Asteriacites and other trace fossils from the Po Formation (Visean–Serpukhovian), Ganmachidam Hill, Spiti Valley (Himalaya) and its paleoenvironmental significance

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(Manuscript received November 16, 2016; accepted in revised form June 9, 2017)

Abstract: An assemblage of trace fossils comprising *Asteriacites stelliformis*, *A. quinquefolius*, *Biformites insolitus*, *Helminthoidichnites*? isp., *Lingulichnus* isp., *Lockeia siliquaria*, *Palaeophycus tubularis*, *Planolites* isp., *Protovirgularia* isp. A, *Protovirgularia* isp. B, *Protovirgularia* isp. C, *Psammichnites* isp., *Rusophycus* isp., and *Treptichnus* isp. from the Po Formation (Visean–Serpukhovian) exposed along the base of Ganmachidam Hill near the village of Chichong, Spiti Valley in the Himalaya, is described. Storm beds (tempestites) are highly bioturbated. Sedimentary structures such as hummocky cross-stratification (HCS), low-angle planar and trough cross beds, and shallow, slightly asymmetrical gutter casts are observed. The overall trace fossil assemblage indicates the presence of upper shoreface to lower shoreface *Cruziana* ichnofacies of an open shelf.

Keywords: Po Formation, Visean–Serpukhovian, Spiti, Trace fossils, *Cruziana* ichnofacies.

Introduction

The trace fossil assemblage reported here derives from the Po Formation (Visean–Serpukhovian) cropping out at the base of Ganmachidam Hill, close to the Chichong village in the Spiti Valley of the Tethyan Himalaya (Figs. 1, 2). The Po Formation is exposed in the northwestern (Losar section), northern (Lingti Valley) and northeastern (Poh–Kaurik section) parts of the Spiti Valley, forming an arch-like pattern. It is not developed in the central and southern parts of the Spiti Valley and is entirely missing in the adjacent Kinnaur region.

The Po Formation constitutes a part of the Kanawar Group (Hayden 1904; Bhargava & Bassi 1998), exposed at various sites at Poh (old spelling Po), Thabo, Ganmachidam Hill (Chichong village, SW of Losar), Takche Nala, Kabjiama Nala, upper Lahaul and Zanskar valleys (Hayden 1904; Srikantia l981; Gaetani et al. 1986; Bagati 1990; Vannay 1993; Garzanti et al. 1994; Bhargava & Bassi 1998). It conformably overlies the siliciclastic-carbonate Lipak Formation (Givetian to Tournaisian; Draganits et al. 2002) which includes gypsum beds in its upper part, particularly at Dhuna Dangse (in the vicinity of Takche) and Hurling–Shalkar stretch in the lower Spiti Valley (Hayden 1904; Bhargava & Bassi 1998). The Po and the overlying Ganmachidam formations are intimately related and nowhere developed independently; they are either both present or both absent. The absence of the Po–Ganmachidam Formations in most parts of the Himalaya is related to shallowing/regression of the sea initiated during the deposition of gypsum in the upper part of the underlying Lipak Formation (Bhargava & Bassi 1998). As a consequence, the sedimentation of the Po Formation was confined to the distal and deeper parts of the erstwhile basin. The southern and central parts not only remained a topographically positive area but were also uplifted during the late Carboniferous and contributed to diamictons of the Ganmachidam Formation (?early Pennsylvanian–early Asselian). In some parts even the underlying Lipak Formation (Givetian–Tournaisian) was also eroded; as a result, the Gechang Formation (Asselian–Sakmarian) and Gungri Formation (Wuchiapingian–early Changhsingian) were deposited over the Devonian Muth Formation during the Permian transgression (Bhargava & Bassi 1998; Fig. 1b). However, Gaetani & Garzanti (1991) and Garzanti et al. (1994, 1996) considered that the selective development of the Lipak Formation results from the origin of complex half-graben structures related to the opening of the Neo-Tethys.

The Po Formation in the vicinity of its type section at Poh village is 600 m thick and contains plant fossils, nautiloids, crinoids, bryozoans and other invertebrate fauna (Hayden 1904; Ranga Rao et al. 1984; Bhargava & Bassi 1998). At Thabo (old spelling Tabo), the basal part of the Po Formation contains plant fossils which were named as the “Tabo Plant Stage” (Hayden 1904). The Po Formation, on the basis of brachiopod and associated fauna, is considered to range from Visean to Serpukhovian (Bhargava & Bassi 1998).

A wide range of depositional settings have been suggested for the Po Formation, including shallow marine (Hayden

1904; Ranga Rao et al. 1984), shallow inner shelf to shoreface with high sediment input (Shanker et al. 1993), tide-dominated coastal setting to middle shelf (Garzanti et al. 1996), and middle shelf to upper shoreface (Bhargava & Bassi 1998).

Previous workers also reported trace fossils including *Asteriacites*, *Aulichnites*, *Gyrochorte*, *Phycodes*, *Planolites*, *Rusophycus*, *Rhizocorallium* and *Skolithos* from the Po Formation (Bhargava & Bassi 1998) but the trace fossils have never been subjected to ichnotaxonomic considerations or analysed in terms of their paleoenvironmental implications.

