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TREPTICHNUS ICHNOGENUS FROM THE CAMBRIAN OF INDIA AND BHUTAN: ITS RELEVANCE TO THE PRECAMBRIAN-CAMBRIAN BOUNDARY

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ABSTRACT

Treptichnus pedum and the *Treptichnus lublinensis* (first record from the Himalaya) are reported from the Cambrian successions of the Spiti Valley (Tethyan Himalaya) and the Nigali Dhar syncline (Lesser Himalaya) respectively. The paper also discusses morphological variation, palaeoenvironmental and stratigraphic significance of *Treptichnus* and revises the known occurrences of *Phycodes pedum* and/or *Treptichnus*, synonymous and analogous from the Cambrian of India and Bhutan. In the Himalaya, the record of *Treptichnus/Phycodes*, including the ichnospecies *Treptichnus pedum*, is from the Cambrian Series 2, Stage 4 to Furongian (Paibian) part, hence cannot be utilised for demarcating the Precambrian-Cambrian boundary in the Himalaya. The late appearance of *Treptichnus* ichnogenus in the Cambrian of the Indian Himalaya is attributed to higher latitudinal position of India during the Early Cambrian. As a result, possibly the *Treptichnus* producing organism, i.e. priapulid worms emerged in the latter part of the Cambrian Series 2, Stage 4 in both the regions.

Keyword: *Treptichnus pedum*, *Treptichnus lublinensis*, Lesser Himalaya, Tethyan Himalaya, Precambrian-Cambrian transition, palaeoecological – paleoenvironmental significance

INTRODUCTION

A spreite bearing complex zigzag burrow system, first described under the name *Phycodes pedum* Seilacher 1955, has been variously renamed either as *Treptichnus pedum* (Jensen and Grant, 1992; Jensen, 1997), *Trichophycus pedum* (Geyer and Uchman 1995), or *Manykodes pedum* (Dzik, 2005) as summarized below.

Seilacher (1955) first described a complex burrow system as *Phycodes pedum* from the *Neobolus* beds (Cambrian of Salt Range), Pakistan.

Jensen and Grant (1992) described *Treptichnus pedum (Phycodes pedum*) as having shorter, more closely set, curved segments, and a less ordered arrangement of segments. They stated that the *P. pedum* does share some important common features with the ichnogenus *Treptichnus*-like branches added distally. They proposed transferring of *P. pedum* Seilacher, 1955 to *Treptichnus pedum* (Seilacher, 1955).

Geyer and Uchman (1995) described *Trichophycus pedum* as an ichnospecies having horizontal axis of trace forming a winding or looping stem-like axis cylinder, and lateral probes consisting of curving, teichichnoid, arcuate, bent structures which are arranged obliquely and concordantly inclined; probes usually grouped along convex side of axis cyclinder, burrow system branched or unbranched. These authors disagreed with Jensen and Grant (1992) and stated that *Treptichnus* is more regular and symmetric and a permanently open burrow-systems that lacks reworking; it includes solitary simple structure, consisting of regular and more-or-less symmetrical segments, which are part of a permanently open burrow-system. These authors placed *Phycodes pedum* Seilacher 1955 under *Trichophycus pedum*.

Jensen (1997) opined that it is hard to decide whether burrow is open or back-filled and maintained the assignment of *Phycodes pedum* to *Treptichnus pedum*.

Dzik (2005) established a new genus *Manykodes* selecting *Treptichnus rectangularis* Orlowski and Zylinska, 1996 as a type species from the basal Cambrian Holy Cross Mountains and defined as "probable priapulid worms burrowing series of cylindrical empty chambers in mud with walls strengthened with mucus; the burrowing started laterally from the preceding chamber to give a more or less regular zigzag pattern". He grouped the *Phycodes pedum* Seilacher, 1955 under *Manykodes pedum* (Seilacher, 1955).

Landing *et al.* (2013) and Geyer and Landing (2016) proposed that a *Treptichnus pedum* ichnozone Assemblage, not an FAD, best defines the base of Cambrian GSSP (Narbonne *et al.,* 1987; Landing *et al.,* 1988; Narbonne and Myrow, 1988). Geyer and Landing (2016) also stated that coining of various names depended on the interpretation of the mode of formation of this ichnofossil.

The detailed description and morphological features of each synonymous ichnotaxa are different; we are, therefore, tempted to surmise that it is not necessary to disturb the status quo of *Phycodes pedum* Seilacher 1955 and instead of placing it under various controversial ichnogenra, several varieties of *Phycodes pedum* could be erected. However, till some unanimous decision is arrived at, we have adopted *Treptichnus* in this paper.

Treptichnus "turned-trail (Greek) of feet (Latin)" is a 3D burrow system (Archer and Maples, 1984; Maples and Archer, 1987) known from the latest Neoproterozoic? (Bank, 1970; Jensen *et al.,* 2000) to Eocene sediments (Crimes *et al.,* 1981; Uchman *et al.,* 2014). Treptichnid-like burrows are also known from the latest Ediacaran trace fossil zone (Jensen, 2003). The Global Standard Stratotype Section and Point (GSSP) for the Precambrian-Cambrian boundary is marked on the basis of the FAD of the *Treptichnus pedum* (earlier described as *Phycodes pedum*) at the base of the *Treptichnus pedum* assemblage Zone of the Fortunian Stage (Terreneuvian Series) of the Cambrian

System (Narbonne *et al.,* 1987; Braiser *et al.,* 1994; Landing, 1994, Peng *et al.,* 2012; Landing *et al.,* 2013; Geyer and Landing, 2016). Gehling *et al.* (2001) recorded *T. pedum* 4.1 m below the marked base of the *Treptichnus pedum* Zone. Consequently, Landing *et al.,* (2013) suggested that the Precambrian-Cambrian boundary be demarcated above the "highest Ediacaran-type fossils" and below the first appearance datum of *T. pedum.* More recently, Babcock *et al.* (2014) proposed a reassessment of the Cambrian GSSP due to wide variation in appearance of *T. pedum* at the Precambrian-Cambrian interval in several continents. Babcock *et al.* (2014) and Walde *et al.* (2015) suggested a revision of the Cambrian GSSP, with a change of the GSSP definition, point and horizon (see also Clausen *et al.,* 2015). Geyer and Landing (2016) suggested "despite arguments for a revision and redefinition of the lower boundary of the Cambrian System, the best definition of the basal Cambrian GSSP is at Fortune Head and does not rely on the *Treptichnus*/*Trichophycus pedum* (abbreviated below as *T. pedum*) first appearance datum, but rather on the base of the *T. pedum* Assemblage Zone at the highest occurrence of Ediacaran taxa and in the lower range of *T. pedum*". Therefore, still *Treptichnus pedum* remains the most important ichnofossil to demarcate the basal part of the Cambrian system.

