Early Cambrian Ichnofossils from the Mussoorie Syncline and revision of Trace Fossil Biozonation of the Lesser Himalaya, India

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Abstract: A new locality bearing ichnofossils of the *Cruziana* Assemblage Zone-III from the Mussoorie syncline, Lesser Himalaya, is located in rocks of Member-B of the Dhaulagiri Formation, Tal Group, exposed along the Maldewta-Chhimoli fresh road cut section. The site yielded ichnofossils *Bergaueria perata, Cochlichnus anguineus,* ?*Diplocraterion* isp., *Dimorphichnus obliquus,* diplichnitiform *Cruziana bonariensis, Diplichnites gouldi, Glockeria* isp., *Helminthopsis* isp., *Monomorphichnus lineatus, Phycodes palmatum, Palaeophycus striatus, Planolites beverleyensis*, *Planolites montanus*, *Treptichnus cf. T. pedum*, scratch marks and an undetermined worm impression. An Early Cambrian age (Cambrian Series 2) is assigned to the ichnofossil-bearing strata based on the stratigraphic position between the *Drepanuroides* and *Palaeoolenus* trilobite zones. A revised Cambrian ichnofossil zonation is presented for the Tal Group of the Mussoorie syncline. Together with their occurrence on rippled surfaces, and the lateral displacement of some trackways (due to current action), a sub-aqueous shallow-marine depositional setting is proposed for the rocks of Member-B.

Key words: Ichnology, *Cruziana* Assemblage Zone, Cambrian Series 2, shallow-marine, northern India

1 Introduction

Ichnofossils are significant in Early Cambrian successions as the behaviors they represent provide primary evidence of the early history of metazoans (Seilacher, 1956; Crimes, 1992a; Zhu, 1997). In the Lesser Himalaya, Cambrian successions are exposed along the Nigali, Korgai, Mussoorie, and Garhwal synclines, in a sequence known as the Tal Group. In the Mussoorie syncline the Precambrian-Cambrian boundary is well marked in the basal part of the Tal Group (Bhatt et al., 1983) and the first trilobite of latest Early Cambrian age occurs right at the juncture of the lower and middle Tal formations (Hughes et al., 2005). Traces of trilobite or arthropod affinities are also well concentrated along this boundary. However, the traces of gastropods, mollusks and other remains of unknown affinities are also reported from the lower part of the Tal Group (Singh, 2011).

In general, a highly diversified ichnological record is known from the rocks of the Tal Group, including *Asterosoma, Astropolichnus, Cruziana, Cylindrichnus,* ?*Cochlichnus, Daedalus, Didymaulichnus, Dimorphichnus, Diplichnites, Glockerichnus, Helminthopsis, Hormosiroidea, Lorenzinia, Monomorphichnus, Merostomichnites, Neonereites, Palaeophycus, Psammichnites, Planolites, Phycodes, Rusophycus, Skolithos, Streptichnus, Tapherhelminthopsis,* ?*Taenidium* and ?*Treptichnus* (see Singh and Rai, 1987; Rai, 1987; Joshi and Mathur, 1987; De et al., 1994; Kumar et al., 1983; Banerjee and Narain, 1976; Bhargava, et al., 1998; Mathur et al., 1988; Bhargava, 1984; Tiwari & Parcha, 2006; Hughes et al., 2005; Desai et al., 2011; Singh, 2009, 2011). However, most of the ichnofossils are known from the rocks representing the boundary between the lower and upper Tal formations (see Hughes et al., 2005). On the basis of Small Shelly Fossils (SSF), brachiopods, gastropod, trace fossils and trilobite fauna, the Tal Group has been considered to be Early to ?Late Cambrian in age (see Hughes et al., 2005). However, body fossils younger than late Early Cambrian have not been reported from the Tal Group, and the Middle to Late Cambrian age of the upper part of the Tal Group is based only on assumption and stratigraphic-lithological correlation. Detrital zircon from the very top of the Tal Group in the Mussoorie syncline is dated as no younger than 525±8 Ma (Myrow et al., 2003).

In the present work, a new locality bearing well-preserved ichnofossils from the Dhaulagiri Formation (upper part of the Tal Group) is described and may add

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some data to the ichnofossil biostratigraphy and paleoenvironmental interpretation of the rocks of the Tal Group of the Mussoorie syncline (Lesser Himalaya). The present collection of ichnofossils is stratigraphically significant because they were recovered from the lower part of the Dhaulagiri Formation. Based on this new material, the trace fossil biozonation of the Cambrian rocks of the Lesser Himalayan is revised.

2 Geological Setting

In the Krol-Tal belt of the Lesser Himalaya, the Tal Group is exposed in the core of NW–SE extending synclines, i.e., the Nigalidhar, Korgai, Mussoorie, Garhwal and Nainital synclines (Fig.1a). Numerous researchers have studied the stratigraphy, sedimentology and biostratigraphy of the Tal Group (for extensive bibliography, refer to Hughes et al., 2005). Lithostratigraphically, the Tal Group is broadly divided into the Lower and Upper Tal formations separated by a disconformity (Middlemiss, 1887; Auden, 1934). However, Bhargava (1979) divided the Tal Group into the Lower, Middle and Upper Tal units. In the Mussoorie syncline, Shanker et al. (1993) classified the Tal Group into Deo Ka Tibba (587 m in thickness) and Dhaulagiri (1715 m in thickness) formations corresponding to the Lower and Upper Tal formations, respectively. They further subdivided the Deo Ka Tibba Formation into four members, i.e., the Chert Phosphate (150 m thick), Argillaceous (254 m thick), Arenaceous (382 m thick) and the Calcareous (35 m thick) members. Shanker et al. (1993) also subdivided the Dhaulagiri Formation into five members: Member–A (Quartzite, 70 m thick), Member-B (Black shale and Sandstone, 23 m thick), Member-C (Feldspathic quartzarenite, 375 m thick), Member-D (Algal limestone, 61 m thick), and Member-E (Quartzarenite, shale and siltstone, 1186 m thick). In the Mussoorie syncline, the Precambrian–Cambrian boundary is placed slightly above the base of the Tal Group within the Chert Phosphorite Member of the Deo Ka Tibba Formation (Bhatt et al., 1983, Bhatt, 1991). The Deo Ka Tibba and Dhaulagiri formations represent a thick siliciclastic succession that crops out along the Maldewta-Sarkhet-Chhimoli fresh road-cut section in the Mussoorie syncline. The generalized stratigraphy of the Tal Group in the Mussoorie syncline is illustrated in Fig. 1e.