This study presents a fresh collection of trace fossils from the Po Formation and includes documentation of 11 ichnogenera comprising 14 ichnospecies, including resting traces of asteroids and ophiuroids (ichnogenus *Asteriacites* von Schlotheim, 1820) found in the Po Formation (Visean–Serpukhovian) exposed along the slope of Ganmachidam Hill, Spiti region of northwestern Himalaya.

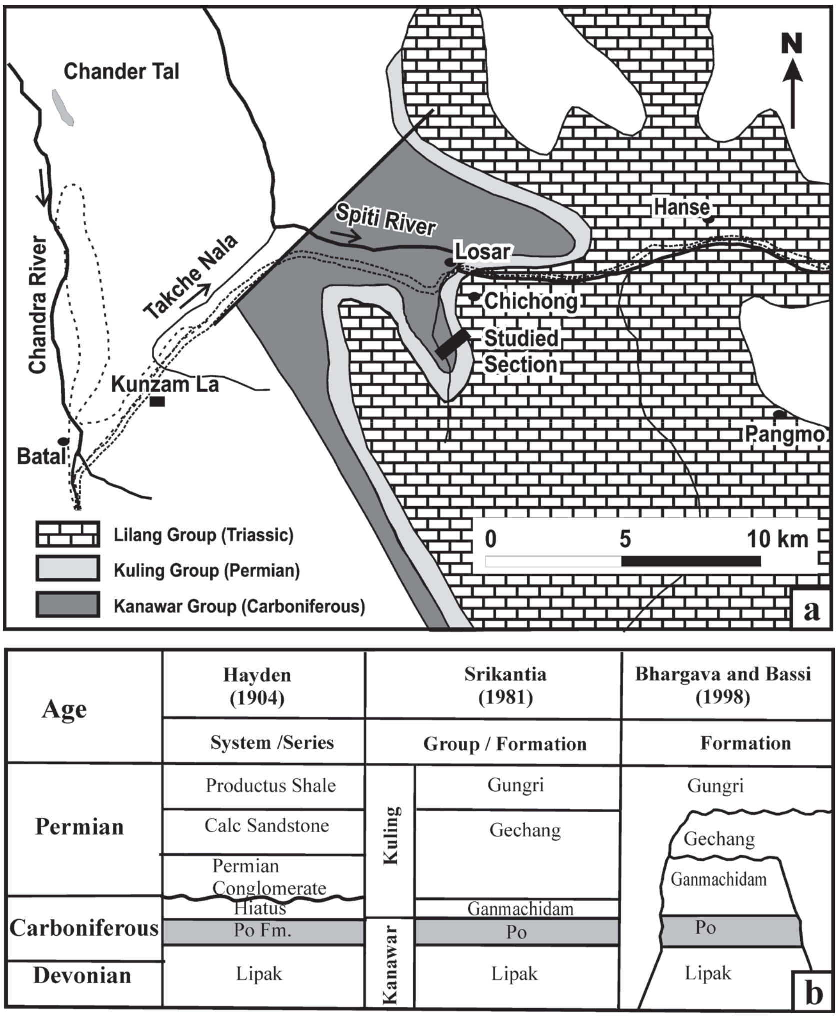

Fig. 1. a — simplified geological map of the study area near the Chichong village and Ganmachidam Hill in the NW part of the Spiti Basin (modified after Bhargava & Bassi 1998); **b** — lithostratigraphic classification scheme of the Po Formation in Spiti region of the Tethyan Himalaya (after Bhargava & Bassi 1998).

Stratigraphic section and lithological details

Along the Chichong village (the present study section), the upper part of the Po Formation (up to 163 m thick) is exposed at the base of Ganmachidam Hill (Figs. 1, 2). It comprises dark blackish shale, fine-grained siltstone and massive to bedded sandstone beds. We measured the lowermost 65 m of the section at the base of Ganmachidam Hill which is extensively bioturbated in three specific levels (Fig. 3). The measured section consists of black shales, fine-grained siltstones/sandstones and medium-grained thickly bedded to massive sandstone beds (Fig. 3). The lithological contact between the Po Formation and the underlying Lipak Formation is fully covered by debris at the base of the measured section. The Po Formation is conformably overlain by the Ganmachidam Diamictite Formation (?Bashkirian–early Asselian).

The measured section is subdivided into seven vertically stacked upwards-coarsening parasequences (PA to PG), separated by transgressive surfaces (TS1 to TS6) (Fig. 3). An ideal parasequence is subdivided into three units (A–C) (Fig. 2b). Unit A is represented by transgressive dark shale, B by strongly bioturbated alternation of fine-grained sandstone, shale and siltstone intervals, and C by unbioturbated medium-grained thickly bedded sandstone beds. However, in TS 2, 3 and 6, Unit A is directly overlain by Unit C, indicating a rapid shallowing and an abrupt influx of coarser material. The parasequences (PA) comprise tempestites composed of prominent shale–siltstone-thinly bedded fine-grained sandstone, and preserve the maximum number and diversity of trace fossils. TS 6 to 7 are 2.7 to 23 m thick, respectively; the thickness of the parasequences decreases in the middle part of the section and then increases upward. Bioturbate structures were recorded in parasequences PA, PE and PG, conspicuously in the tempestite parts. Overall, the frequency and diversity of trace fossils decrease upward in these parasequences.