In the Himalayan Cambrian successions, the FAD of *Treptichnus pedum* (described as *Phycodes pedum* in most pre-2010 publications) and its range is not well constrained. Various records of the occurrences of *Phycodes* Richter 1850 and *Treptichnus* Miller 1889 have been intermingled. Several published articles record *Phycodes* (*Treptichnus*) *pedum* but many specimens lack characteristic features necessary to assign to this ichnospecies. In some publications, though the generic assignment is correct, the specific characters have not been minutely studied and all the specimens have been dumped with *Treptichnus pedum* (Srivastava, 2012). *Treptichnus* ichnogenus and its species *Treptichnus pedum* and *Treptichnusi sp.,* have been used to delineate the base of the Terreneuvian Series of the Cambrian or the base of the Lower Cambrian (Kumar *et al.,* 1984; Parcha, 1998; Tangri *et al.,* 2003; Parcha and Pandey, 2011; Pandey *et al.,* 2014), though these occurrences are well within the trilobite zones and much above the Precambrian-Cambrian boundary (Jell and Hughes, 1997; Peng *et al.,* 2009; Singh *et al.,* 2016a, 2016b; Hughes, 2016). Moreover, the validity of many of the specimens described as *Treptichnus* and/or *Phycodes pedum* is questionable (Hughes *et al*., 2005, 2013; Singh *et al*., 2014), hence are revised herein.

So far, the *Treptichnus pedum* has not been recorded from the Precambrian-Cambrian boundary interval from the Himalaya. It could be due to inadequate search, lack of suitable facies and some other reason discussed in sequel. In this paper we describe well preserved specimens of *Treptichnus pedum* (Seilacher, 1955) from the Cambrian succession of the Spiti region (Tethyan Himalaya) and *Treptichnus lublinensis* Paczesna 1986, from the Tal Group (Fig.1) of the Nigali Dhar syncline (Lesser Himalaya), being the first record from the Himalaya. We also revise the previously known occurrences of *Treptichnus (Phycodes) pedum,* synonymous and analogous from the Indian plate (except the Salt Range) to evaluate the utility, particularly, of *Treptichnus pedum* for demarcating the Precambrian-Cambrian boundary in the Himalaya.

GEOLOGICAL SETTING

The Cambrian rocks in the Himalaya occur in the Tethyan and Lesser Himalayan litho-tectonic zones. In the Tethyan Himalayan Zone (THZ), the Cambrian rocks are well exposed in Kashmir, Zanskar-Spiti, Kinnaur, Kumaun-Garhwal and Bhutan regions (Fig.1a). In the Lesser Himalaya Zone (LHZ), the Cambrian rocks occur in the cores of NW-SE trending Nigali Dhar, Korgai, Mussoorie and Garhwal synclines of the Inner Krol Belt (IKB) and possibly in Nainital syncline and Nepal (Fig.1a). The THZ and IKB are widely separated by the Greater Himalayan Zone (GHZ). The present work is confined to the Nigali Dhar syncline (LHZ) and the Spiti Valley (THZ).

In the Spiti Valley, the Cambrian rocks, grouped under the Kunzam La (=Parahio) Formation (Haimanta Group) (Fig.1a, d), are well exposed along the Upper Spiti (Kunzam La-Takche track), Chandra Tal and Pin-Parahio valleys. In the Spiti region, the Cambrian rocks yielded abundant trace fossils (Bhargava *et al.,* 1982, 1986; Parcha and Pandey, 2011; Sudan *et al.,* 2000; Sudan and Sharma, 2001; Virmani and Singh, 2013, Hughes *et al.,* 2013); brachiopod and trilobites (Hayden, 1904; Reed, 1910; Shah and Paul, 1987; Jell and Hughes, 1997; Peng *et al.,* 2009; Singh *et al.,* 2014, 2015, 2016a, 2016b) of the Early-Middle Cambrian age. *Treptichnus pedum* (*Phycodes pedum*) is described from the Kunzam La Formation (Sudan and Sharma, 2001). The exposed basal rocks of the Kunzam La Formation in the Parahio Valley containing *Diplichnites* traces of Cambrian affinity (Bhargava *et al.,* 1982) belong to definite Cambrian Series 2, Stage 4 (Hughes *et al.,* 2013; Singh *et al.,* 2014; 2015). Presently, two specimens of the *Treptichnus pedum* (Fig. 2 C, D) collected from the Cambrian Kunzam La (=Parahio) Formation of the Parahio Valley are illustrated and described.

In the Nigali Dhar Syncline, the Cambrian rocks of the Tal Group, divisible into Shaliyan, Sankholi and Koti-Dhaman formations (Bhargava, 1976) (Fig. 1c, e), are well exposed at Pritari-Dochhi and Ganog localities, and along the Koti-Dhaman road sections. The trace fossils (Bhargava, 1984; De *et al.,* 1994; Bhargava *et al.,* 1998; Desai *et al.,* 2010; Singh *et al.,* 2015); early Cambrian trilobite (Bhargava *et al.,* 1998; Hughes *et al.,* 2005, Singh *et al.,* 2015, *under review*) from the middle part and the Ediacaran body fossil from the basal part of the Tal Group (Tarhan *et al.,* 2014, Sharma *et al.,* 2015) are known from the Nigali Dhar Syncline. Record of *Phycodes pedum* from the Nigali Dhar Syncline by De et *al.*,(1994) has been questioned by Hughes *et al.,* (2005). Trilobites of *Drepanopyge gopeni* level of the Cambrian Series 2 (Hughes *et al.,* 2005, Singh *et al.,* 2015; Hughes, 2016) are known from the upper part of the Sankholi Formation and *Redlichia noetlingi* Zone is known from the basal part of the Koti-Dhaman Formation.

In the present paper, *Treptichnus lublinensis* (Fig. 2A-B) is recorded from the Sankholi Formation, 98 m below the *Drepanopyge gopeni* level, which is much above the Precambrian-Cambrian boundary succession.

SYSTEMATIC DESCRIPTION

Treptichnus taxonomy is primarily based on the morphological variation of the general course (first order) and basic segments of the structures (second order) (cf. Buatois and Mángano, 1993; Uchman, 1998; Geyer and Uchman, 1995). The generic concept of Buatois and Mángano, (1993) and Jensen and Grant, 1992; Jensen, 1997; Geyer and Uchman (1995) is