3 Maldewta-Sarkhet-Chhimoli Road-Cut Section

In the southern limb of the Mussoorie syncline, the Krol-Tal succession is well exposed along the route from Maldewta to Chhimoli, which is along the Bandal Nala (Fig. 1b, c). The Krol-Tal succession at Maldewta is well known for its discovery of a Small Shelly Fauna (SSF_1) of the Early Cambrian Terreneuvian age from the basal part of the Tal Group (Juyal, 1979; Azmi et al., 1981, Azmi and Joshi, 1983, Bhat et al., 1983, and Bhat, 1991). Ichnofossils were collected from the rocks of the Tal Group about 3.4 km away from Sarkhet village (Fig. 1c). The ichnofossil-bearing section displays alternation of bluish silty shale and sandstones about 14 m thick and is stratigraphically assigned to the middle part of Member-B of the Dhaulagiri Formation (Upper Tal Group). At the fossiliferous locality, the road cut almost follows the Bandal Nala and there is exposure of similar outcrops along the Bandal Nala (Fig. 1c). The bedding planes are always interfaces of sandstone and silty shales covered with current ripple structures (Fig. 1d).

4 Ichnology Systematics

Ichnogenus: ***Bergaueria*** Prantl, 1945

Bergaueria perata Prantl, 1945

(Pl. 3. Fig. 2. Bp)

Material: One sandstone slab with two specimens, one well preserved. CAS/BP/7000/12

Description: The specimen is formed of one plug-shaped, cylindrical to gently conical burrows with a rounded to nearly flat base. The basal part shows a very faint concentric ornamentation on upper surface. A prominent central cone-like structure is preserved in the specimen. The specimen has a diameter of about 3.2 cm.

Remarks: Pemberton et al. (1988) presented detailed work on the diagnostic characters of *Bergaueria perata* as a bergauerian with 'smooth walls; rounded lower end may exhibit faint radial ridges emanating from one or more weak central depression'. Pickerill (1989) suggested that the concentric ornamentation was a key character for the diagnosis of the taxon. The lack of a central depression is essentially the one characteristic that distinguishes *Bergaueria hemispherica* Crimes et al., 1977 from *B. perata*. *Bergaueria* is known from the Cambrian successions of Ukraine (Palij, 1976; Palij et al. 1983), Poland (Radwanski and Roniewicz, 1963; Paczesna, 1986), USA (McKee, 1945; Seilacher, 1956; Alpert, 1973), and Alberta and Newfoundland in Canada (Arai and McGugan, 1968).

