (MIMPm-1 and 2) and eight more specimens observed at Gelmon.

Description: The maximum mesh size (MMS) ranges from 8–10 mm and the bordering riblets/string diameter (SD) between 1 and 1.7 mm. The nets are of moderate size and more or less of hexagonal shape and are preserved as semi-relief on the sole of fine-to-medium sandstone. Seilacher (1977a) proposed sub-ichnogeneric names for *Palaeodictyon* as: (1) *Glenodictyum* to indicate only horizontal hexagonal meshes, (2) *Ramodictyon* when vertical shafts are preserved, and (3) *Squamodictyon* to indicate scale like meshes. The described specimens are showing only horizontal hexagonal

meshes so they may belong to ichnogenera *Glenodictyon*.

Remarks: According to the classification scheme of Uchman (1995), which uses string diameter and mesh diameter as diagnostic criteria, the trace may belong to *P. maximum*. Solitary burrowers, colonial burrowers, nonburrowing protists or multicellular organisms, organisms feeding in their burrow system on cultivated or trapped micro-organisms have been some of the suggested organisms responsible for the specimens (Uchman 1995; Honeycutt and Plotnick 2005). Książkiewicz (1977) observed that most of the *Palaeodictyon* isp. producers lived and worked below sand layers, but some were able to live in mud, and probably to ingest both mud and fine-grained sand. *Palaeodictyon* isp. is a typical

deep-water graphoglyptid, mostly in flysch sediments, and usually of *Nereites* ichnofacies. However, Uchman (1995) indicated the presence of *Palaeodictyon* isp. in shallow-water deposits, and the problematic occurrence in freshwater sediments.

Ichnogenus: *Palaeodictyon* Meneghini 1850 in Savi and Meneghini 1850

Ichnospecies: *Palaeodictyon strozzi* Meneghini 1850 in Savi and Meneghini 1850 (figure 5c)

Materials: Seven specimens collected (MIMPs – 1 to 7) with more field observations at Gelmon occurring on the sole of thin-bedded, very fine sandstone.

Description: The maximum mesh size (MMS) ranges from 3–5 mm and the bordering riblets/string diameter (SD) between 0.2 and 0.8 mm. The nets are of moderate size and more or less of hexagonal shape and are in semi-relief on the sole of fine-to-medium sandstone. The horizontal nature of the hexagonal meshes indicates that the described specimens belong to ichnogenera *Glenodictyon*.

Remarks: Similar remarks may be assigned for *Palaeodictyon strozzi* as that of *P. maximum*.

4.2 Post-depositional traces

The quiet stable conditions prevailed during the development of pre-depositional traces were interrupted abruptly by turbidity currents and the newly deposited sediments established an environment suitable for more opportunistic, less stable fauna (Seilacher 1977b; Frey and Seilacher 1980). The trails produced by these opportunistic organisms that flourished in a relatively short period after the turbidite depositions are classified as post-depositional trace fossils. The post-depositional association essentially consists of dwelling and feeding traces. They occur as endichnial structures according to the toponomic classification of Martinsson (1970). The post-depositional association mainly includes elements of the *Skolithos* ichnofacies (cf. Uchman and Wetzel 2011).

Ichnogenus: *Acanthorhapse* Książkiewicz 1977

Ichnospecies: *Acanthorhapse* isp. Książkiewicz 1977 (figure 5d)

Materials: Two specimens collected from Thongjaorok.

Description: Small arcuate strings having uniform diameter of about 1.5 mm and a length of 10–20 mm. Numerous thorn-like appendages are present on the convex side of the string. The strings have to some extent a semi-circular curvature with no straight segment; preserved as hypichnial burrow.

Remarks: The appendages of the herein described specimens are nearly uniform in diameter thus differing from *A. deliculuta* and *A. incerta* where the appendages are narrowed at the base and pointed

at the outer end; string diameter is slightly more than 1 mm in the described specimens but less than 1 mm in *A. deliculuta* and *A. incerta*. As only two specimens were observed it is difficult to assign them to a new ichnospecies. The studied ichnospecies, however, is very close to *A. deliculuta* (Książkiewicz 1977). *Acanthorhapse* isp. marked specialised strategies that were developed in response to depleted food conditions and absence of sunlight. That is, the animals which are responsible for such traces have the behaviour for cultivation of microbes or construction of structures that served as traps of microbes. This is a good adaptation of oligotrophic environments, with incidental food supply and high competition for gathering of food. They are typical of base of slope environments such as deep water turbidites (flysch deposits) (Seilacher 2007).

Ichnogenus: *Ancorichnus* Heinberg 1974

Ichnospecies: *Ancorichnus ancorichnus* Heinberg 1974 (figure 5e)

Materials: Three specimens observed in massive fine sandstone at Thongjaorok.

Description: Horizontal, unbranched, winding cylindrical full relief burrows having gentle annulations on the surface. Width of burrow is approximately 17 mm, and thickness of the mantle varies between 3 and 4 mm; spacing between successive menisci is about 2–3 mm. Course of burrow is slightly undulating and subparallel to the bedding plane. The core is slightly darker than the outer layer.

Remarks: Heinberg (1974) and Heinberg and Birkelund (1984) related *Ancorichnus* isp. to locomotion of an infaunal soft-bodied organism such as priapulids, siphunculids, or ethologically equivalent worms. The presence of a mantle distinguishes *Ancorichnus* from morphologically similar ichnogenes such as *Beaconites*. *Ancorichnus* has been documented from lower offshore depositional environment (MacEachern and Pemberton 1992).