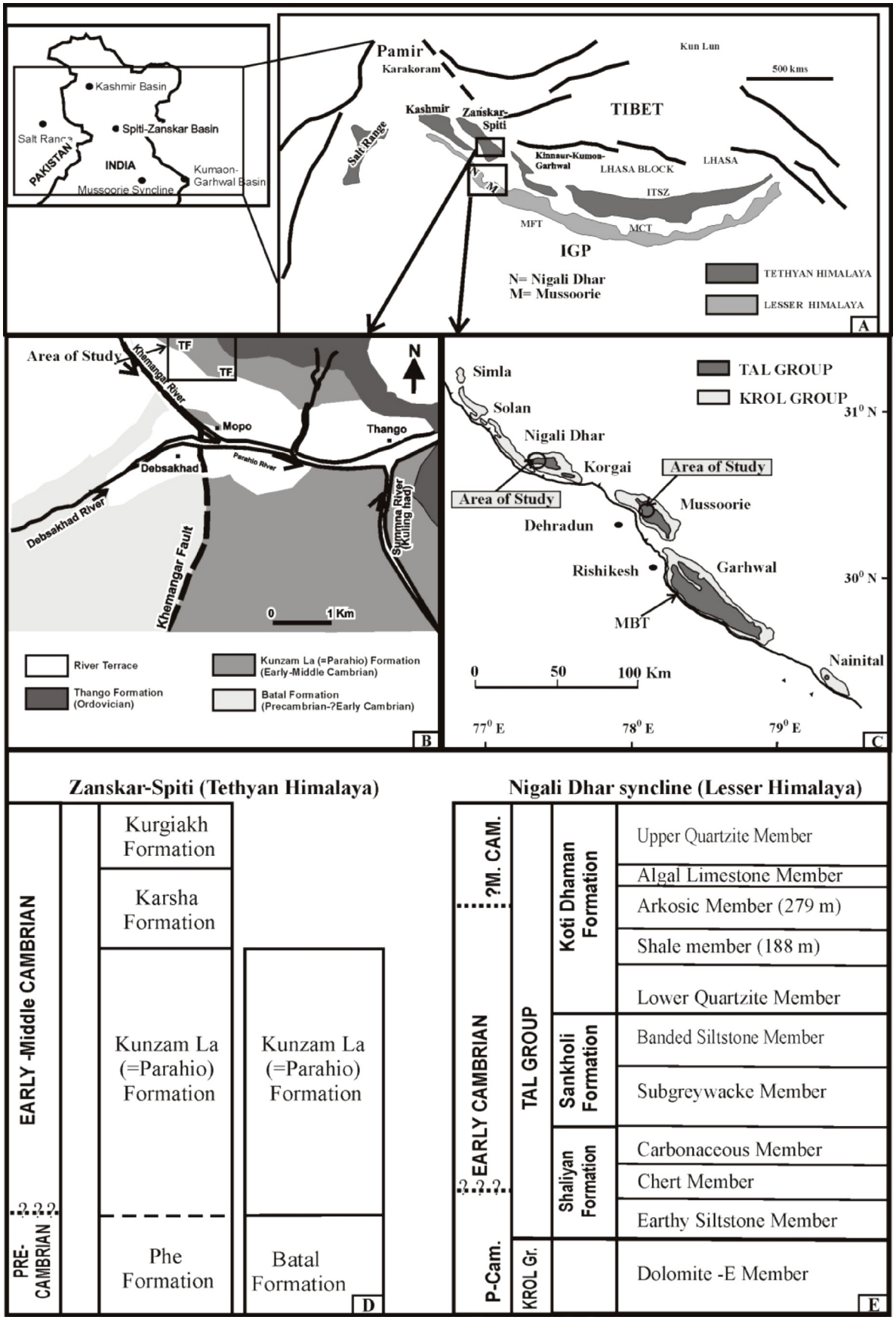


Fig.1. Location (A), geological maps (B, C) and Lithostratigraphic classifications (D, E) of Cambrian rocks of the Zanskar-Spiti (Tethyan Himalayan Zone) and the Nigali Dhar syncline (Lesser Himalayan Zone).

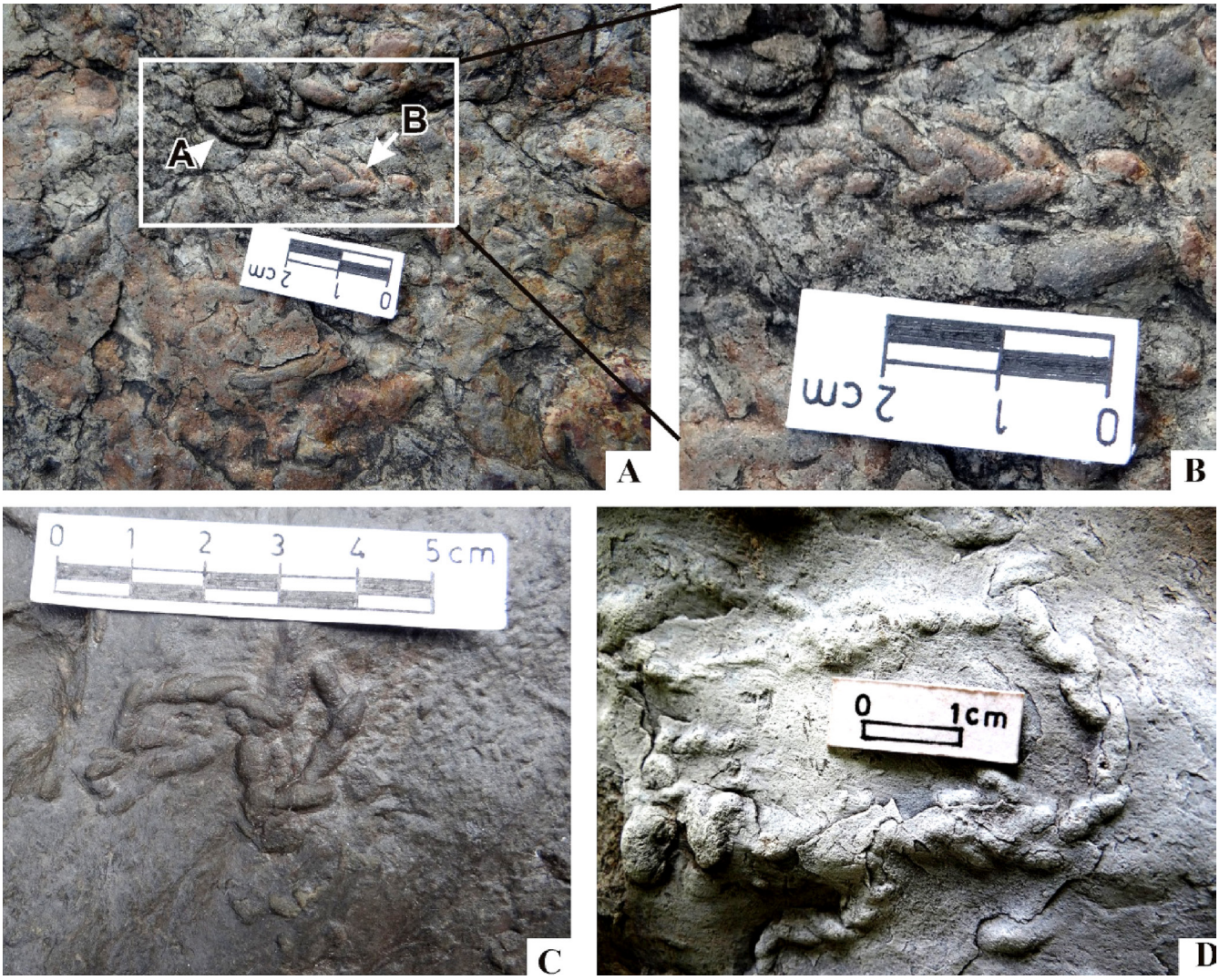


Fig. 2. (A). *Treptichnus lublinensis* from the Sankholi Formation (Tal Group), Nigali Dhar syncline; and (B) Enlarge view of *Treptichnus lublinensis*; (C) *Treptichnus pedum* from the Parahio Valley along the upstream of Khemangar Khad near the locality Kaltarbo. The specimen was collected 76 m below the *Oryctocephalus indicus* bearing beds of the Cambrian Series 3, Stage 5; (D) *Treptichnus pedum* from the Parahio Valley section (Spiti) and collected 30 m below the *Yuehisienszella* bearing beds (Singh, et al.,, 2014) of the Cambrian Series 2, Stage 4.

followed here.