Ichnogenus: ***Cochlichnus*** Hitchcock, 1858

Cochlichnus anguineus Hitchcock, 1858

Pl-1, Fig. 1. Cc

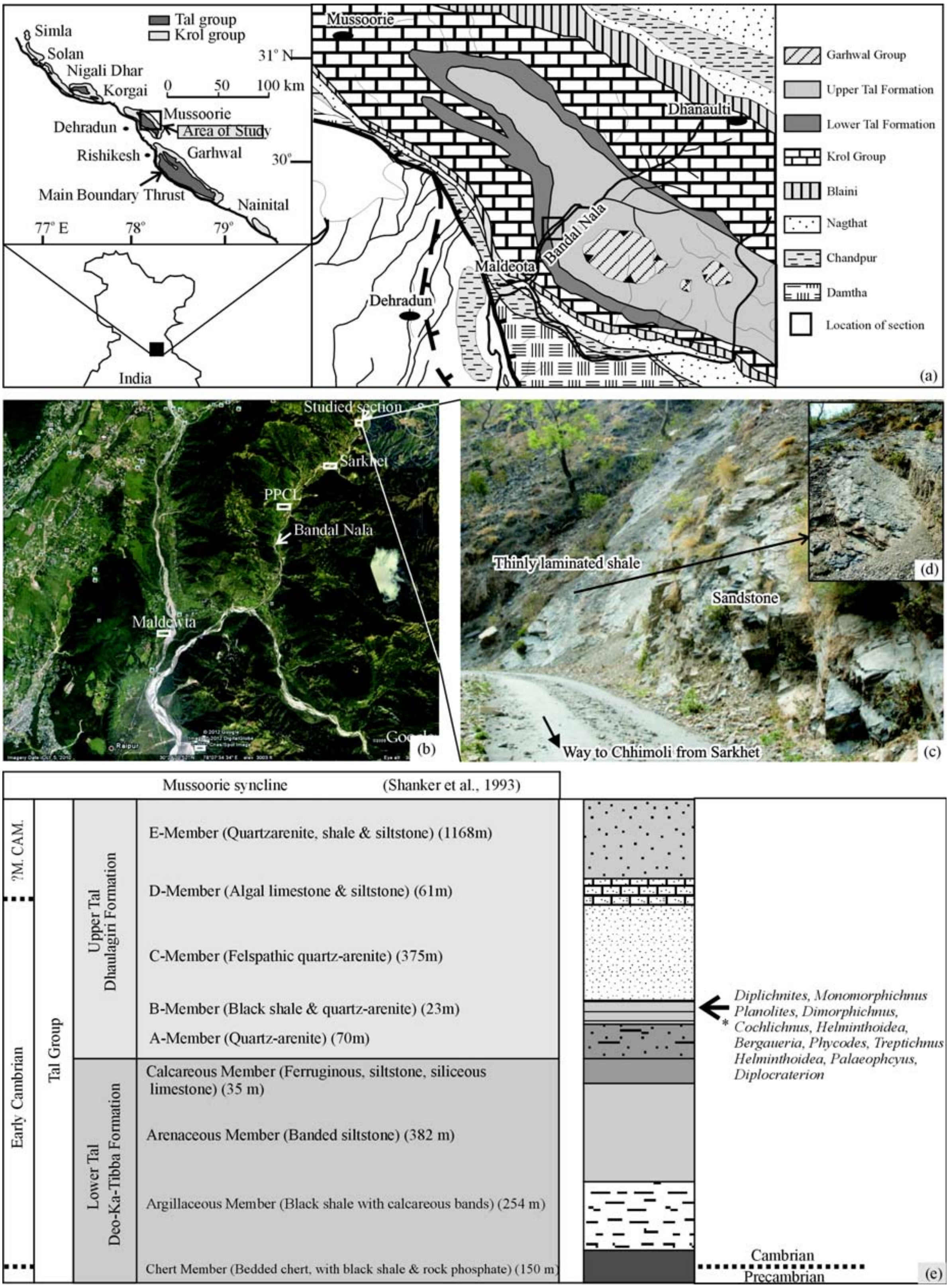

Fig. 1. a) Geological map of the Mussoorie syncline, Lesser Himalaya, India (modified after Rupke and Sharma, 1967); b) Google earth image showing the location of the studied section, Maldeowta-Sarkhet-Chhimoli road, and Bandal Nala, Mussoorie syncline; c) Outcrops of the Member-B (Dhaulagiri Formation, Upper Tal) exposed along the road cut near 3.5 km north of the Sarkhet village on way to Chhimoli village; d) Photograph showing current rippled surface (bedding plane) in which the traces of arthropod or trilobitic origin are preserved; e) Lithostratigraphic classification of the Tal Group (after Shankar et al., 1993) and schematic stratigraphic column of the Tal Group (not to scale). Ichno-fossiliferous level is shown by an arrow and asterisk.

Material: Single specimen in association with *Treptichnus* preserved in fine-grained sandstone (CAS/BP/7001/12).

Description: An unbranched, meandering trace characterized by a regular sine or clothoid wave shape and preserved in convex hyporelief. The width of the meandering trace is 0.7 to 0.9 mm and the preserved length is 21 mm. The amplitude of the sine curve is 0.1-0.2 mm whereas the wavelength is 4.6 to 7.6 mm.

Remarks: The material is relatively well preserved showing a regular sinuous pattern. Fillion and Pickerill (1990) and Buatois et al. (1997) stated that all the trails or burrows showing regular sinuosity should be included in *Cochlichnus anguineus*. Therefore, not surprisingly, a wide stratigraphic range from Precambrian (Fedonkin, 1983) to Holocene is known. Early Cambrian *Cochlichnus* specimens have been reported from New South Wales, eastern Australia (Webby, 1970), the Mickwitzia Sandstone in Spain (Jensen, 1997), and the Khmelnitsky Formation of Podolia in Ukraine (Gureev, 1983). This ichnogenus is regarded as representing the feeding trace of annelids on the sea floor or locomotion traces of nematodes or insect larvae (Seilacher, 1963; Moussa, 1970; Fillion and Pickerill, 1990; Metz, 1996).

Ichnogenus: ***Diplichnites*** Dawson 1873

Diplichnites gouldi Gevers in Gevers et al., 1971

(Pl. 2, Fig. 1. Dipg.)

Material: One sandstone slab (CAS/BP/70020/12).

Description: The trace consists of a paired long row of ridges, preserved as negative relief on the sole of the sandstone bed. The trace is 25 cm long and 3 cm wide with the ridges about 5 to 9 mm apart. At some places along the axis of the trace there are only one series of impressions preserved, which may be because only one claw came into contact with the sediment surface.

Remarks: This ichnogenus is defined as the walking tracks of trilobites (Seilacher, 1955). *Diplichnites* has been reported widely in Cambrian rocks (Seilacher, 1955; Martinsson, 1965; Crimes, 1970a; Crimes et al. 1977; Singh 2009).

diplichnitiform *Cruziana bonariensis*, Seilacher 2007

(Pl. 2, Fig. 3. Dipcb)

Material: One sandstone slab with one specimen (CAS/BP/7008/12).

Description: The specimen consists of unequal and diachronous tracks of a sidling trilobite that had at least seven to nine pairs with claws. Lateral impressions were caused by the probing of claws, the endopodites of which penetrated deeper than usual.

Remarks: Seilacher (2007) recognised the diplichnitiform version of *Cruziana bonariensis* from the Akakus Sandstone of Libya. In contrast to true *Diplichnites* (or *Petalichnus*), however, it does not express simple walking. Rather it represents a kind of probing in which the endopodites penetrated deeper than usual and notably the sets were not made synchronously on both sides (Seilacher, 2007). The present specimen resembles in all diagnostic characters the diplichnitiform *Cruziana bonariensis*; however, the five-clawed legs are not well preserved.

Ichnogenus: ***Dimorphichnus*** Seilacher 1955

Dimorphichnus obliquus Seilacher 1955

(Pl.2. Fig. 6. Dio)

Material: One fine-grained sandstone slab with one specimen (CAS/BP/70011/12).

Descriptions: This specimen consists of nine to ten elongated ridges, regularly repeating towards the side, with faintly preserved elongated ridges in between. The trace shows the slow sliding of the track maker when the water was less uneven.

Remarks: The generic and specific names of *Dimorphichnus obliquus* were created by Seilacher (1955) for tracks imprinted by the sideways movement of trilobites, similar to the case of some living crustaceans, such as crabs. *Dimorphichnus obliquus* is known from the Lower Cambrian of the Salt Range (Seilacher 1955, Schindewolf and Seilacher, 1955).

Ichnogenus: ***Diplocraterion*** Torell, 1870

***?Diplocraterion* isp.,**

(Pl. 3, Fig. 4. Dc)

Material: One fine-grained sandstone slab with more than five specimens (CAS/BP/70017/12).