Ichnogenus: *Archaeonassa* Fenton and Fenton 1937

Ichnospecies: *Archaeonassa* isp. Fenton and Fenton 1937 (figure 5f)

Materials: Three specimens observed in thin-bedded fine sandstone at Thongjaorok.

Description: Simple, horizontal, unbranched, straight to curved or gently winding trail constituted by two symmetrical lobes separated by a central furrow, preserved as positive epirelief. Width of the structures is 6–16 mm.

Remarks: *Archaeonassa* is a poorly known ichnogenus which is a member of the *Scolicia* group. The ichnotaxonomic status of *Archaeonassa* is still debated (Yochelson and Fedonkin 1997); usually interpreted as a pascichnia produced by arthropods and mollusks (Mángano et al. 2005). *Archaeonassa* has

Figure 6. (a) *Aulichnites parkerensis* in wave rippled fine sandstone surface, Thongjaorok. (b) *Chondrites targionii* in very fine sandstone, Gelmon. (c) *Circulichnus* isp. in the sole of siltstone bed, Gelmon. (d) *Furculosus* isp. in medium grained massive and highly bioturbated sandstone, Thongjaorok. (e) *Gordia marina* in weathered silty shale, Thongjaorok. (f) *Gyrochorte comosa* in fine sandstone at 24°48'02"N and 93°42'18"E (an unnamed locality).

been reported from floodplain deposits (Buatois and Mangano 2002). The ichnogenus is interpreted chiefly as the work of gastropods in proximity of the sediment/water interface; may also have been produced by echinoids, and represent the exogenic expression of either surface or shallow subsurface locomotion.

Ichnogenus: *Aulichnites* Fenton and Fenton 1937
Ichnospecies: *Aulichnites parkerensis* Fenton and Fenton 1937 (figure 6a)

Materials: Twenty specimens found occurring in fine sandstone at Gelmon and 15 specimens observed in wave-rippled fine sandstone surface from Thongjaorok.

Description: The trails are 5–8 mm wide, strongly curved, in general. The two convex ridges are smooth

and separated by rather deep median groove. Surfaces of the ridges are flattened.

Remarks: Sinuosity, shape, size and trails closely approaches *Aulichnites*. It has been interpreted as crawling and/or grazing trails, most probably made by gastropods or arthropods (Kumar and Pandey 2008). Gong (1999) proposed clams as the producers of *Aulichnites parkerensis*. *Aulichnites* has been associated with shallow marine environment (Frey and Howard 1990).

Ichnogenus: *Chondrites* Brongniart 1828

Ichnospecies: *Chondrites targionii* Brongniart 1828 (figure 6b)

Materials: Three specimens collected from Gelmon (MIMCh – 1 to 3), which are associated with very fine sandstone.

Description: The structures consist of a network of filled burrows which are branching regularly and occur as *en masse*. First order branches dominate. The angle of branching is usually sharp. Most of the tunnels are more or less straight, radiating with average width of 3 mm and length ranging between 20 and 60 mm; longest tunnel is about 100 mm.

Remarks: The size and shape of the specimens are in the range of *Chondrites targionii* described by Uchman (1999). Tracemaker is able to live at the oxic/anoxic interface, in dysaerobic conditions, as a chemosymbiont (Fu 1991). In the studied section, *Chondrites* appear sparsely. The high degree of branching suggests construction by endobenthic deposit feeders. Simpson (1957) presumes the unsegmented 'worms' like siphunculids as the producers, but Schäfer (1972) relates *Chondrites* to recent polychaete forms.

Ichnogenus: *Circulichnus* Vyalov 1971

Ichnospecies: *Circulichnus* isp. Vyalov 1971 (figure 6c)

Materials: Five specimens observed in siltstone bed at Gelmon.

Descriptions: Circular, ring-shaped, unlined trace on bedding plane. Outer diameter is 10–15 mm and burrow is about 1–1.5 mm thick.

Remarks: The Laisong specimen is considerably close to the typespecimen described by Vyalov (1971). Closely resembles in shape and size to *C. montanus* described from Carboniferous lacustrine deposits of Argentina by Buatois and Mángano (1993). *C. montanus* is a feeding structure (fodinichnia) probably produced by vermiform animals. Fillion and Pickerill (1984) regarded them as marginal marine, eurybathic ichnotaxon.

Ichnogenus: *Furculosus* Roniewicz and Pienkowski 1977

Ichnospecies: *Furculosus* isp. Roniewicz and Pienkowski 1977 (figure 6d)

Materials: Ten specimens collected (MIMF – 1 to 10) from medium-grained, massive and highly bioturbated sandstone and more field occurrences at Thongjaorok.

Description: Horizontal to sub-horizontal tubes, circular in outline, smooth, unlined and up to 6 mm in diameter. The distance between the two limbs is usually 18–20 mm and the length of the tubes reaches up to 50 mm.

Remarks: Trace fossil *Furculosus* isp. is one of the four genera which are U-shaped. The four ichnogenera are *Diplocraterion*, having a vertical U-structure and spreite; *Rhizocorallium*, composed of a sub-horizontal spreiten U-structure; *Arenicolites*, showing a vertical U-structure without spreite; and *Furculosus*, showing a sub-horizontal or oblique 'U' without spreite; they could have been made

by suspension feeding/dwelling animals (Mikuláš et al. 2004). They are characteristic of settings with strong wave and current energy, but have been registered in different facies from flysch successions to fine-grained rocks and hemipelagic limestones (Mikuláš et al. 2004; Chen et al. 2011).

Ichnogenus: *Gordia* Emmons 1844

Ichnospecies: *Gordia marina* Emmons 1844 (figure 6e)

Materials: Three specimens each collected from silty shale at Thongjaorok (MIMGo – 1 to 3) and Gelmon (MIMGo – 4 to 6) with more field occurrences.