Ichnogenus ***Treptichnus*** Miller, 1889

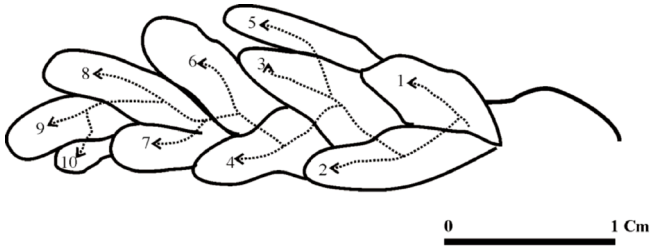
(Type ichnospecies: *Treptichnus bifurcus* Miller, 1889, p.581, fig.1095)

Treptichnus pedum (Seilacher, 1955)
(Figs. 2. C-D)

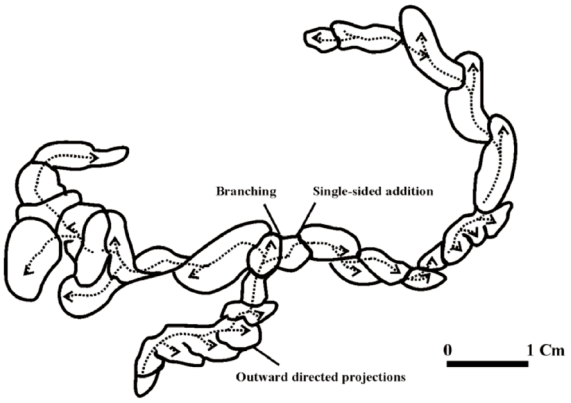
Descriptions: Preserved as a hyporelief structure, it consists of rows of smooth, unornamented, small curved burrows, joining each other at low angles and intersecting to form projections and also showing single-sided addition (Figs. 2.C-D, 3.B-C). Burrow path is winding, looping, and in part straight where single-sided additions exist. A zigzag pattern is partially developed (Figs. 2. C-D). Length of segments varies from 2-5 millimeters (Fig. 2.C) and 2-4 millimeters (Fig. 2.D).

Remarks: *Treptichnus* is interpreted as a systematic feeding structure with each segment reaching up to the sediment surface (Seilacher and Hemleben, 1966; Jensen, 1997). *Treptichnus* is mainly known from the Early Cambrian successions of Yunnan (Zhu, 1997), Mickwitzia sandstone, Sweden (Jensen, 1997), Chapel Island Formation, Newfoundland (Gehling *et al.,* 2001), Wulongqing Formation, China (Weber *et al.,* 2012) and Late Precambrian-Middle Cambrian Pele La Group exposed in the Tang Chu-Wachi La sector of the Bhutan Himalaya (Tangri *et al.,* 2003).

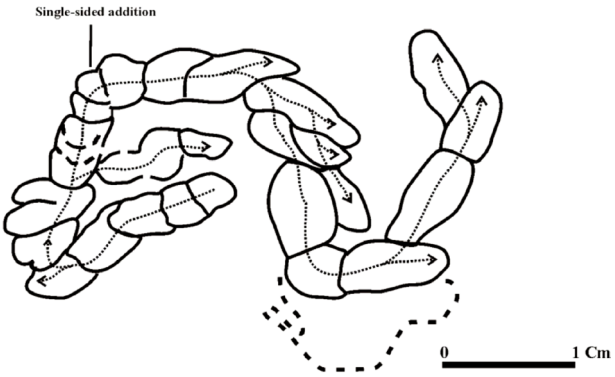
Our specimen (Fig. 2D) occurs 30 m below the *Yuehisienszella*- bearing beds of the Kunzam La (Parahio) Formation, Cambrian Series 2, Stage 4 (Singh *et al.,* 2014). Below the *T. pedum* bearing level, 97 m of the Kunzam La (=Parahio) Formation is exposed in the Parahio Valley, which contains trace, fossils e.g. *Diplichnites*, *Monomorphichnus* and *Dimorphichnus* of Palaeozoic affinity (Virmani and Singh, 2013; Virmani *et al.,* 2013; Hughes *et al.,* 2013). The Precambrian-Cambrian boundary interval could not be recognised in the Parahio Valley (Hayden, 1904), where the lowest occurrence of the *Treptichnus pedum* falls in the Cambrian Series 2, Stage 4. Another specimen (Fig. 2C) was collected 76 m below the *Oryctocephalus indicus* bearing beds of the Cambrian Series 3,



(A) *Treptichnus lublinensis* "feather-stitch trail"



(B) *Treptichnus pedum* (=*Trichophycus pedum*)



(C) *Treptichnus pedum* (=*Trichophycus pedum*)

Fig.3. (A, B, C) Drawings of *Treptichnus* specimens showing the morphological variation and nature of movement of trace maker

Stage 5 (Singh *et al.,* 2016). The recorded *Treptichnus pedum* hence is not older than Cambrian Series 2, Stage 4.

Treptichnus lublinensis Paczesna, 1986
(Figs. 2. A, B)

Descriptions: Feeding structure, preserved as hyporelief, "*Feather-stitch trail*" dense arrangement of thick nine to ten segments, and irregular shape of diverging burrows (Figs. 2.A, B, 3A). The *Treptichnus* recorded from the Nigali Dhar syncline in morphology closely resembles *Treptichnus lublinensis* recorded from the Poland (Paczesna, 1986). However, our specimen differs in showing the "feather-stitch trail" pattern of Seilacher (1955) and Wilson (1948).

Remarks: Buatois and Mángano (1993) grouped this "feather-stitch trail" under *Treptichnus* ichnogenus. *T. lublinensis* differs from other *Treptichnus* ichnospecies by its tendency to meander and by irregular shape of diverging burrows and their dense arrangement relative to long axis of the trace (Paczesna, 1986). In our specimen, meandering is not observed, however, the diverging burrows are densely arranged and are irregular in shape (Fig. 2A). According to Buatois and Mángano (1993), "feather-stitch trail" described by Seilacher and Hemleben (1966) probably belongs to another ichnospecies of *Treptichnus,* in which regular pattern of diverging segments is recognised. Our specimen does not exhibit the regular pattern and closely resembles *T. lublinensis* described from the Poland (Paczesna, 1986). The present specimen stratigraphically lies below the *Drepanopyge gopeni* trilobite level (Cambrian Series 2, Stage 4).

OCCURRENCES OF *TREPTICHNUS* (*PHYCODES*) *PEDUM*, SYNONYMOUS AND ANALOGOUS FROM THE INDIAN PLATE

The published occurrences of *Treptichnus pedum*, synonymous and analogous from the Cambrian successions of the Indian plate (excluding Salt Range) are listed in Table 1. A comparative account of respective stratigraphic positions is plotted in Fig.4.