Unit A is interpreted to have been deposited in a low-energy setting (offshore). Fine-grained sandstone and siltstone beds (Unit B) in the lower 12.2 to 22.7 m of the section exhibit hummocky cross-stratification (HCS) (Fig. 4d,c), low-angle planar and trough cross beds (Fig. 4f,g) and a shallow, slightly asymmetrical gutter cast at the base of the unit (Fig. 4d,e). The gutter cast is square-shaped (i.e., flat-based), 56 mm deep and 148 mm wide. Ripple cross-lamination is the dominant

Fig. 2. a — field photograph of the section measured at the base of the Ganmachidam Hill near Chichong village, Spiti region of Northwest Himalaya; **b** — an ideal upward-coarsening parasequence with sub-environments (Unit: A–C); **c** — highly bioturbated unit B of the parasequence PA; **d** — transition from parasequence PA to PB.

internal sedimentary structure in fine-grained sandstone and siltstone, although low-angle cross bedding and oscillatory cross-lamination are also present (Fig. 4f, g). The transition from offshore mudstone (Unit A) to the hummocky cross-stratified fine-grained sandstone–siltstone interval (Unit B) indicates a deposition in storm-dominated shoreface. This unit is strongly bioturbated in the lowermost parasequence (PA) and partially bioturbated in other parasequences (PE and PG). The recorded trace fossils include *Asteriacites stelliformis*, *A. quinquefolius*, *Biformites insolitus*, *Helminthoidichnites*? isp., *Lingulichnus* isp., *Lockeia siliquaria*, *Palaeophycus tubularis*, *Planolites* isp., *Protovirgularia* isp. A, *Protovirgularia* isp. B, *Protovirgularia* isp. C, *Psammichnites* isp., *Rusophycus* isp. and *Treptichnus* isp. Microbial mat structures (MISS) found in the lower part of the section are confined to interfaces of fine-grained siltstone and sandstone within Unit B.

Unit C represents the upper shoreface. Upward in the section, the cycles are thinner with a higher proportion of sand together with a decrease in the frequency and abundance of HCS beds and bioturbation. The abundance of trace fossils in the tempestite sequence suggests that the storm flushed not only silt/sand, but also nutritive material creating ideal conditions for proliferation of fauna. These parasequences record shoreline progradation (cf. van Wagoner et al. 1990) and reflect a progressive increase in hydraulic energy, sand content and mobility of the substrate which, in turn, controlled the distribution of trace fossils in the stratal packages of the Po Formation.

Systematic ichnology

The collected specimens that are described in the following chapter are housed in the collection of the Centre of Advanced Study in Geology, Panjab University, Chandigarh, India.

Asteriacites von Schlotheim, 1820

Star-shaped burrows consisting of five arms departing from a central discoid area and tapering towards the tips, preserved as convex hyporelief at the base of hummocky cross-stratified sandstone and siltstone interval in the lower and middle part of the studied section. High-density (per m^2) occurrences are not observed but isolated specimens are randomly distributed on the sole of HCS beds. Two species of *Asteriacites*, namely *A. stelliformis* and *A. quinquefolius*, were identified based on morphometric analysis (Fig. 5) (maximum width vs. maximum length of arm) suggested by Knaust & Neumann (2016). These two ichnospecies differ from *A. lumbricalis* which is restricted to imprints with slender and elongated arms emerging from a discoid centre (produced by an ophiuroid).

Asteriacites is generally interpreted as a resting trace of asterozoans, such as sea stars (Asteroidea) and brittle stars (Ophiuroidea) and has been reported from shallow marginal-marine to deeper sea from the Cambrian to Recent (Seilacher 1953; Crimes & Zhiwen 1986; West & Ward 1990; Mikuláš 1992; Mángano et al. 1999; Chen & McNamara 2006; Schatz et al. 2013; Baucon & Carvalho 2016). It was originally described as a body fossil (Walch 1773). Recently, Schlirf (2012) considered *Asteriacites* as a *nomen dubium* (considering the type material of the type ichnospecies is lost) and recommended its discontinuation in favour of *Heliophycus*. Therefore, the taxonomical attributes of the *Asteriacites* were disputed until recently (Knaust 2012; Schlirf 2012; Paranjape et al. 2013; Gurav et al. 2014). Rediscovery of the type material in the von Schlotheim collection and an efficient revision of the ichnogenus *Asteriacites* by Knaust & Neumann (2016) justified the validity of *Asteriacites* von Schlotheim, 1820 as an ichnogenus.

Asteriacites stelliformis
(Miller and Dyer, 1878)
Fig. 6a, d; Fig. 7b, c, e

Material: Approximately one third from the overall number of 76 specimens of *Asteriacites* ispp. documented in the outcrop (29 specimens of *Asteriacites* isp. collected) belong to *A. stelliformis*. The remaining two thirds of *Asteriacites* isp. belong to *A. quinquefolius* or cannot be determined on the ichnospecies level.

Star-shaped imprints (convex hyporeliefs) consisting of relatively short arms. Most specimens bear five arms, but only a few specimens show approximately even angles between the neighbouring ones. For a regular pentagram, the angle of 72° is determined, which is close to that in some specimens (e.g., Fig. 6d). Angles measured on the figured specimens (Figs. 6a, d; 7b, c, e) range from 26° (Fig. 7e) to 120° (Fig. 6a); the difference in angles can be understood by movements of the trace-maker rather than by water currents. The length of arms varies between 10 and 50 mm.