Description: Studied specimens appear as thin (0.6–1.0 mm) and discontinuous hypichnial string. The shape is semi-arcuate, with many thin traces disposed in different directions and commonly overlapping each other.

Remarks: The trace is a thin surface trail or shallow sub-surface burrow characterized by overcrossing and looping which is not as intense as in *Mermia*. The presence of overcrossing distinguishes it from *Helminthoidichnites* and *Helminthopsis* (Buatois et al. 1998). The ichnospecies is assigned to *Gordia marina*, which is one of the four ichnospecies of *Gordia* that are considered valid (Buatois et al. 1998). Several tracemakers have been assigned to *Gordia* according to the environment; see Uchman et al. (2009) for a detailed review.

Ichnogenus: *Gyrochorte* Heer 1865

Ichnospecies: *Gyrochorte comosa* Heer 1865 (figure 6f)

Materials: Three specimens each collected from Thongjaorok (MIMGy – 1 to 3) and Gelmon (MIMGy – 4 to 6) in fine sandstone and more field occurrences at these two sections and 24°48'02"N and 93°42'18"E (an unnamed locality).

Description: Burrows are in the form of bilobate, horizontal traces, 4–6 mm wide and up to 3 mm high above bedding plane. Interpenetration of burrows is common. The three-dimensional patterns of the burrows within the sediments has not been observed. The herein described specimens have indistinct pads and the delicate internal structure corresponding to oblique spreiten has been not recognized. The specimens are similar to those illustrated by Fürsich et al. (2006) and assigned to *Gyrochorte comosa*.

Remarks: *Gyrochorte* has been reported from India by Ghare and Kulkarni (1986) and Patel et al. (2008). They are commonly interpreted as traces of animal-like polychaete worm passing through the sediment in inclined position, selecting sediment for food over the entire length of its body. The sediment was transported backward along the body by the animal as documented by ridges on bedding planes (Heinberg 1973). According to de Gibert and Benner (2002), the tracemaker

Figure 7. *Gyrophyllites kwassizensis* preserved in thin (4 cm) silty shale bed, Gelmon. (b) *Nereites missouriensis* in wave-rippled silty shale bed, Atuyang. (c) *Ophiomorpha nodosa* in medium-grained sandstone, Leimatak. (d) *Palaeophycus striatus*, observed in fine sandstone at Thongjaorok. (e) *Palaeophycus tubularis* observed in shale and silty shale at Keithelmanbi. (f) *Parahaentzschelinia surlyki* in fine sandstone at Thongjaorok.

must have been a detritus-feeding annelid with an opportunistic strategy for colonizing sandy bottoms after high energy event deposition.

Ichnotaxonomy: *Gyrophyllites* Glocker 1841

Ichnospecies: *Gyrophyllites kwassizensis* Glocker 1841 (figure 7a)

Materials: Two specimens collected from Gelmon locality (MIMGyro – 1 and 2) found preserved in thin (40 mm) silty shale bed.

Description: The rosetted structures comprised of 12 closely spaced leaf-like furrows. Diameter of the rosette is about 40 mm and the radiating lobes are up to 5–6 mm wide with the distal margin of the rosette rounded; the central shaft has a diameter of about 2–3 mm. The structures are lined with dark argillaceous substance.

Remarks: The specimens described have close affinity with *G. kwassizensis*. The central shaft of stellate trace fossils is generally regarded as the burrow where the tracemaker lived (Häntzschel 1970), and from which the radial tunnels were constructed and refilled, probably in search for food. The burrow is designated as a fodinichnion of polychaetes. The stem or shaft of the burrow may mark the path of the animal, when it left one rosette-like burrow for another place to dig by means of the proboscis, which dug sideways and descending until it reaches a firmer or coarser sand layer, presumably also poorer in food. They are found on the muddy tops, rather than on the sandy soles, of flysch turbidites (Książkiewicz 1977).

Ichnotaxonomy: *Nereites* Weller 1899

Ichnospecies: *Nereites missouriensis* Weller 1899 (figure 7b)

Materials: Four specimens collected from Atuyang (24°48'06.17"N and 93°42'09.74"E) (MIMNe-1 to 4). The specimens are associated with wave-rippled silty shale bed.

Description: The specimen is irregularly curved with deep smooth-walled dimples, horizontal and unbranched. Chain restricted in length. Some menisci are separated by sandy films. The width of the meniscate filling is between 3 and 4 mm. The exterior of the trails present a well developed chain of closely packed sediment pustules. The total width of the burrow is ~10 mm and the maximum preserved length is ~180 mm. The menisci are poorly distinguishable; distance between which is not constant and relatively small.

Remarks: The ichnogenus *Nereites* include diverse winding and meandering traces of different ichnotaxa (Uchman 1995). The specimens studied are small in size and have been interpreted as the work of a worm-like, deposit feeder (Häntzschel 1975) or other organisms such as mollusks, arthropods, or holothuroids (Rindsberg 1994). If organic matter deposition increased, the oxygen flux into the sediment is lowered and the producers of *Nereites* respond; they are quite sensitive to oxygenation within the sediment while feeding about 10 mm above the redox boundary in non-bloom times (Wetzel 2010). *Nereites missouriensis* is interpreted as a eurybathic form mainly registered in flysch deposits (Uchman et al. 2005). It has also been reported from the distal delta-front environment in relation to opportunistic colonization during intervals of low-energy (Carmona et al. 2009).