Kashmir: Shah and Sudan (1983) described *Phycodes pedum* (p. 196, pl. II. f), *Phycodes*? *antecedens* (p.196, pl. II. e) and *Phycodes palmatum* (p.196, pl. II. a, b, c, d) from the Nutunus Formation (Middle Cambrian). The specimen described as *Phycodes pedum* (p.196, pl. II. F, Shah and Sudan, 1983) shows broad morphological characters of the *Treptichnus*; however, the critical features like small curved burrows, joining each other at low angles and intersecting to form projections and also showing single-sided addition necessary to assign *Treptichnus pedum* are not well preserved in the figured specimen. The specimens described as *Phycodes*? *antecedens* (p.196, pl. II. e) and *Phycodes palmatum* (p.196, pl. II. a, b, c, d) are straight to slightly curved, bedding-parallel burrows with sediment fillings similar to surrounding material are more akin to the ichnogenus *Paleophycus* (cf. Weber *et al.,* 2012).

Zanskar: Parcha (1998) described five specimens as *Phycodes pedum* and two of *Phycodes palmatum* from the Kurgiakh Formation (Middle Cambrian). The specimen figured (p. 639, pl.1, fig. 5) shows poorly preserved short curved chain of probes and in morphology resembles *Trichophycus pedum* described from the Nama Group (Geyer and Uchman, 1995). The other specimens illustrated by Parcha (1998, pl. 2, fig. 2; p. 640 and pl. 3 fig. 2, p. 641) are beaded chain-like structure consisting of longitudinally flattened nodes with slightly irregular surface faintly preserved on the bedding plane. Both the figures (p. 640, pl.2, fig. 2; p. 641, pl. 3, fig.2) seem to be of the same specimen photographed from different angles.These structures closely resemble *Teichichnus nodosus* (cf. Fillion and Pickerill, 1990). Still another specimen (Parcha, 1998, p.640, pl.2, fig.3) shows talon-like structure which shows a gently sloping proximal tube with radially arranged cylindrical branches. Morphologically, it resembles, *Phycodes ungulatus* (cf. Fillion and Pickerill, 1990). Another specimen illustrated by Parcha (1998, pl.2, fig.4, p. 640, Parcha, 1998) shows dense assemblage of horizontal cylinders

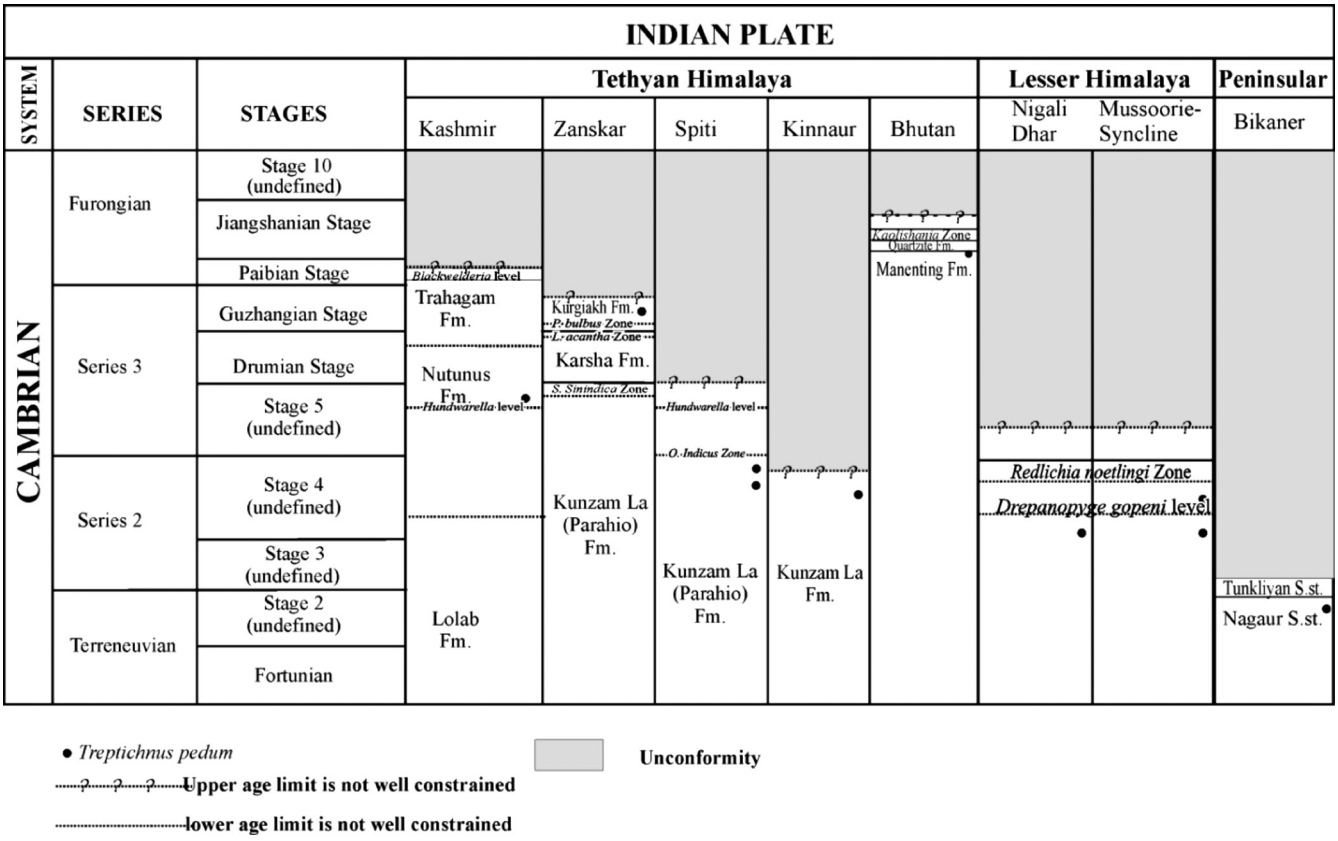


Fig.4. Distribution of *Treptichnus pedum* in the Cambrian strata of Kashmir, Zanskar, Spiti, Kinnaur and Bhutan (Tethyan Himalayan Zone), and Nigali Dhar, Mussoorie synclines (Lesser Himalayan Zone) and Bikaner (Peninsular India) sections of Indian Plate (except Salt Range).

without probe structures and seems to be ichnogenus *Planolites* (cf. Fillion and Pickerill, 1990).

Parcha and Singh (2010) described two specimens as *Treptichnus pedum*. The specimen at p. 508; fig. 3.1 (Parcha and Singh, 2010) is preserved as full-relief burrow consisting of a horizontal, cylindrical, stem-like axis that winds or loops, with lateral probes, and is associated with abundant *Planolites*. The burrows closely resemble *Phycodes palmatum* in their many branching galleries from one gallery and turning up near the aperture (Singh, 2009a), hence more appropriately should be grouped under *Phycodes palmatum*. Another specimen described as *Treptichnus pedum* (Parcha and Singh, 2010, p.512, fig. 4.12) was previously described as *Planolites* (Parcha, 1998, p. 639, pl. 1, fig.4); it is reassigned here to *Planolites*.