Description: The specimen contains a pair of vertical *Spreiten* (‘to spread out’) burrows, rounded in shape and 5 mm in diameter, both openings of the U-shaped tube are very close, 2 mm apart from each other. The infill material is coarser than the host rock.

Remarks: *Arenicolites* differs from *Diplocraterion* in the absence of a *spreite* (Hakes, 1976) and so since the present specimen contains the *spreite*, hence it is referred to *Diplocraterion*. The ichnogenus includes all U-shaped *spreiten* burrows that are perpendicular to bedding planes. *Diplocraterion* is known to occur in rocks ranging from

Cambrian to Oligocene and is generally regarded as the dwelling burrow of suspension feeding organisms (Fürsich, 1974) or benthic predators (Bromley, 1996) in high-energy environments with a relatively strong wave and current energy (Häntzschel, 1975; Fillion and Pickerill, 1990).

Ichnogenus: ***Glockeria*** Książkiewicz, 1968

***Glockeria* isp.**

(Pl. 3, Fig. 5. G)

Material: One fine-grained silty-shale slab with one specimen (CAS/BP/70018/12).

Description: The trace is radiating, with the elements radially elongated, approximating a stellate pattern. The specimen is 4 cm in radial extent; an individual element is 3 to 3.2 cm long.

Remarks: Graphoglyptids, are trace fossils that exhibit ornate burrow geometries and are mainly found in the distal turbidite facies of deep-sea environments. *Glockeria* differs from *Tuapseichnium* (Vyalov 1971), another radiating graphoglyptid, in that the latter shows a radiating form with a branching into antler- or net-like bilateral pattern consisting of U-shaped burrows.

Ichnogenus: ***Phycodes*** Richter, 1850

Phycodes palmatum Hall, 1852

(Pl. 1, Fig. 2. Pp)

Materiel: One fine-grained sandstone slab with one specimen (CAS/BP/7005/12).

Description: A horizontally oriented, curved burrow, bifurcating in the middle and rear end with two branches overlapping each other at one end. The trace is preserved in positive hyporelief. The burrow length is 11.8 cm and the width varies from 2.3 cm to 4.1 cm. The individual branch is smooth.

Remarks: Ichnospecies of *Phycodes* differ in pattern, size, nature, style and rank of bifurcation and the presence or absence of *spreite*. Similar specimens to that described here have been described from the Parahio Formation of the Tethyan Himalaya (Parcha, 1998; Singh, 2009). This ichnogenus is more commonly known from low-energy shallow-marine environments but has also been reported from non-marine, brackish water and deep-marine environments (Fürsich and Mayr, 1981).

Ichnogenus: ***Helminthopsis*** Heer, 1877

***Helminthopsis* isp.**

(Pl. 1, Fig. 3. He)

Material: One sandstone slab with one specimen (CAS/BP/70014/12).

Description: An unbranched, horizontal, gently meandering burrow (trail) with smooth walls. The diameter of the burrow ranges from 2 to 4 mm and length up to 6 cm. Burrow fills are homogeneous. Some parts of the wall show collapse features; some segments of burrow are straight.

Remarks: Häntzschel (1975) briefly discussed the variations of the ichnogenus *Helminthopsis*, which can be clearly different from *Helminthoida* and lacks the regular tight meandering pattern. Our specimen shows the characters of *Helminthopsis* and hence is referred to this ichnotaxon. According to Książkiewicz (1977) *Helminthopsis* is a postdepositional feeding burrow.

Ichnogenus: ***Monomorphichnus*** Crimes, 1970

Monomorphichnus lineatus

(Pl. 2, figs. 2, 4, 5Mnl, 7 Mnl)

Material: Four fine-grained silty-shale slabs with each containing one specimen (CAS/BP/7007/12, 70013/12, 70010/12, and CAS/BP/70015/12).

Description: One set composed of five to seven parallel to sub-parallel, straight to slightly bent ridges preserved in positive hyporelief (Pl.2, Fig.5 Mnl). Each ridge is of uneven length (1.9–4.8 cm) and 1–2 mm wide, with the distance between ridges 1.2–12 mm. Another set is composed of seven parallel, straight to slightly bent ridges preserved as negative impressions. Each ridge is of uneven length (1.3–4.1cm) and 1 mm wide, with 1–6 mm between the linear ridges (Pl.2, Fig.7 Mnl). Other specimens (Pl. 2, figs. 2, 4) show two sets of straight to slightly bent ridges preserved as negative impressions. The ridges are uneven in length and range from 0.6 to 1.1 cm in length and 1 mm wide.

Remarks: *Monomorphichnus* is defined by sets of elongated, narrow ridges, which are interpreted as the result of sideways-swimming or raking arthropods. Seilacher (1985, 1990) regarded this ichnogenus as synonymous with *Dimorphichnus*. Jensen (1997) considered that both ichnogenera might represent different behaviors of the same producer. *Monomorphichnus lineatus* differs from *Monomorphichnus bilinearis* (Crimes, 1970b) in lacking bifid scratches. It differs from *M. multilineatus* (Alpert, 1976) in lacking central ridges deeper than the outer ridges.

Ichnogenus: ***Planolites*** Nicholson, 1873
Planolites montanus Richter, 1937
(Pl. 1, Fig. 4. Pm.)

Material: One sandstone slab with two specimens (CAS/BP/7002/12).

Description: This trace is made up of horizontal burrows, gently curved, convex epireliefs with smooth walls, and diameter range from 1 to 3 mm. It seems that the burrow was open to the surface along its whole length; it is completely unlined and non-ornamented infilled with fine sandy material from the overlying bed.

Remarks: The ichnogenus *Planolites* has been a topic of considerable discussion and different ichnospecies are identified based on the burrow fills and lining (Alpert, 1975; Pemberton and Frey, 1982, Fillion, 1989). According to Pemberton & Frey (1982), this ichnospecies includes *Planolites ballandus* Webby (1970) and *Planolites nematus* Kowalski (1987) based on the diameter (less than 1 mm) of the preserved traces. *Planolites* is interpreted as a feeding structure of deposit feeders, mainly worms or possibly larval insects in continental deposits (Pemberton & Frey, 1982, Buatois & Mángano 1993). *Planolites* shows a wide tolerance for different substrate types and salinities. *Planolites* commonly occurs in low protected beaches, tidal flats, and shoals and point bars within tidal streams but also deep water (Pettibone, 1963; Frey, 1970; Howards & Frey, 1975).