Ichnogenus: *Ophiomorpha* Lundgren 1891

Ichnospecies: *Ophiomorpha nodosa* Lundgren 1891 (figure 7c)

Materials: Five specimens each collected from Gelmon (MIMOph - 1 to 5), Gopibung (MIMOph - 6 to 10), Leimatak (MIMOph - 11 to 15) and Thongjaorok (MIMOph - 16 to 20) with many more field occurrences in the above places. The Gelmon and Gopibung specimens are found in silty shale and fine sandstone; Leimatak specimens are observed in fine-to-medium and thin-bedded to massive sandstone; Thongjaorok specimens are associated with silty shale-fine sandstone intercalation as well as in fine-to-medium sandstone which are thinly-bedded to massive.

Description: Horizontal and vertical, mainly straight tubes, occasionally branched burrow systems showing Y-shaped branching (Rajkumar et al. 2008). Individual cylindrical tubes are 10–30 mm in diameter, with oval cross-sections, and around 100 mm long. Burrows have 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.

Remarks: *Ophiomorpha* tracemaker is difficult to access, being a possible combination of deposit and/or suspension feeding; in modern environments, *Ophiomorpha* isp. were produced by callianassid crustaceans (Uchman and Gaździcki 2006). Pellets are usually interpreted as supporting the structure during and after burrow construction (Bromley and Ekdale 1998). The ichnogenus is found to occur in a wide environmental range from shallow-water deposits represented mainly by *O. nodosa* to deep-sea environments represented mainly by *O. rudis* (Tchoumatchenco and Uchman 2001); most typical of the relatively high-energy, proximal, *Skolithos* ichnofacies (Pemberton et al. 2001).

Ichnogenus: *Palaeophycus* Hall 1847

Ichnospecies: *Palaeophycus striatus* Hall 1847 (figure 7d)

Materials: One specimen each collected from Gelmon (MIMPa - 1), Gopibung (MIMP - 2) and Thongjaorok (MIMPa - 3) with more field occurrences. The Gelmon and Gopibung specimens are associated with silty shales, and Thongjaorok specimen with fine sandstone.

Description: The specimens studied have lengths about 150–200 mm with burrow diameters ranging between 20 and 25 mm. Burrow fill is structureless. Striae are 0.5–1 mm and nearly as long as the whole length of the specimens. Burrow collapse is absent.

Remarks: *Palaeophycus* is distinguished from *Planolites* by the presence of wall linings and by burrow-fill identical to the host rock in the former (Pemberton and Frey 1982) and from *Macaronichnus* by the active burrow-fill of the latter (Curran 1985). The ichnospecies is described as a eurybathic facies-crossing dwelling structure (domichnia) of suspension feeders or predators, such as polychaetes (Pemberton and Frey 1982). The predaceous glycerid polychaete, *Glyceria*, has been taken as an excellent modern analog for the *Palaeophycus* organism. *P. striatus* is mainly registered in marine environments (Krapovickas et al. 2008).

Ichnogenus: *Palaeophycus* Hall 1847

Ichnospecies: *Palaeophycus tubularis* Hall 1847 (figure 7e)

Materials: Five, two and six specimens respectively observed at Gopibung, Keithelmanbi and Leimatak sections. They are all associated with shale and silty shale.

Description: Slight to prominently curved or even meandering (two meanders at maximum), thinly-lined horizontal and unbranched burrows. Surface walls

are irregularly smooth and lack striations or annulations. Burrow diameters typically are about 10–15 mm and the length about 350–400 mm. The burrow fill is identical to the host rock. Cross-cutting and interpenetration is seen between specimens.

Remarks: The specimens observed are thinly lined and are very much like *P. tubularis*; probably produced by worm-like creature living in water-saturated sediment produced in marine environments. They represent passive sedimentation within an open dwelling burrow constructed by predaceous or suspension feeding organisms, predominantly annelids (Pemberton and Frey 1982).

Ichnogenus: *Parahaentzschelinia* Chamberlain 1971

Ichnospecies: *Parahaentzschelinia surlyki* Chamberlain 1971 (figure 7f)

Materials: Four specimens observed in fine sandstone at Thongjaorok.

Description: Vertically bundled small tunnels radiating obliquely upward from a central, straight main tunnel and preserved in full relief. Diameter of the small tunnel is ~3 mm. Surface patterns are less than 60 mm across; central main tunnel is about 1.3 mm across.

Remarks: *Parahaentzschelinia surlyki* differs from the type species *P. ardelia* (Chamberlain 1971) in its characteristic irregular well-developed wall structure, its larger size and vertical main tunnel. The main structure seems to have developed as the trace maker repeatedly extended itself up and outward from a fixed point within the sediment in search for food and is classified as domichnion. The thick wall lining of *P. surlyki* may be related to substrate coherence, which was probably incohesive and loose at the time of burrowing.

Ichnogenus: *Phycodes* Hall 1852

Ichnospecies: *Phycodes palmatus* Hall 1852 (figure 8a)

Materials: Two specimens collected from Gelmon (MIMPhy – 1) from shale (MIMPhy – 2) and silty shale, with a few more field occurrences.

Description: The specimen from Gelmon locality consists of three unequal branches that were given off from a single point. The traces are oval in cross sections, which could be due to compaction. Length varies from 100–122 mm, with diameter of the branching tube about 15 mm at the apex and near the joints. Burrows filled by very fine-grained sand in a silty mudstone host.

Remarks: *Phycodes* is commonly present at the base of thin siltstone or silty sandstone beds within shales (Mángano *et al.* 2005). The tracemaker is mainly assigned to a sediment-feeding vermiform annelid, a pennatulacean, or an anthoptiloid sea pen. *Phycodes palmatus* is mainly related with shallow water environments, being characteristic

trace fossil of the *Cruziana* ichnofacies, and less frequently found in deep-marine and non-marine conditions (Han and Pickerill 1994).