Asteriacites arms sometimes exhibit broad U-shaped or chevron-like imbricate ornamentation. Such features are attributed to the tube feet / ambulacra activity during the burrowing process (Seilacher 1953).

Asteriacites quinquefolius Quenstedt, 1876
Fig. 6b–c, e–f; Fig. 7a, d, f

Material: See the listing of specimens of *A. stelliformis*.

Star-shaped imprints (convex hyporeliefs) composed of typically five wide arms; width:length ratio of the arms is less than 1:2. The ground plan of the specimens varies from a nearly regular pentagram (Fig. 7a) to asymmetrical

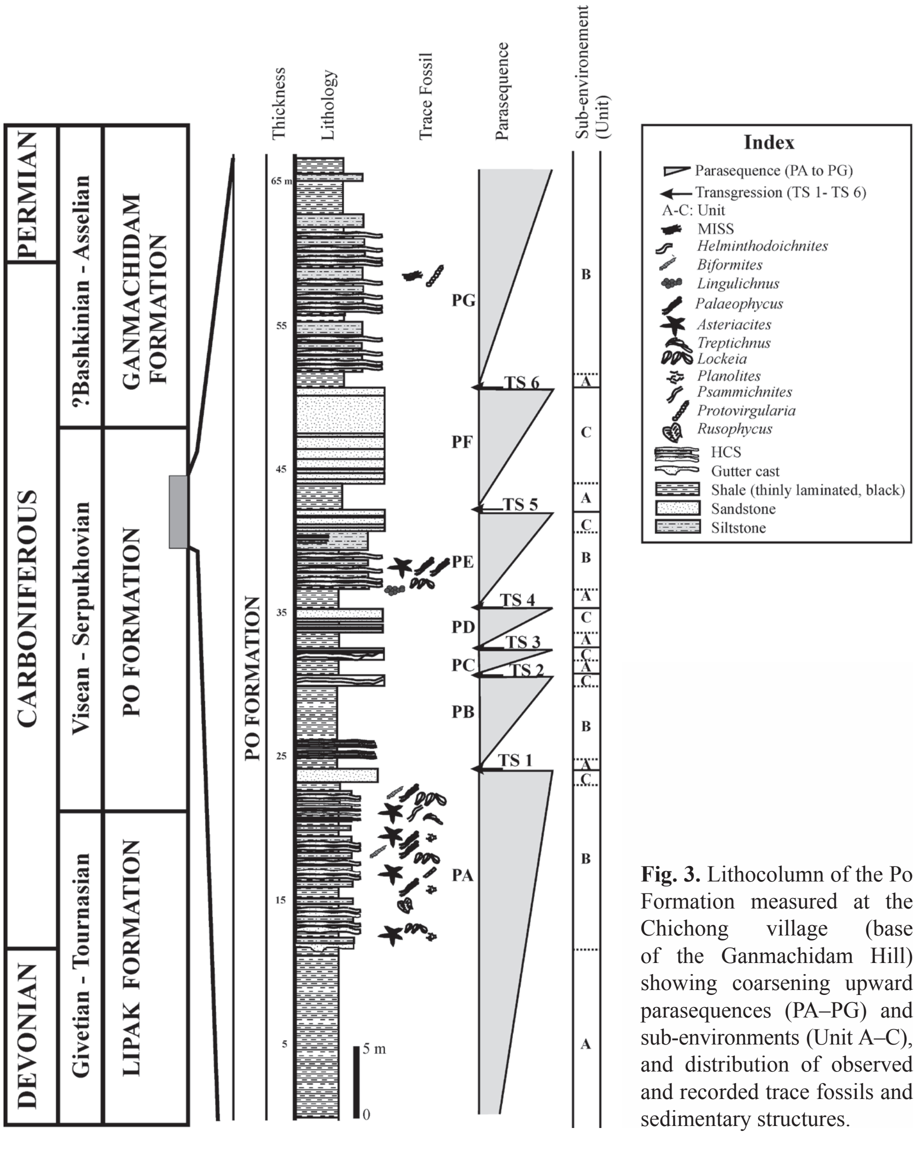

Fig. 3. Lithocolumn of the Po Formation measured at the Chichong village (base of the Ganmachidam Hill) showing coarsening upward parasequences (PA–PG) and sub-environments (Unit A–C), and distribution of observed and recorded trace fossils and sedimentary structures.