Planolites beverleyensis (Billings, 1862)
(Pl. 1, Figs. 7 Plb and 8 Plb.)

Material: Two specimens preserved in two blocks of fine-grained bluish-grey shale (CAS/BP/7003/12 and CAS/BP/7009/12).

Description: The burrow is cylindrical to sub-cylindrical, preserved as convex epirelief with smooth walls, straight to slightly curved at one end, with a diameter range from 6 to 8 mm; length reaches up to 4.3 cm. The burrows are infilled with fine-grained sand differing in colour from the host rock and they occur isolated from one another on the bedding surface.

Remarks: This ichnotaxon is very common in the Early Cambrian succession worldwide; it is mainly reported from the Cambrian strata of the Holy Cross Mts (Orlowski, 1989) and the Himalaya (Singh, 2009, 2011).

Ichnogenus: ***Palaeophycus*** Hall, 1847
Palaeophycus striatus Hall, 1852

(Pl. 1, figs. 5, 6, pals, Pl.3, Fig.3. pals)

Material: Four specimens preserved as hyporelief in three fine- to medium-grained sandstone blocks (CAS/BP/7006/12; 7004/12 and CAS/BP/70019/12).

Description: The burrow is subcylindrical, slightly flattened, with a diameter of 10 mm. It is preserved as positive hyporelief; one extremity of the burrow is curved and plunges into the substrate, the outer burrow surface is lined by longitudinal parallel grooves, and the infill is composed of sediment identical to the surrounding rocks.

Remarks: According to Pemberton & Frey (1982), *Palaeophycus striatus* differs from the other ichnospecies of *Palaeophycus* by its ornamentation, i.e., with parallel and continuous grooves. There are various views regarding the preservational potential of the grooves on the surfaces of *Palaeophycus striatus.* Maples & Suttner (1990) stated that their preservation depended on the composition and consistency of the substrate and that the grooves are better preserved in fine-grained sediments. However, Buatois *et al*. (1997) emphasized that the presence of grooves on the surfaces of *P. striatus* suggests a relative firmness of the substrate, perhaps at a stage of transition between soft- and firm ground.

Ichnogenus: ***Treptichnus*** Miller, 1889

Treptichnus pedum (Seilacher, 1955)
Treptichnus* cf. *T. pedum
(Pl-1, Fig. 1. Tt)

Material: A single specimen preserved in fine-grained sandstone (CAS/BP/7001/12).

Description: The specimen consists of a main horizontal, undulatory burrow with three to four probes (see right corner of the image) that join the main burrow at an angle to parallel. The main burrow is 20 cm long and the probes are 1.2 cm to 5.6 cm long. At one end of the burrow the probes more or less follow the course of the main burrow.

Remarks: The morphological characteristic of the present specimen fits within the range of forms currently included in *T. pedum* (Geyer and Uchman, 1995) hence it is compared with *T. pedum*. *T. pedum* is known from the boundary interval of Precambrian–Cambrian (P–C) transition (Narbonne et al., 1987; Landing, 1994) and even 4 m below the P–C boundary in Newfoundland (Gehling et al., 2001).

The present specimen was collected from the lower part of the Upper Tal Formation hence within younger than P–C boundary strata and thus is not significant for demarcating the actual P–C boundary. De et al. (1994) recorded *Treptichnus* (=*Phycodes*) *pedum* from the Tal Group

(Lesser Himalaya). However, the validity of this report was questioned by Hughes et al., (2005). *Treptichnus* is generally interpreted as a systematic feeding structure with each segment reaching up to the sediment surface (Seilacher and Hamleben, 1966; Jensen, 1997).

Worm impression

(Pl.3. Fig. 1. Wi)

Material: A single specimen preserved in silty shale layer (CAS/BP/70016/12).

Description: A single specimen collected from the Calcareous Member of the Dhaulagiri Formation is a curved impression. The structure is more than 4.3 cm long, and 1.5 cm wide, the central part is preserved as Worm-like negative epirelief. A prominent central carina is visible on the central part of the specimen. The rear end shows the tail structure, which is slightly wider and rounded in appearance; the head part is wider than the tail end. The head end is marked by the impression of *Diplichnites* tracks of trilobites.

5 Discussion

The significance of ichnofossils in Cambrian successions where body fossils are either rare or absent has been pointed out by several authors (Seilacher, 1967, 1970; Crimes, 1970a, b). In such successions ichnofossils can provide the basis for age determination and paleoenvironmental interpretation. The importance of ichnofossils in the Indian Himalayan Cambrian successions, where body fossils are not preserved, has been comprehensively discussed by Hughes (2002) and Hughes et al. (2005). The biostratigraphy of the Tal Group in general and particularly for trilobites was revised by Hughes et al. (2005). Two trilobite zones, the *Drepanuroides* and *Palaeolenus* zones of the Early Cambrian (Series 2), were identified from the NigaliDhar syncline, which occurs in the top part of the Lower Tal Formation and lower part of the Upper Tal Formation, respectively. In the Mussoorie syncline, trilobites are known from only two stratigraphic levels, i.e., the top part of the Arenaceous Member (Deo ka Tibba Formation, Lower Tal) and the Shale Member (Dhaulagiri Formation, Upper Tal). The Early Cambrian trilobite *Redlichia noetlingi* (of the *Drepanuroides* Zone) from the Arenaceous Member (Joshi et al. 1989) was revised and re-assigned to *Eoredlichia* (Hughes et al., 2005). Similarly, *Tungsella* cf. *obesa* from the Arenaceous Member was re-assigned to *Wuttingaspis* and is within the *Drepanourides* Zone (Hughes et al., 2005). Rai and Singh (1983) also reported trilobites impressions from the Arenaceous Member exposed near the Kaplani village, 6 km away from Mussoorie city on the road from Mussoorie to Tehri. However, they did not identify these trilobites to generic or species level and described them collectively as trilobite impressions. The trilobite *Xela mathurjoshi* is known from the shale Member-B of the Dhaulagiri Formation (Mathur and Joshi, 1989) and represents the *Paleolenus* Zone (Hughes et al., 2005). The occurrence of Early Cambrian trilobites in the Arenaceous Member (Joshi et al. 1989) of the Deo-Ka-Tibba Formation and Member-B (Mathur and Joshi, 1989) of the Dhaulagiri Formation of the Tal Group provides the basic data for determining the age of those stratigraphic levels where ichnofossils are abundant but body fossils are lacking. Most of the ichnofossils reported from the Tal Group are long ranging in age and therefore are of limited biostratigraphic use. Hughes et al. (2005) discussed and questioned the affinity and assignment of the many lower Cambrian trace fossils reported from the Tal Group.