Ichnogenus: *Protovirgularia* Miller and Dyer 1878

Ichnospecies: *Protovirgularia rugosa* Miller and Dyer 1878 (figure 8b)

Materials: Two specimens collected (MIMPro – 1 and 2) from fine sandstone and many more field occurrences at Leimatak section.

Description: The winding burrow is tubular in nature with burrow diameter varying from 5 to 10 mm, aligned parallel to bedding plane. Generally the burrows are fairly sinuous. Successive pads of silty and fine sandy sediments 1–2 mm thick show characteristic imbricate structure. The specimens are comparable to the type species of *Imbrichnus* (Hallam 1970) in their sinuous course with imbricate structure. At sharp bends, the imbrications tend to splay out.

Remarks: The originally proposed ichnogenus *Imbrichnus* (Hallam 1970), together with other ichnotaxa, were later synonymized within *Protovirgularia* by Seilacher and Seilacher (1994), on the basis of a similar behaviour. *Protovirgularia rugosa* has been related to a deposit feeding nuculoid bivalve (Seilacher and Seilacher 1994), probably *Notonucula* (Bradshaw 2010). The imbricate structures of the specimens indicate locomotive feeding-excreta of a tracemaker on sediment surface after turbidity current events (Gong 1999).

Ichnogenus: *Rhizocorallium* Zenker 1836

Ichnospecies: *Rhizocorallium jenense* Zenker 1836 (figure 8c)

Materials: Two specimens collected from Gopibung (MIMRh – 1 and 2) in silty shale; a cluster (MIMRh – C) comprising of about 10 specimens in shale from Thongjaorok was collected.

Description: The Gopibung specimens are well preserved with protrusive sprieten. One of the tubes is about 13 mm in diameter 40 mm apart; short and about 110 mm long, which could be possibly due to fragmentation. The second specimen is about 40 mm apart with the tube diameter approximately 6 mm. It is slightly curved protrusive burrow with sprietens and tube having scratch marks. The Thongjaorok specimens are somewhat different in outlook as they are found as a cluster. Burrows are retrusive type and commonly oblique to the bedding plane. The marginal tube is about 6 mm wide. They are preserved in muddy sediments and the fills are fine sands.

Remarks: *Rhizocorallium 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 and Mork 2001) and to transgressive surfaces, produced during

Figure 8. (a) *Phycodes palmatus* found in shale at Gelmon. (b) *Protovirgularia rugosa* found in fine sandstone, Leimatak. (c) *Rhizocorallium jenense* in shale, inset is a fragmented portion showing the sprietens, which can be seen clearly right below the portion indicated by arrow. The specimens are from Thongjaorok. (d) *Scolicia plana*, associated with massive fine sandstone, Gelmon. (e) *Skolithos linearis* seen on bedding plane of massive fine sandstone, Thongjaorok. (f) *Skolithos linearis* in vertical section from Leimatak in thin-bedded fine sandstone. (g) *Spongiomorpha suevica* with silty shale host, Keithelmanbi.

a period of non-deposition, before and at the beginning of the subsequent deposition (Uchman *et al.* 2000; Rodriguez Tovar *et al.* 2007). The studied specimens are very much likely associated with transgressive surface as the burrow systems were usually formed when crustaceans colonized an exhumed firmground after sea level fall and before sandy shoreface sediments were introduced.

Ichnogenus: *Scolicia* de Quatrefages 1849

Ichnospecies: *Scolicia planna* Książkiewicz 1970 (figure 8d)

Materials: Three and two specimens collected from Gelmon (MIMSCO – 1 to 3) and Leimatak

(MIMSCO – 1 to 3) sections respectively. They are all associated with massive fine sandstone.

Description: Meandering, smooth, bilobate hypichnial ridge, about 25 mm wide and up to 5 mm high, divided by a semicircular axial furrow about 10 mm wide; preserved as semi-relief in fine-grained sandstone.

Remarks: Uchman (1995) reviewed this ichnogenus and included *Taphrhelminthopsis*, *Laminites*, *Subphyllochora* and *Taphrhelminthoida* as toponomic variants of *Scolicia*; the producers are irregular echinoids of the *Spatangus* group, with two drainage tufts that produce the drain channels. The medial string is considered faecal in origin,

because of its darkness compared to the surrounding sediments, indicating that the tracemaker was actively feeding as it passed through the sediment. Holothurians or large polychaetes are considered as the most likely tracemakers. The deposit-feeding behaviour of the tracemaker makes *Scolicia* an elite ichnofabric forming trace fossil (sensu Ekdale and Bromley 1991).

Ichnogenus: *Skolithos* Haldeman 1840

Ichnospecies: *Skolithos linearis* Haldeman 1840 (figure 8e and f)

Materials: Many field observations at Gelmon, Gopibung, Leimatak sections and Thongjaorok. Two specimens (MIMSk-1 and 2) collected from Leimatak. The specimens are associated with varied sediments like shale, silty shale, thin-bedded to massive fine sandstone.

Description: The specimens are predominantly vertical to sub-vertical, straight, cylindrical showing more or less uniform diameter from 3–20 mm. Length between 40 and 270 mm, but frequently about 120 mm. Filled with structureless, medium sand, similar to the host rock. More or less isolated burrows occur, predominantly as small, ring-like projections on top of bedding planes.