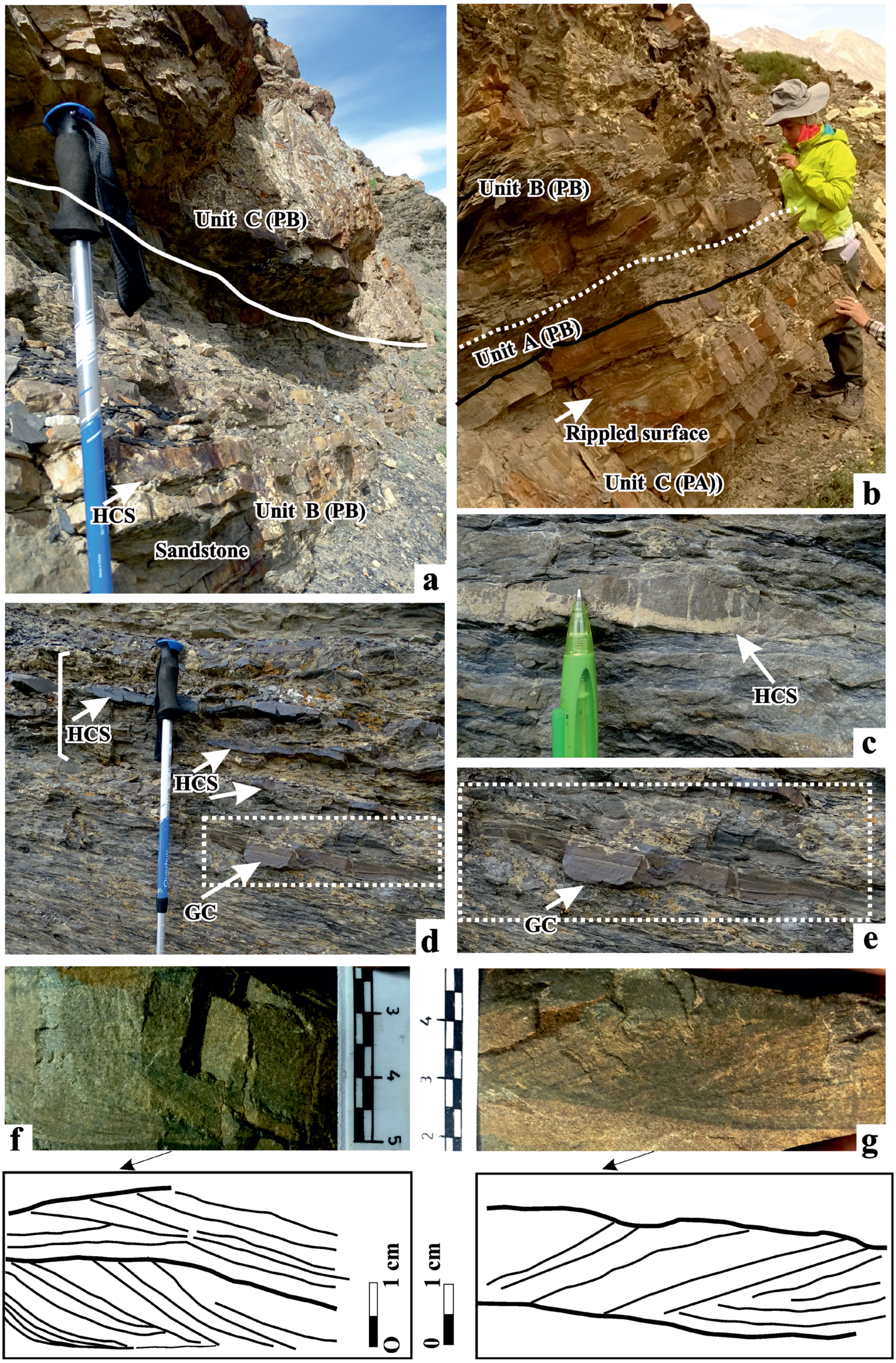

Fig. 4. Sedimentary structures in the Po Formation; **a** — HCS in sandstone (Unit B, parasequence PB), scale=rod is 50 cm; **b** — rippled surface in sandstone (unit C, parasequence PA); **c–e** — HCS and gutter cast in unit B of parasequence PA; (e) enlargement of c; scale=rod is 100 cm; **f,g** — low-angle planar and trough cross beds preserved as internal structures in bioturbated sandstone and siltstone of unit B of Parasequence (PA).

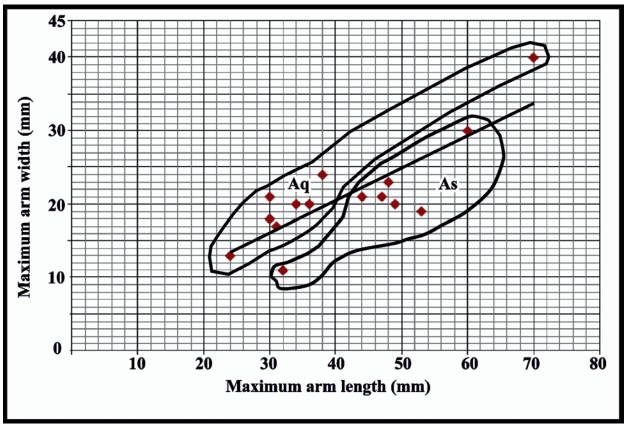

Fig. 5. Morphometric analysis of maximum arm length and width of the 19 specimens of *Asteriacites* von Schlotheim, 1820 recovered from basal part of the Po Formation, showing grouping of *A. stelliformis* (As) and *A. quinquefolius* (Aq). Measurement method adopted from Knaust & Neumann (2016).

structures still consisting of five arms (Figs. 6e, 7d). The surface of the arms is typically ornamented by fine chevron-like (Fig. 6e) imbricate (Fig. 7d) structures, similarly to that of *A. stelliformis* (described above). In certain specimens, some arms (typically one arm) show the width:length ratio higher than 1:2 but most arms have the ratio less than 1:2. In such cases (Fig. 7d, f), we determine these specimens as *A. quinquefolius*.