Treptichnus pedum is of biostratigraphical use in Precambrian–Cambrian boundary successions worldwide. In the Lesser Himalaya, *Treptichnus pedum* is reported from the lower part of the Tal Group (De et al., 1994) but Hughes et al. (2005) questioned the records of this significant ichnotaxa from the Tal Group. The new collection of ichnofossils from the Tal Group at a new locality in the Mussoorie syncline is significant as they occur in strata representing the *Palaeolenus* Zone. Earlier workers have identified only three ichnogenera at this stratigraphic level from Nigali Dhar syncline (Bhargava, 1984; Bhargava et al., 1998). However, in the present work, 17 ichnogenera have been collected and described. Based on these ichnofossils and other collections of ichnofossils made from the lower stratigraphic units (refer to Singh, 2011), the *Cruziana* Assemblage Zone can be recognized (=Zone –III of Crimes, 1987).

An attempt also has been made to revise the ichnofossil assemblage zones proposed for the Tal Group by Desai et al. (2011). They (Desai et al., 2011) proposed three distinctive ichnofossil zones based on the Tal Group of the Nigali Dhar syncline (Himachal Pradesh), i.e., i) *Palaeophycus-Phycodes* Zone-IIa, and ii) *Daedalus-Phycodes* Zone-IIb in the Sankholi Formation (=Deo Ka Tibba Formation), and iii) *Cruziana* Zone-III in the Koti-Dhaman Formation (=Dhaulagiri Formation), which they correlated with the ichnofossil zones of Crimes (1987). However, the proposed ichnofossil zones, i.e. Zone-IIa and Zone-IIb of the Tal Group are questionable. In the Mussoorie syncline, Zone-IIa and Zone-IIb are not observed but Zone-III is identified and that occurs in the middle part of the Arenaceous Member of the Deo-Ka-Tibba Formation to Member-B of the Dhaulagiri Formation (Fig.2). In the Mussoorie syncline, ichnofossils *Diplichnites*, *Dimorphichnus*, *Monomorphichnus* of the

Cruziana ichnofacies (Singh & Rai, 1983; Singh, 2011) are known from the Deo-Ka-Tibba Formation (=Sankholi Formation of NigaliDhar syncline). Trilobite impressions are also known from top part of the Arenaceous Member of Deo-Ka-Tibba Formation in the Mussoorie syncline (Rai and Singh, 1983). Singh (2011) reported *Psammichnites gigas*, *Diplichnites*, *Monomorphichnus*, ? *Hormosiroidea* and *Palaeophycus* from the Arenaceous Member and grouped them under Zone-III of Crimes (1987), which represents a Tommotian-Atdabanian age. Besides the ichnofossils, body fossils of the trilobites *Drepanopyge gopeni* and *Protolenella* cf. *P. angustilimbata* of the *Drepanuroides* Zone (Hughes et al., 2005) are also known from the top part of the Sankholi Formation (=Deo-Ka-Tibba Formation). The occurrences of trilobites indicate that the strata below the *Drepanuoriudes* Zone of Sankholi Formation possibly are pre-trilobitic strata in the Tal Group. The ichnofossil zones of Crimes (1987) are useful to date this pre-trilobitic part of the Early Cambrian succession because above these strata, the traces are long ranging and hence less biostratigraphically important.

Together with their occurrences on rippled surfaces, and the lateral displacement of some trackways (due to current action), a sub-aqueous shallow-marine depositional setting is proposed for the rocks of Member-B of the Dhaulagiri Formation (Tal Group).

6 Conclusions

Here we revise the trace fossil zones proposed by Desai et al. (2011) for the Lesser Himalayan Tal Group. In the Mussoorie syncline, trace fossil zones i.e., Zone-IIa and Zone-IIb are not observed but Zone-III (Crimes, 1987) is identified. It occurs in the middle part of the Arenaceous Member of the Deo-Ka-Tibba Formation to Member-B of the Dhaulagiri Formation (Fig.2). The originally proposed ichnofossil zones, i.e., Zones IIa and IIb have not been found and hence are questionable for the Lower Tal Formation (Deo Ka Tibba or Sankholi formations). Besides this the present work also records for the first time the 13 ichnogenera and 14 ichnospecies from the levels representing the Early Cambrian, which is based on the stratigraphic position of these ichnofossil-bearing strata between the *Drepanuroides* and *Palaeoolenus* trilobite zones Cambrian Series 2 in the Mussoorie syncline (Lesser Himalaya, India).