Remarks: Archetypal *Skolithos* ichnofacies are related to relatively high energy environments, shallow water conditions, in nearshore to marginal marine settings (cf. Fillion and Pickerill 1990). Marine *Skolithos* is mainly interpreted as a domichnion structure made by polychaetes like *Arenicola*, *Onuphis*, *Sabellaria* and phoroids or annelids (Schlirf and Uchman 2005). Rajkumar *et al.* (2008) reported *Skolithos linearis* from the Disang–Barail transition sediments of Manipur indicating shallow-marine environment, with occasional high-energy conditions.

Ichnogenus: *Spongeliomorpha* Saporta 1887

Ichnospecies: *Spongeliomorpha suevica* Saporta 1887 (figure 8g)

Materials: Four fragmented specimens observed near Keithelmanbi and one relatively large network at Gelmon. The Keithelmanbi specimens are associated with silty shale and the Gelmon specimens with fine sandstone.

Description: Burrows with ornaments of short ridges on the surface. Burrow diameter is 25 mm with massive fills composed of sandy sediment; preserved as hypichnion in silty shale and fine sandstone.

Remarks: Specimens from Keithelmanbi are fragmentary; however, the Gelmon specimens are more complete though the surfaces are partially eroded. The short scratches are oriented parallel to incline with the axis of the burrow. The specimen differs from *Spongeliomorpha sicula* (D'Alessandro and Bromley 1995) in the absence of longitudinally extended ridges and ovoid chambers; from *S. chevronensis* by the

absence of regularly distributed oblique ridges, and from *S. sinuostriata* by lack of long and sinuous scratch ornaments (Muñiz and Mayoral 2001). The trace makers may be either shrimps or stomatopods (Patel and Desai 2001). *Spongeliomorpha* isp. is characteristic of high energy shallow water environment. The burrow systems were formed when crustaceans colonized an exhumed firmground after sea level fall and before sandy shoreface sediments were introduced (de Gibert and Ekdale 2010).

Ichnogenus: *Taphrhelminthopsis* Sacco 1888

Ichnospecies: *Taphrhelminthopsis auricularis* 1888 (figure 9a)

Materials: Twelve and seven specimens studied at Leimatak and Gelmon sections, respectively with more field occurrences. The specimens are found in thin-bedded fine sandstone.

Description: The width of the specimen is about 3 mm and the ridges 2 mm high. The lateral ridges slope gently toward the trough and are generally smooth. The associated sediments are fine-grained sandstone. Most of the traces are casts.

Remarks: The specimens may be assigned to *Taphrhelminthopsis auricularis* (Sacco 1888; Książkiewicz 1977). The traces were formed either as surface locomotion trails by animals crawling on the sea bottom or are excavated burrows which were formed when current removed the soft muddy filling of the full burrow and filled the excavated furrow with sand (Seilacher 1962). Profuse occurrences of *Taphrhelminthopsis* are mainly connected with a well-oxygenated bottom. More distal and frequent sedimentation of turbidites could positively influence the preservational potential of the surface forms but the oxygen condition was the main controlling factor for the occurrence of the ichnofauna.

Ichnogenus: *Teichichnus* Seilacher 1955

Ichnospecies: *Teichichnus* isp. Seilacher 1955 (figure 9b)

Materials: Five specimens observed at Gelmon in silty shale.

Description: Horizontal burrows with retrusive spreiten stacked vertical to bedding; preserved in full relief; burrow diameter 10–15 mm and depth up to 50 mm.

Remarks: The studied specimens have close affinity with *Teichichnus rectus*. Seilacher (1955) compared these forms to the modern structures made by the recent polychaete *Nereis diversicolor*. *Teichichnus* isp. is a wall-like, internally laminated trace produced by the vertical migration of horizontal cylindrical burrows formed by deposit-feeders (Häntzschel 1975); generally related to burrows of annelids or arthropods and can be classified as a fodinichnion (Vossler and Pemberton 1989). Structures of this

Figure 9. (a) *Taphrheminthopsis auricularis* in fine sandstone, Leimatak. (b) *Teichichnus* isp. in silty shale, Gelmon. (c) *Teredolites longissimus* in massive fine sandstone, Tentha. (d) *Thalassinoides horizontalis* in thin-bedded fine sandstone, Gelmon. (e) *Thalassinoides paradoxicus* in silty shale, Atuyang. (f) *Zoophycos* isp. in thin-bedded fine sandstone, Gelmon.

type can be produced as a result of disturbance and redistribution of sediment by displacement of the burrow system, leaving a reworked filling, floor or spreite. *Teichichnus* isp. is a chronologically long ranging ichnogenus which apparently represents the mining pattern of an intrastratal deposit feeder (Häntzschel 1975). The trace represents a mixed *Skolithos*–*Cruziana* ichnofacies (McIlroy 2004).

Ichnogenus: *Teredolites* Leymerie 1842

Ichnospecies: *Teredolites longissimus* Kelly and Bromley 1984 (figure 9c)

Materials: Four well preserved specimens observed in massive fine sandstone at Tentha Hill (24°34'12.34"N and 093°58'56.43"E; 788 m).

Description: Clusters of tubes with subcircular cross-sections, commonly sinuous to contort. Diameter

of the tubes is about 6–8 mm; surface of which resemble carbonised woody substrate.

Remarks: Dwelling and feeding traces made by wood-boring bivalves or suspension feeders such as the modern shipworm, *Teredo*. They range in age from Cretaceous to Recent. In fact, some horizons are pretty much taken over by *Teredolites*, indicative of considerable amount of woody (or *xylic*) substrates. Bromley *et al.* (1984) recognized that this was a fundamentally different condition from the traditional soft-firm-hardground spectrum, and helpfully named as 'woodgrounds' (i.e., coal, peat, or wood) submerged in open marine waters that uniquely identifies the occurrences of woodgrounds in the rock record; *Teredolites longissimus* are found in flood-dominated tidal facies within a delta front shoreface (cf. Gingras *et al.* 2004); marginal/shallow marine (Tewari *et al.* 1998).