Biformites **Linck, 1949**

The ichnogenus of *Biformites* Linck, 1949 was recently revised by Schlirf (2012) and Knaust & Neumann (2016) as narrow, bedding-parallel, vermiform, hook-shaped or sinuous imprints with slightly tapering terminations, unbranched or with secondary successive branching, with or without ornament. Knaust & Neumann (2016) erected the ichnofamily Biformitidae for imprints resulting from locomotion using asterozoan arms, selected *Biformites* Linck, 1949 as the type ichnogenus, and included the other ichnogenera *Arcichnus* Sutcliffe, 1997, *Harpichnus* Vallon et al., 2015 and *Pentichnus* Maerz et al., 1976 under this family. They also stated that ichnogenera *Zhadaichnus* Yang and Song, 1985 and *Ophioichnus* Bell, 2004 are junior synonyms of *Biformites*.

Biformites insolitus **Linck, 1949**
Fig. 8f

Material: Three specimens; all collected.

Narrow (0.2–0.6 cm), short (0.5–2.6 cm), vermiform, slightly tapering, straight to curved, bisymmetrically arranged sets of transverse, elongate ridges or protuberances preserved on lower bedding planes. They can be, considering all aspects of morphology, determined as *Biformites insolitus*; this trace fossil is interpreted as imprints of arms of walking ophiuroids (cf. Boyer 1979; Schlirf 2012; Knaust & Neumann 2016).

Helminthoidichnites **Fitch, 1850**

Simple, horizontal, small, thin, unbranched, non-meandering, straight or curved, more rarely circular trails or burrows that commonly display overlap between specimens but lack self-overcrossing (Buatois et al. 1998). *Helminthoidichnites* is regarded as a grazing trace probably produced by vermiform animals (Buatois et al. 1998).

Helminthoidichnites **isp.**
Fig. 8a

Material: Ten specimens observed in the outcrop; three collected.

Small, mostly straight to slightly curved, smoothly horizontal trails displaying some angular turns in their path and preserved as positive hyporelief. No lateral grooves or levees have been observed. One end of the path of trail displays circular mounds. Diameter of the trace varies from 0.5 to 1.2 mm and the figured/collected trail is 47 mm long. The specimen also shows close morphological resemblance to *Haplotichnus indianensis* Miller, 1889 recorded from the lower Pennsylvanian of Orange County, Indiana (Rindsberg & Kopaska-Merkel 2005). However, recently Getty & Bush (2017) convincingly illustrated that *Haplotichnus indianensis* Miller, 1889 exhibits bifurcating projections at the bends similar to *Treptichnus bifurcus*; therefore, they synonymized *Haplotichnus* with the ichnogenus *Treptichnus*. Demircan & Uchman (2016) considered *Haplotichnus indianensis* Miller, 1889 as *Gordia indianensis*. Our specimens do not exhibit the ichnogeneric character of either *Treptichnus* or *Gordia*; hence they were grouped under the ichnogenus *Helminthoidichnites*.

Lingulichnus **Hakes, 1976**

Vertically to obliquely orientated sediment-filled tubes with elliptical to sub-circular cross sections (Zonneveld & Pemberton 2003). *Lingulichnus* has been interpreted as a dwelling trace of a lingulid brachiopod (Hakes 1976; Szmuc et al. 1976; Zonneveld & Pemberton 2003; Zonneveld et al. 2007; Alonso-Muruaga et al. 2013).

Lingulichnus **isp.**
Fig. 9j

Material: Two bedding planes with dozens of specimens observed in the outcrop and collected.

Circular to elliptical, endichnial, vertically to near-vertically orientated sediment-filled structures preserved in full relief. They occur as dense assemblages of specimens tightly arranged (ca. 10 specimens per 2×2 cm; Fig. 9j). The determination of these trace fossils as *Lingulichnus* follows the description of Zonneveld & Pemberton (2003).