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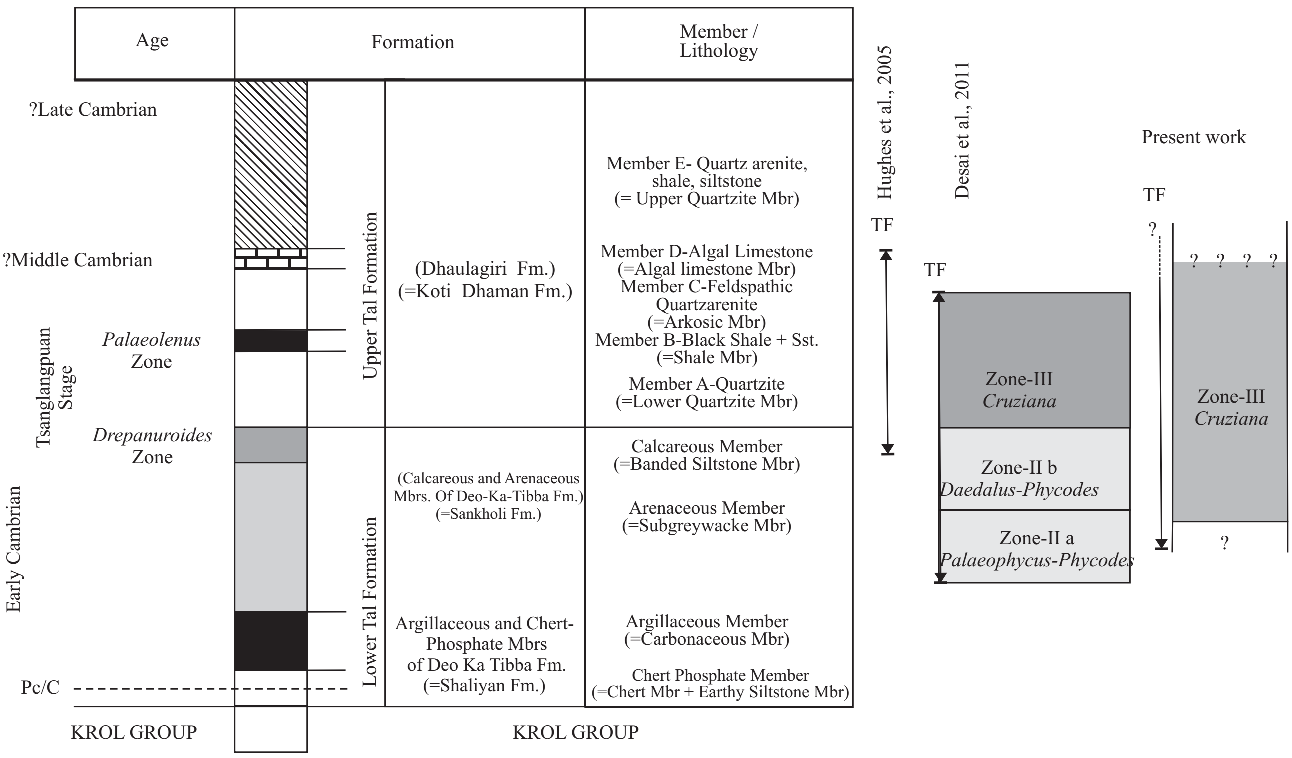

Fig. 2. Compiled comparative lithostratigraphic data of the Tal Group from the Nigalidhar and Mussoorie synclines of the Lesser Himalaya and the present ichnofossil zonation of this study and Singh (2011) are plotted against the compiled section.

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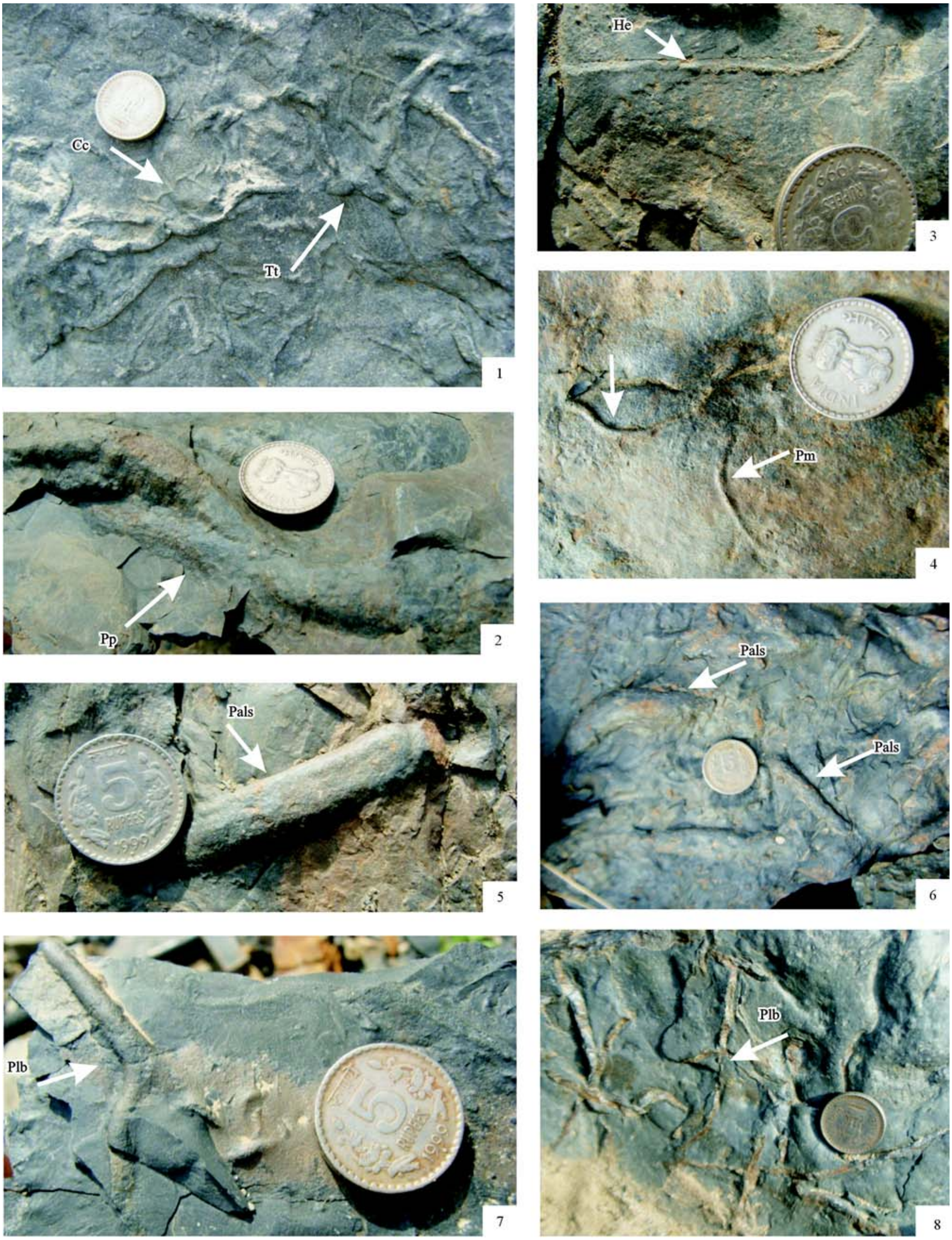