Spiti: Bhargava and Bassi (1988) described one specimen as *Phycodes pedum* (p. 230, pl-1, fig. 8) from the Thango Formation (Parahio Valley). The specimen closely resembles, in morphology, *Phycodes ungulates* (Fillion and Pickerill, 1990) in talon-like structure, in which a gently sloping proximal tube is arranged with radially cylindrical branches off (cf. Fillion and Pickerill, 1990).

Sudan and Sharma (2001) described a single specimen as *Treptichnus pedum* (p.165-166, pl.1, fig. h) from the Kunzam La section of the Spiti region. The specimen having twig-like projections at the angle of juncture between elongated, horizontal and thin burrow segments closely resembles *T. bifurcus* Miller, 1889.

Parcha and Pandey (2011) described two specimens as *Treptichnus* isp., (p. 1101, figs. 4E and Gb) from the Kunzam La Formation (Parahio Valley) and compared these with the *Treptichnus aequalternus* (Schlirf, 2000). *T. aequalternus* bears treptichnid characters more or less similar to *T. pollardi,* which are not present in the specimens illustrated by Parcha and Pandey (2011). Hughes *et al.* (2013) have also cast doubt on the identification of ichnogenus *Treptichnus* by Parcha and Pandey (2011). In our opinion, both figured specimens show slightly curved, regularly alternating set of burrows and resemble *Paleophycus*-type trace (cf. Weber *et al*., 2012).

Kinnaur: Bhargava and Bassi (1988) described one specimen as *Phycodes pedum* (p. 230, pl-1, figs. 5), now reassigned herein as *Treptichnus pedum*, from the Kunzam La (=Parahio) Formation exposed one kilometer west of Kiarkoti, Chorgad Valley in Kinnaur (SE extension of the Spiti region). The preserved specimen shows sausage-shaped subparallel branches aligned in one direction from the main burrow. However, the specimen is somewhat larger in size and shape.

Nigali Dhar syncline: De *et al.* (1994) described one specimen as *Phycodes* sp. (p. 82, pl.2, fig. 1) from the Tal Group of the Nigali Dhar syncline. Hughes *et al.* (2005) questioned its validity. The specimen shows straight to curved, sand infilled, horizontal, crowded, overlapping burrow tubes without ornamentation. The specimen neither shows the critical feature of *Treptichnus pedum* and nor of the ichnogenera *Treptichnus* and *Phycodes*; it closely resembles *Paleophycus*-type traces (cf. Weber *et al.,* 2012), hence grouped under *Paleophycus*.

Desai *et al.* (2010) reported *Phycodes cf. circinatus*, *Phycodes curvipalmatum*, *Phycodes palmatus*, *Streptichnus* isp., and ?*Treptichnus pedum* from the Tal Group of rocks. The figured specimen (Desai *et al*., 2010,p. 241, fig. 4G)

Table: 1. Literature compilation and revision of previously described *Treptichnus*, synonymous and analogous structures (likely synonymous or otherwise allied, on the basis of shared morphological characters)

Author	Trace fossil	Figure No.	Formation / Age / Area	Revised in present work
Singh and Rai, 1983	*Phycodes* Richter, 1850	Pl-IV, 31	Tal Group/ Early Cambrian/ Mussoorie syncline (Lesser Himalaya)	*Phycodes* Richter, 1850
Shah and Sudan, 1983	*Phycodes pedum*	P.II.f	Nutunus Fm./ Middle Cambrian/ Kashmir Basin (Tethyan Himalaya)	*Treptichnus pedum*
	Phycodes?antecedens Webby, 1970	P. II. e	Nutunus Fm./ Middle Cambrian/ Kashmir Basin (Tethyan Himalaya)	*Paleophycus* (cf. Webber et al., 2012)
	Phycodes palmatum (Hall)	P. II, a-d	Nutunus Fm./ Middle Cambrian/ Kashmir Basin (Tethyan Himalaya)	*Paleophycus* (cf. Webber et al., 2012)
Bhargava and Bassi (1988)	*Phycodes pedum*	Pl. 1, Fig. 5	Kunzam La Fm. / Early Cambrian, Kinnaur region (Tethyan Himalaya)	*Treptichnus pedum*
Bhargava and Bassi (1988)	*Phycodes pedum*	Pl. 1, Fig. 8	Thango Formation, Spiti (Tethyan Himalaya)	*Phycodes ungulatus* (cf. Fillion & Pickerill, 1990)
De *et al.* (1994)	*Phycodes isp.*	Pl. 2, Fig. 1	Tal Group / Cambrian/ Nigali Dhar syncline (Lesser Himalaya)	*Palaeophycus*-type traces (cf. Weber et al., 2012)
Shah et al., 1998	*Phycodes palmatum*	Pl-1, b, e	Cambrian of Zanskar region (Tethyan Himalaya)	*Phycodes palmatum*
Parcha (1998)	*Phycodes pedum*	Pl. 1, Fig. 5	Kurgiakh Fm. /Middle Cambrian/ Zanskar region (Tethyan Himalaya)	? *Treptichnus pedum*
	Phycodes palmatum	Pl. 2, Fig. 1	Kurgiakh Fm. /Middle Cambrian/ Zanskar region (Tethyan Himalaya)	*Phycodes palmatum*
	Phycodes pedum	Pl. 2, Figs. 2	Kurgiakh Fm. /Middle Cambrian/ Zanskar region (Tethyan Himalaya)	*Teichichnus nodosus* (cf. Fillion & Pickerill, 1990)
	Phycodes pedum	Pl. 2, Figs. 3	Kurgiakh Fm. /Middle Cambrian/ Zanskar region (Tethyan Himalaya)	*Phycodes ungulatus* (cf. Fillion & Pickerill, 1990)
	Phycodes pedum	Pl. 2, Figs. 4	Kurgiakh Fm. /Middle Cambrian/ Zanskar region (Tethyan Himalaya)	*Planolites*
	Phycodes palmatum	Pl.2, Fig.5	Kurgiakh Fm. /Middle Cambrian/ Zanskar region (Tethyan Himalaya)	*Planolites*
	Phycodes pedum	Pl. 3, Fig. 2	Kurgiakh Fm. /Middle Cambrian/ Zanskar region (Tethyan Himalaya)	*Teichichnus nodosus* (cf. Fillion & Pickerill, 1990)
Sudan and Sharma (2001)	*Treptichnus pedum*	Pl. 1, Fig. h	Kunzam *La* Fm./ Lower Cambrian , Spiti (Tethyan Himalaya)	*Treptichnus bifurcus* Miller, 1889
		Pl. 1, Fig. i	Kunzam *La* Fm./ Lower Cambrian, Spiti (Tethyan Himalaya)	*?Treptichnus pedum*
Tangri *et al.* (2003)	*Phycodes pedum*	Pl. 1, Fig. 3	Manenting Fm./ Lower Cambrian Bhutan (Tethyan Himalaya)	*Treptichnus pedum*
Parcha and Singh (2010)	*Treptichnus pedum*	Fig. 3.1	Cambrian, Zanskar region (Tethyan Himalaya)	*Phycodes palmatum*
	Treptichnus pedum	Fig. 4.12	Cambrian, Zanskar region (Tethyan Himalaya)	*Planolites*
Desai et al., (2010)	*Phycodes* cf. *circinatus*	Fig. 3J	Sankholi Formation / Lower Cambrian, Nigali Dhar syncline (Lesser Himalaya)	*?Phycodes isp.*
	Phycodes curvipalmatum	Fig.3,K,L	Sankholi & Koti Dhaman formations / Lower Cambrian, Nigali Dhar syncline (Lesser Himalaya)	*Phycodes curvipalmatum*
	Phycodes palmatus	Fig.3.I	Sankholi Formation / Lower Cambrian, Nigali Dhar syncline (Lesser Himalaya)	*Phycodes palmatus*
	Streptichnus isp.,	Fig.4. F	Sankholi Formation / Lower Cambrian, Nigali Dhar syncline (Lesser Himalaya)	*? Streptichnus* isp.,
	?Treptichnus pedum	Fig.4.G	Sankholi Formation / Lower Cambrian, Nigali Dhar syncline (Lesser Himalaya)	*Treptichnus pedum* (cf. Geyer & Uchman, 1995)
Parcha and Pandey (2011)	*Treptichnus isp.*	Fig. 4, E	Kunzam La Fm./ Lower Cambrian, Spiti (Tethyan Himalaya)	*Palaeophycus*-type traces (cf. Weber et al., 2012)
	Treptichnus isp.	Fig. 4, Gb	Kunzam La Fm. / Lower Cambrian, Spiti (Tethyan Himalaya)	*Palaeophycus*-type traces (cf. Weber et al., 2012)
Srivastava (2012)	*Treptichnus pedum*	Fig.3-c,	Nagaur Sandstone/ Lower Cambrian, Bikaner-Nagaur Basin (Rajasthan)	*Treptichnus* isp.
	Treptichnus pedum	Fig.3-e,	Nagaur Sandstone/ Lower Cambrian, Bikaner-Nagaur Basin (Rajasthan)	*T. bifurcus*
	Treptichnus pedum	Fig.3-f	Nagaur Sandstone/ Lower Cambrian, Bikaner-Nagaur Basin (Rajasthan)	*Treptichnus pedum*
	Treptichnus pedum	Fig.3-h	Nagaur Sandstone/ Lower Cambrian, Bikaner-Nagaur Basin (Rajasthan)	*T. bifurcus*
	Treptichnus pedum	Fig.3-i	Nagaur Sandstone / Lower Cambrian, Bikaner-Nagaur Basin (Rajasthan)	*T. bifurcus*
Tewari et al., 2013	*Treptichnus isp.*	Fig.3.f	Dhaulagiri Formation / Early Cambrian / Mussoorie syncline (Lesser Himalaya)	*Treptichnus cf. bifurcus*
Singh *et al.* (2014)	*Treptichnus* cf. *T. pedum*	Pl. 1, Fig. 1	Dhaulagiri Formation / Early Cambrian, Mussoorie syncline (Lesser Himalaya)	*Treptichnus* cf. *T. pedum*
Pandey *et al.* (2014)	*Treptichnus pedum*	Figs. 4(D), 6(A-D)	Nagaur Sandstone / Lower Cambrian, Bikaner-Nagaur Basin (Rajasthan)	*Treptichnus pedum*