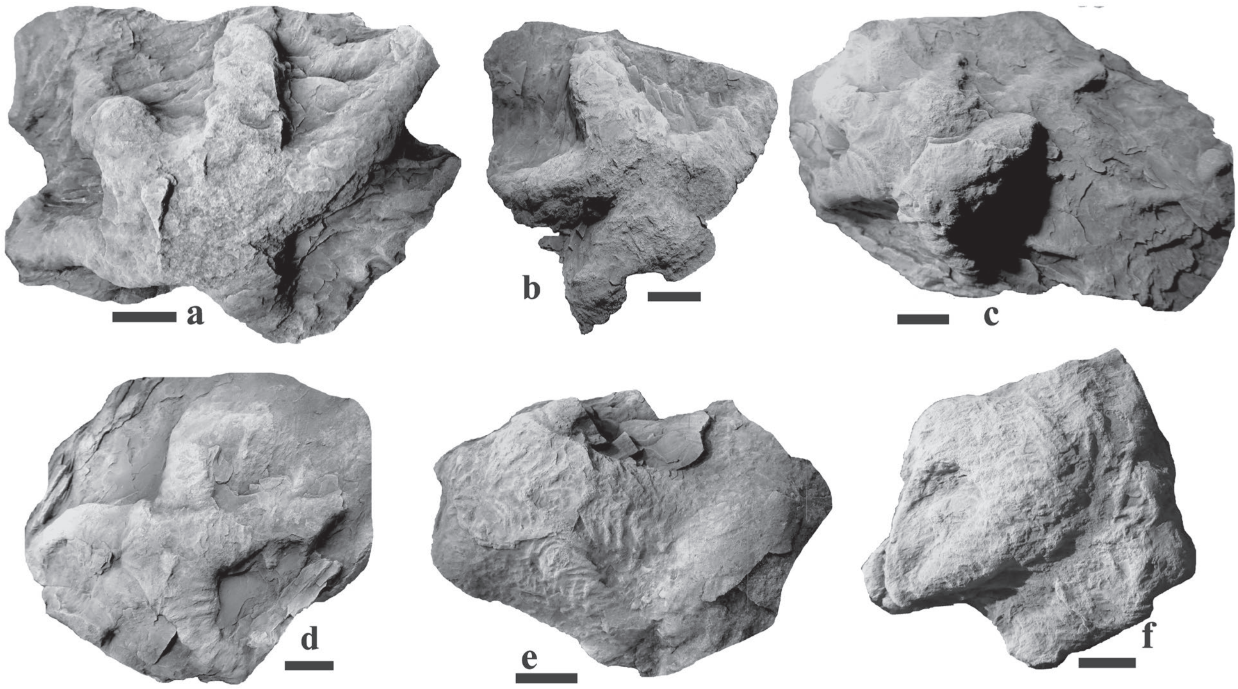

Fig. 6. Resting traces *Asteriacites* von Schlotheim, 1820 burrowed by sea stars (Asteroidea); basal part of the Po Formation at Chichong (Ganmachidam Hill) section (Spiti region, Himalaya), scale bar=1 cm. **a** — *Asteriacites stelliformis,* CAS/LO/2016/-PO-4; **b** — *A. quinquefolius,* CAS/LO/2016/-PO-3; **c** — *A. quinquefolius,* CAS/LO/2016/-PO-15; **d** — *A. stelliformis,* CAS/LO/2016/-PO-6; **e** — *A. quinquefolius,* CAS/LO/2016/-PO-9; **f** — *A. quinquefolius,* CAS/LO/ 2016/-PO-7.

Lockeia James, 1879

Lockeia is a cubichnion produced mostly by bivalves (Seilacher & Seilacher 1994) in various environments. *Lockeia* is known to occur in a wide range of mostly marine environments from shallow to deep marine and even in non-marine continental deposits (Seilacher 1953; Pickerill 1977; Bromley & Asgaard 1979; Crimes et al. 1981; Archer & Maples 1984) and considered as a resting trace of bivalves (Seilacher 1953; Osgood 1970; Pickerill 1977; Vossler & Pemberton 1988; Seilacher & Seilacher 1994) or a dwelling trace (domichnion) of suspension feeders (Mángano et al. 2002a).

Lockeia siliquaria James, 1879
Fig. 9 e, f, h, k; Fig. 8c

Material: 15 specimens observed in the outcrop; 7 of them were collected.

Bilaterally symmetrical, almond-shaped, sandstone-filled bodies tapering at both ends to a sharp point, variously orientated, densely aggregated (Fig. 9e), preserved as convex hyporeliefs. They are 0.8–1.5 cm long and 0.5–0.8 cm wide. The central median ridge or crest is poorly developed or missing.

Palaeophycus Hall, 1847

Trace fossils of *Palaeophycus* are open burrows, horizontal, slightly sinuous. They are both smooth and ornamented burrows, variable in diameter; the crucial determination features are a prominent wall lining and a passive fill (Osgood 1970; Alpert 1975; Pemberton & Frey 1982; Fillion & Pickerill 1990; Stanley & Pickerill 1994; Keighley & Pickerill 1995; Jensen 1997). *Palaeophycus* is interpreted as dwelling structures of suspension feeders or predators (Osgood 1970; Pemberton & Frey 1982; Uchman 1995; Tchoumatchenco & Uchman 2001; Mángano & Buatois 2003).

Palaeophycus tubularis Hall, 1847
Fig. 9k; Fig. 8a, b, d

Material: About 20 specimens observed in the outcrop; 5 of them collected.

Straight to slightly curved, horizontal, undulose, essentially horizontal, thinly lined, smooth-walled cylindrical to subcylindrical open burrows preserved as full relief in fine grained sandstone and siltstone. Burrow diameters and lengths vary from 2 to 8 mm and 30 to 90 mm, respectively. The burrow fill is similar to the host rock, typically massive. The burrows occur very frequently in most of the rocks. *Palaeophycus* was found in association with *Lockeia siliquaria* (Fig. 9k) as well as with *Helminthoidichnites*-type traces (Fig. 8a). One specimen of *Palaeophycus* is preserved as a convex epirelief and shows a burrow collapse (Fig. 8a).

Planolites Nicholson, 1873

Straight or moderately curved, smooth, exceptionally branching tunnels of circular outline, parallel to bedding,