Ichnogenus: *Thalassinoides* Myrow 1995

Ichnospecies: *Thalassinoides horizontalis* Myrow 1995 (figure 9d)

Material: Five specimens were collected (MIMThh – 1 to 5) with many field occurrences at Gelmon. The host sediments are thin-bedded fine sandstone.

Description: Smooth-walled, unlined, horizontal branched burrows. The bedding-parallel boxwork or polygonal frameworks contain both Y and T junctions. Burrows lack swelling at junctions. Burrow diameters are constant within each specimen at 7 mm and 10 mm.

Remarks: *Thalassinoides* isp. is generally interpreted as a fodinichnial (Bromley 1996) or domichnial structure, passively filled, mainly attributed to crustaceans (Frey *et al.* 1984). They are facies-crossing form, being related to a variety of marine environments, from tidal flat and shoreline to offshore outer shelf and deep-sea (Myrow 1995), but most typically registered in shallow-marine environments. Usually related to oxygenated, soft and fairly cohesive substrates (Bromley 1996); occur in firmground and in the first stage of hardground development (Myrow 1995); related with the *Glossifungites* ichnofacies (Savrdá *et al.* 2001). Compared to several ichnospecies of *Thalassinoides* isp., recognized as valid and useful (cf. Ekdale and Bromley 2003), the studied specimens have been assigned to *T. horizontalis* Myrow based on the horizontal orientation and absence of vertically oriented offshoots (cf. Blissett and Pickerill 2004).

Ichnogenus: *Thalassinoides* Woodward 1830

Ichnospecies: *Thalassinoides paradoxicus* Woodward 1830 (figure 9e)

Material: Twenty specimens studied with many more field occurrences at Gelmon, Gopibung, Leimatak sections and Thongjaorok. Only three specimens (MIMThp – 1 to 3) collected from Thongjaorok. They are usually associated with shale, silty shale and fine sandstone.

Description: Smooth-walled, irregularly branched; mainly Y-shaped. Burrow diameter varies from 3 to 50 mm (average of about 20 mm) (Rajkumar 2005; Rajkumar *et al.* 2008), with intermittent enlargements in the bifurcation points. Size of burrow fills different from that of the host material.

Remarks: The high irregularity of size and geometry of burrow system allow us the assignation of the studied specimens to *Thalassinoides paradoxicus* Woodward. Typically found occurring in shallow-marine environments. Usually related to oxygenated, soft and fairly cohesive substrates (Bromley 1996); occur in firmground and in the first stage of hardground development (Myrow 1995); related with the *Glossifungites* ichnofacies (Savrdá *et al.* 2001).

Ichnogenus: *Zoophycos* Massalango 1855

Ichnospecies: *Zoophycos* isp. Massalango 1855 (figure 9f)

Material: Two moderately well preserved (but fractured) specimens collected from thin-bedded fine sandstone, Gelmon (MMZ – 1 and 2).

Description: One of the specimens shows two lobes with sprieten directing in different directions. The morphology of the body is nearly flat. Lobes rimmed by moderately well-developed marginal tube. Sprietens are curved with primary laminae. Entry tube from which the lobes may have arisen is not visible as the specimen is fragmented. However, a faint spot that likely represent the cone axis is oriented almost transverse to the bedding. The loop is 60–130 mm across and spiral is about 10 mm high. Length of the specimen is about 250 mm.

Remarks: The specimens are probably horizontal sections of helical lobes of *Zoophycos*. The form can be compared to *Zoophycos insignis* on the basis of lobed appearance (cf. Patel *et al.* 2009). It is a complex fodinichnial structure. Palaeozoic occurrences are registered in environments going from the nearshore to slope and deep basin (Bottjer *et al.* 1988). Buatois *et al.* (2005) reported *Zoophycos* as a common component of Carboniferous estuarine deposits. The tracemaker tolerated several bathymetrical settings, being an element of *Cruziana*, *Zoophycos* and *Nereites* ichnofacies; quiet water, stressed environments seem to be the preferential conditions under which *Zoophycos* tracemaker established (Pemberton *et al.* 2001); occurrence in shallow depositional setting for the Cenozoic (cf. Pervesler and Uchman 2004). The palaeoenvironment for the *Zoophycos* isp. bearing horizon at Gelmon locality may be below storm wave base, based on the absence of any tempestites in the horizon.

5. Palaeoenvironmental implications

Analysis of the moderately abundant and diverse trace fossils and associated sedimentary structures of the Laisong (flysch) sediments offer significant information to interpret palaeoenvironment and sea-level dynamics during the Late Eocene–Early Oligocene.