as ?*Treptichnus pedum* closely resembles, in morphology, *Trichophycus* (*Phycodes*) *pedum* described from the Nama Group (Geyer and Uchman, 1995), while the identification of *Phycodes* cf. *circinatus* is suspect.

Mussoorie syncline: Singh and Rai (1983) described one specimen as *Phycodes* isp. (p. 31, pl-IV) from the Arenaceous Member of the Tal Group, Mussoorie syncline. Geyer and Uchman (1995) grouped this under the *Trichophycus pedum*. The specimen closely resembles the ichnogenus *Phycodes* in morphological parameter.

Tewari *et al.* (2013) described one specimen as *Treptichnus* isp. (p. 1470, fig. 3f) from the Dhaulagiri Formation of the Tal Group, Mussoorie syncline. The specimen closely resembles *T. bifurcus* in morphological features as having short twig-like projections at the angle of junction between segments. The figured specimen (p. 1470, fig. 3f) shows the middle plane view of the *T. bifurcus* (cf. Buatois and Mángano, 1993,p. 219, fig. 2).

More recently, Singh *et al.* (2014) described one specimen of *Treptichnus* cf. *T.pedum* (pp.385 &391, pl-1, fig.1Tt) from the

Dhaulagiri Formation (Tal Group) of Mussoorie syncline. The specimen consists of a main horizontal undulatory burrow with three to four probes as a single-sided addition. The morphological characteristics of the specimen fits within the range of forms currently included in the *T. pedum* (Buatois and Mángano, 1993; Geyer and Uchman, 1995; Jensen, 1997), though, the typical zigzag pattern of *Treptichnus pedum* is lacking.

Bikaner: Srivastava (2012) recorded *Treptichnus pedum* from the Nagaur Sandstone Formation (p. 166, figs. 3.c, e, f, h, i) of the Bikaner-Nagaur Basin and correlated the horizon with the Ediacaran-Cambrian boundary interval. Out of five figured specimens, three of them (figs. 3. e, h, i) show twig-like projections at the angle of junction between segments and are presently grouped under the *T. bifurcus.* One figured specimen (p. 166, fig. 3f) resembles *T. pedum*. Another specimen (p. 166, fig. 3c) shows general character of *Treptichnus* ichnogenus, but lacks the typical character like small curved burrows, joining each other at low angles and intersecting to form projections and also showing single-sided addition of *Treptichnus pedum*.

Pandey *et al.,* (2014) described a few specimens of *Treptichnus pedum* (p.133, fig. 4D (Tp) and p. 135, fig. 6 (A-D) from the Cambrian Nagaur Sandstone (Nagaur Group), Bikaner. The specimens share critical morphological features with *Treptichnus pedum* (cf. Jensen, 1997; Geyer and Uchman, 1995). They stated that the *Treptichnus pedum* bearing beds of the Nagaur Sandstone (Nagaur Group) belong to *Cruziana tenella* ichnozone of Cambrian Stage 2 (upper part of Terreneuvian); however they did not exclude possibility of Middle Cambrian age.

Bhutan: *Treptichnus pedum* has been known from the Pele La Group exposed in the Tang Chu-Wachi La sector of the Bhutan Himalaya (Tangri *et al.,*2003). In Bhutan, *T. pedum* was recorded from the middle part of the Maneting Formation and used for delineation of the Precambrian-Cambrian boundary interval. *T. pedum* is preserved as hyporelief in the grey quartzarenite in association with *Didymaulichnus*, *Planolites* and *Arenicolites*. The observation on image of figured specimen (Tangri *et al.,* 2003, p. 712, pl.1, fig.3) shows typical pattern of *Trichophycus pedum* (cf. Geyer and Uchman, 1995).