Plate 1 Ichnofossils from the Member-B (Dhaulagiri Formation, Upper Tal). Coin scale bar=2.3 cm. Fig.1Cc=*Cochlichnus anguineus*, Fig.1Tt=*Treptichnus* cf. *T. pedum*, Fig.2Pp= *Phycodes palmatum*, Fig.3 He= *Helminthopsis* isp., Fig.4 Pm=*Planolites montanus*, Figs.5,6 Pals= *Palaeophycus striatus*, Figs.7 Plb & 8 Plb=*Planolites beverleyensis*

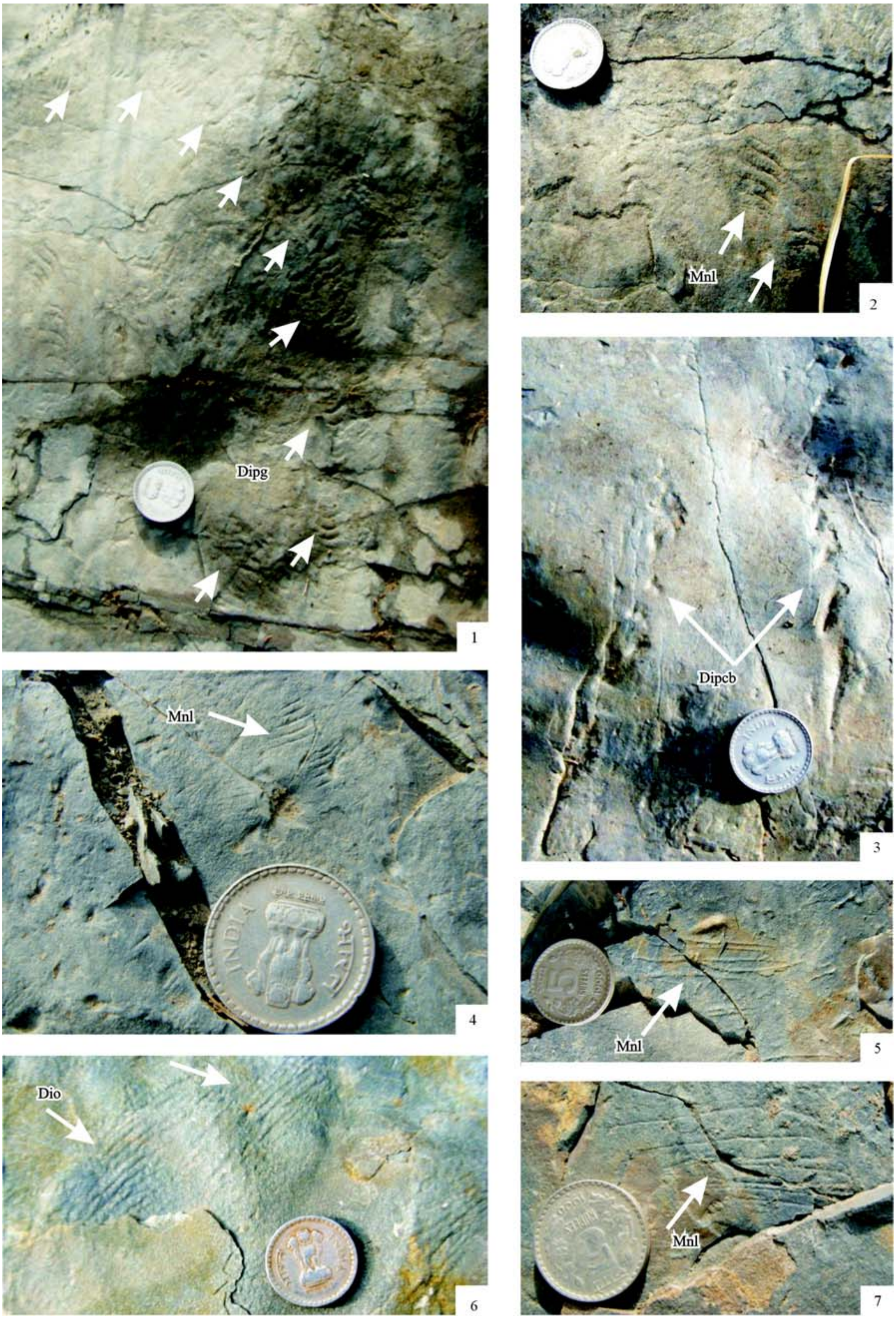

Plate 2 Ichnofossils from the Member-B (Dhaulagiri Formation, Upper Tal). Coin scale bar is 2.3 cm long. Fig. 1 Dipg= *Diplichnites gouldi*, Fig.2, 4 Mnl= *Monomorphichnus lineatus*, Fig.3 Dipcb= diplichniteform *Cruziana bonariensis*, Figs. 5, 7 Mnl= *Monomorphichnus lineatus*, Fig.6 Dio= *Dimorphichnus obliquus*

Plate 3 Ichnofossils from the Member-B (Dhaulagiri Formation, Upper Tal). Coin scale bar is 2.3 cm. Fig.1 Wi= Worm impression, Fig.2 Bp= *Bergaueria perata*, Fig.3 Pals= *Palaeophycus striatus*, Fig. 4Dc= *Diplocraterion* isp., Fig. 5 G= *Glockeria isp.*