Ichnogenera such as *Bergaueria hemispherica*, *Furculosus* isp., *Gyrochorte comosa*, *Ophiomorpha nodosa*, *Skolithos linearis* and *Teredolites longissimus* usually indicate shallow marine setting with high-energy conditions typical of the *Skolithos* ichnofacies. *Skolithos* ichnofacies and their association with herringbone structures distinctive of tidal flats (figure 10a), pot cast (figure 10b), cross-beds, rain prints (figure 10c), hummocky cross beds (figure 10d),

Figure 10. (a) Herringbone structures in medium sandstone, Thongjaorok. The structure is cut vertically by *Ophiomorpha nodosa*. (b) Pot cast in thin-bedded fine sandstone, Thongjaorok. (c) Rain prints in thin-bedded fine sandstone, Gelmon. (d) Hummocky cross-stratifications in silty shale, Thongjaorok. (e) Perissodactyl track with leaf impression preserved in silty shale bed about 3 cm thick (from Rajkumar and Klein 2014). (f) Coal lenses in thin-bedded medium sandstone, Thongjaorok.

gutter casts, etc., are characteristic of a high-energy environment in the foreshore and shoreface zones including beaches, bars and spits (cf. Seilacher 1967; Howard 1975). The presence of perissodactyl foot-prints (figure 10e) (Rajkumar and Klein 2014) and occurrence of coal layer about 2 cm thick at Thongjaorok locality (figure 10f) further suggest a very shallow marginal marine and deltaic settings, respectively.

The presence of *Aulichnites parkerensis*, *Chondrites targionii*, *Helminthopsis tenuis*, *Palaeophycus striatus*, *Palaeophycus tubularis*, *Phycodes palmatus*, and *Thalassinoides paradoxicus*, with a mixture of vertical and horizontal biogenic structures represent *Cruziana* ichnofacies in a typical beach-to-offshore profile characterised by occurrence below fair-weather wave base but above the storm wave base

(Frey and Seilacher 1980); which is also characterized by sedimentary structures such as, rippled and trough-cross beddings, hummocky cross-stratifications, etc. The dominance of horizontal forms over the vertical forms suggests a reduced energy level and minimal abrupt changes in environmental parameters (i.e., temperature, salinity and sedimentation rates). *Cruziana* ichnofacies is also evocative of activities of mobile carnivores and deposit feeders exploiting relatively nutrient-rich, fine-grained sediments deposited in low-energy, offshore environment.

Desmograpton alternatum, *Halopoa imbricata*, *Helminthoraphe flexuosa*, *Nereites missouriensis*, *Palaeodictyon maximum*, *Palaeodictyon strozzi*, *Taphrhelminthopsis* isp. usually occur in deep, quiet environments, mainly representing the *Nereites* ichnofacies in general. However, the co-existence

Figure 11. Schematic diagram showing the likely shoreface profile of the Laisong flysch basin and occurrence of ichnofacies with the foreshore part on the western part of Myanmar continental landmass and the generalized onshore-offshore direction towards WNW.

of *Nereites missourensis* with *Thalassinoides paradoxus* in dark grey shale characterized by the presence of ripple marks and co-occurrence of *Palaeodictyon maximum* and *Palaeodictyon strozzi* with *Thalassinoides horizontalis* in thin-bedded fine sandstone imply the possibility of an otherwise (?localized) shallow marine depositional setting. Uchman (1995) observed the presence of *Palaeodictyon* isp. in shallow-water deposits though *Palaeodictyon* isp. is considered as a typical deep-water graphoglyptids in general.

The *Zoophycos* ichnofacies is represented by the presence of *Zoophycos* isp. in thin-bedded fine sandstones and may represent deposition below storm wave base, which is also supported by the absence of any tempestites in the horizon.

The occurrence of the *Nereites* ichnofacies and *Zoophycos* ichnofacies between sediment strata dominantly characterized by *Skolithos* ichnofacies and *Cruziana* ichnofacies suggest significant variations in the depositional setting, especially with respect to bathymetry and energy conditions. Taking into consideration the tectonic setting in the region during deposition of the Laisong sediment (cf. Soibam 1998, 2000), the occurrence of *Nereites* ichnofacies and *Zoophycos* ichnofacies may represent intermittently subsiding basin rather than the broad abyssal plain. Such a depositional setting may be explained by pulsatic stretching of the Laisong Basin. That is continual sedimentation caused shallowing of the basin. Accommodation space to the shallowed basin could only be provided by deepening of the basin due to crustal stretching, as part of the Indo-Myanmar Basin (Flysch basin) resulted from the stretching (passive rifting) of the western continental margin of the Myanmar land-mass (Soibam et al. 2013); the mechanism on passive continental margin basin development and deposition of flysch sediments may be invoked from Gerhard (2000). Figure 11 represents the schematic diagram showing the likely shoreface profile and occurrence of ichnofacies of the Laisong flysch basin.

6. Conclusions

- The Laisong flysch successions of Manipur, northeast India, contain a relatively diverse trace fossils comprising of 36 ichnospecies belonging to 33 ichnogenera.
- The ichnospecies are classified into *Teredolites* ichnofacies, *Skolithos* ichnofacies, *Cruziana* ichnofacies, *Zoophycos* ichnofacies and *Nereites* ichnofacies.
- Presence of *Teredolites* ichnofacies suggests channel fill deposit in deltaic fan region.

- The occurrence of *Skolithos* ichnofacies and associated sedimentary structures point towards sublittoral marine setting with significant and complex wave activity.
- *Cruziana* ichnofacies implies offshore setting with relatively nutrient-rich, fine-grained sediments deposited in low-energy environments.
- Occurrence of *Zoophycos* ichnofacies and *Nereites* ichnofacies and association of massive and structureless beds, parallel laminations, load casts with characteristic squeezed and lineated downward protrusions that marked the base of turbidites indicate deep turbidite succession.
- The vertical distribution of diverse ichnospecies at different level of Laisong succession (figures 2 and 3) indicates fluctuation in the basin depth that is shallowing and deepening. Regression of the basin was eventually due to sediment accumulation and transgression related to pulsatic crustal stretching leading to deepening of the then western continental margin basin on the Myanmar Plate (Soibam et al. 2013) during the Late Eocene–Early Oligocene times.

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