PRECAMBRIAN-CAMBRIAN BOUNDARY INTERVAL AND *TREPTICHNUS* ICHNOGENUS

A glance at the distribution of *Treptichnus* ichnogenus (Fig. 4) in various sections of Indian plate (except Salt Range) reveals that its earliest appearance is recorded in the Cambrian Stage 2 (Terreneuvian Series) in the Nagaur Sandstone (Bikaner). Though recently Hughes, (2016) suggested the traces of Nagaur Sandstone belongs to late part of the Cambrian Series 2, Stage 4; however, we prefer to follow Pandey *et al.* (2014) and Singh *et al.,* (2014) and place them in Cambrian Stage 2.

The youngest occurrence of *Treptichnus pedum* in Himalaya is from the Maneting Formation (Bhutan) which is biostratigraphically dated as Jiangshanian of Furongian (Hughes *et al.,* 2010; Hughes, 2016). However, Tangri *et al.* (2003) demarcated the Precambrian-Cambrian boundary within the Maneting Formation based on the occurrence of *Cochlichnus* isp, *Helminthopsis* isp, *Gordia* isp and *T. pedum.* The base of the section in Bhutan, which yielded *T. pedum*, is not exposed along the Wachi La section, from which *Kaolishania* Zone (Furongian) is marked. The *Kaolishania* Zone of the Furongian (Hughes *et al.,* 2010) occurs much above the *T. pedum* level (Tangri *et al.,* 2003) and it is difficult to demarcate Precambrian-Cambrian boundary on its basis.

In Kashmir, the *T. pedum* is known from the Nutunus Formation (Shah and Sudan, 1983) which indicates range in age from Cambrian Series 2 (Stage 4) to upper part of the Cambrian Series 3 (Drumian Stage).

In Zanskar, the ?*T. pedum* (Parcha, 1998) is known from the Kurgiakh Formation which yielded trilobites of Guzhangian Stage of the Cambrian Series 3 (Whittington, 1986; Peng *et al.,*2009; Singh, 2011).

The presently recorded *T. pedum* from the Spiti Valley occurs below *Yuehsienszella*-bearing beds (Series 2, Stage 4) and below the *Oryctocephalus indicus* Zone of Cambrian Series 3, Stage 5 (Singh *et al*., 2014; 2015, 2016a), hence is not younger than Cambrian Series 2, Stage 4.

In Kinnaur, there is no body fossil control but stratigraphically, the position of *T. pedum* seems to be comparable with that of the Spiti.

In the Lesser Himalaya, the *T. pedum* is known from the level below the *Drepanopyge gopeni* level in the Mussoorie syncline and represents the Cambrian Series 2, Stage 4 (Singh *et al.,* 2014). *Treptichnus lublinensis* (in present work) is recorded below the *Drepanopyge gopeni* level of the Cambrian Series 2, Stage 4 in the Nigali Dhar syncline.

The above discussion makes it evident that both in the Tethyan and Lesser Himalaya, the record of *Treptichnus pedum* does not represent *Treptichnus pedum* Zone of Fortunian Stage, Terreneuvian Series (Cambrian). Thus, the recorded occurrences of *T. pedum* in the Himalaya are not useful in demarcating the Precambrian-Cambrian boundary.The Precambrian-Cambrian boundary interval in both the lithotectonic zones requires further investigations for a precise biostratigraphic age constraint across this boundary.

It has been also propounded that the increase in the biological activity and diversification of the benthic fauna were diachronous in the wide geographical scale and commenced early in the continents lying in the lower latitude position (Takafuni *et al.,* 2014). The northern part of the Indian plate possibly occupied higher latitudinal position during the Early Cambrian as compared to the Chinese-Magnolian as a result the *Treptichnus* producing pirapulid worms appeared late, which accounts for the absence of *T. pedum* in the strata representing the basal Cambrian age in both the lithotectonic zones. The absence could also be due to lack of suitable lithofacies at Pc/C boundary level.

PALEOENVIRONMENTAL SIGNIFICANCE

Potential facies restriction and broad environmental tolerance and offset range of *Treptichnus pedum* has been discussed by Buatois *et al.* (2013) and Geyer and Uchman (1995). Absence or lack of record of *Treptichnus* at the Precambrian-Cambrian boundary interval in the Lesser and the Tethyan Himalayan tectonic zones seems to be related to the facies control as well as the ecological barrier (latitudinal position). Critical lithofacies analysis of the *T. pedum*-bearing level in the Parahio Valley section indicates low to moderate density of the *T. pedum* at the sole of the thickly bedded fine-grained sandstone of the Shale-Sandstone Facies (Virmani *et al.,* 2015) interpreted to represent moderate energy conditions in middle-lower shoreface environment. Myrow *et al.* (2006) interpreted the Kunzam La

(=Parahio) Formation deposition under storm-influenced deltaic setting which represents deposits of nearshore-shoreface to shoreface-offshore transitional settings. The litho-ichnofacies analysis of the equivalent rocks in the Zanskar region (NW extension of the Spiti region) revealed shoreface-offshore setting (Singh, 2009b). Our interpretation of *T. pedum* bearing strata at the Parahio Valley section indicates a middle-lower shoreface setting which falls under the environmental tolerance range of the *T. pedum* (cf. Buatois *et al.,* 2013).

Preservation of *T. lublinensis* at the sole of the bedded quartzite (Sankholi Formation, Tal Group, Lesser Himalaya) in association with abundant *Planolites* indicates burrowing by the opportunistic organism. The overlying sandstone beds preserve abundant vertical burrows and can be grouped under the *Skolithos* pipe rocks (cf. Droser, 1991). Critical facies analysis indicates that the interval in which the *T. lublinensis* is preserved shows high-energy condition of middle-shoreface deposit and is typified by the *Skolithos* ichnofabric and characterised by slightly higher ichnodiversity than the foreshore and upper shoreface deposits. The Tal Group preserves traces of the *Skolithos* and *Cruziana* ichnofacies (Singh *et al.,* 2014), which appears from the middle to top of the Sankholi Formation and also within the lower part of the Koti Dhaman Formation (Bhargava, 1984; Bhargava *et al.,* 1998; Singh *et al.,* 2014). The *Skolithos* ichnofacies dominantly occurs, while the *Cruziana* ichnofacies shows partial development and only restricted facies followed by storm events. The overall distribution of traces in the Tal Group is irregular and punctured, and traces do not abundantly occur, unlike those in the Cambrian Kunzam La (=Parahio) Formation, Spiti region. This may be due to low preservation potential owing to relatively high-energy environment in the Tal basin. The very low density of *Skolithos* and *Cruziana* ichnofacies are due to shallow-subtidal environment. It is also observed that partial development of the *Cruziana* ichnofacies reflects feeble and infrequent storm events. The low density of *Treptichnus* in the Tal Group reflects shallow-water environment affected by the high turbidity water, which leads to overall reduction of ichnodiversity in these deposit.

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