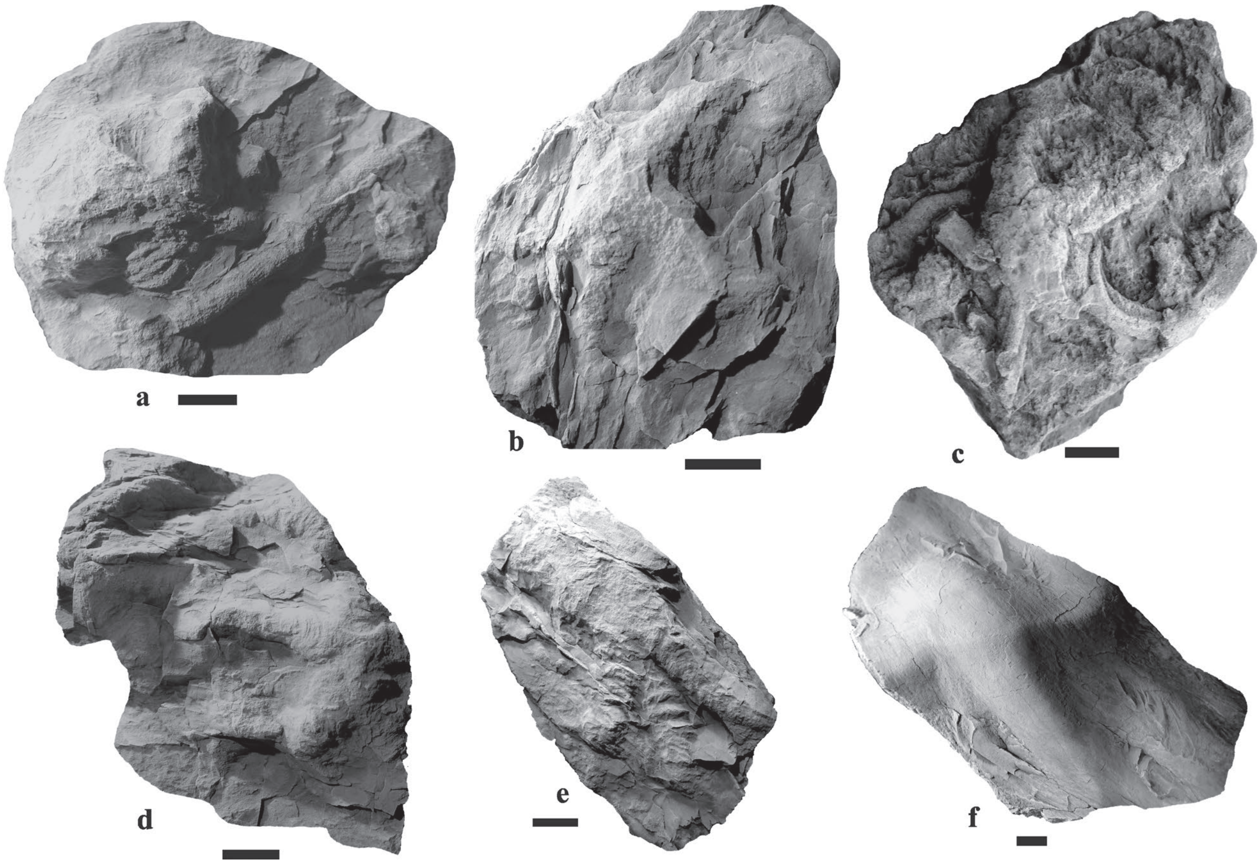

Fig. 7. Resting trace of *Asteriacites* von Schlotheim, 1820 burrowed by sea star (Asteroidea); basal part of the Po Formation at Chichong (Ganmachidam Hill) section (Spiti, Himalaya), scale bar=1 cm. **a** — *A. quinquefolius,* CAS/LO/2016/-PO-8; **b** — *A. stelliformis,* CAS/LO/2016/-PO-1; **c** — *A. stelliformis,* CAS/LO/2016/-PO-14; **d** — *A. quinquefolius,* CAS/LO/2016/-PO-2; **e** — *A. stelliformis,* CAS/LO/2016/-PO-13; **f** — *A. quinquefolius,* CAS/LO/2016/-PO-19.

filled with material differing from the host rock (Häntzschel 1975; Pemberton & Frey 1982). *Planolites* is a eurybathic, extremely facies-crossing ichnogenus and has been interpreted as a product of vermiform deposit-feeders (Häntzschel 1975; Pemberton & Frey 1982; Frey & Howard 1985, 1990; Fillion & Pickerill 1990; Uchman 1995).

Planolites isp.
Fig. 9e, g; Fig. 8e

Material: 16 specimens observed in the outcrop; 5 of them collected.

Small, simple, unlined, horizontal to slightly inclined, rarely branched, straight to curved burrows without a wall. The burrows are 6–35 mm long and 1–4 mm wide. One of the specimens shows faintly developed transverse annulae and irregular morphology with thinning at one end (Fig. 8g). This specimen shows some morphological aspects of *Planolites reinecki* (Stanley & Pickerill 1994; Uchman 1998; Mángano & Buatois 2003) but differs in the absence of both transverse annulae and longitudinal striae.

Protovirgularia M'Coy, 1850

The ichnogenus *Protovirgularia* is described as horizontal or subhorizontal cylindrical burrows, trapezoidal, almond-shaped, or triangular in cross section, distinctly or indistinctly bilobated, occasionally with oval, mound-like terminations of the trace (Pickerill & Narbonne 1995; Uchman 1998; Uchman & Gazdzicki 2006; Fernandez et al. 2010). *Protovirgularia* is interpreted as being produced by bivalves (Han & Pickerill 1994; Seilacher & Seilacher 1994). Several preservational variants of *Protovirgularia* are known (Carmona et al. 2010); they are attributed to substrate conditions (Maples & West 1989; Mángano et al. 1998; Carmona et al. 2010).

***Protovirgularia* isp.** A
Fig. 9b

Material: About a dozen specimens of *Protovirgularia* isp. were observed in the outcrop; collected specimens include 2 specimens of *Protovirgularia* isp. A, 2 specimens of *Protovirgularia* isp. B, and one specimen of *Protovirgularia* isp. C.

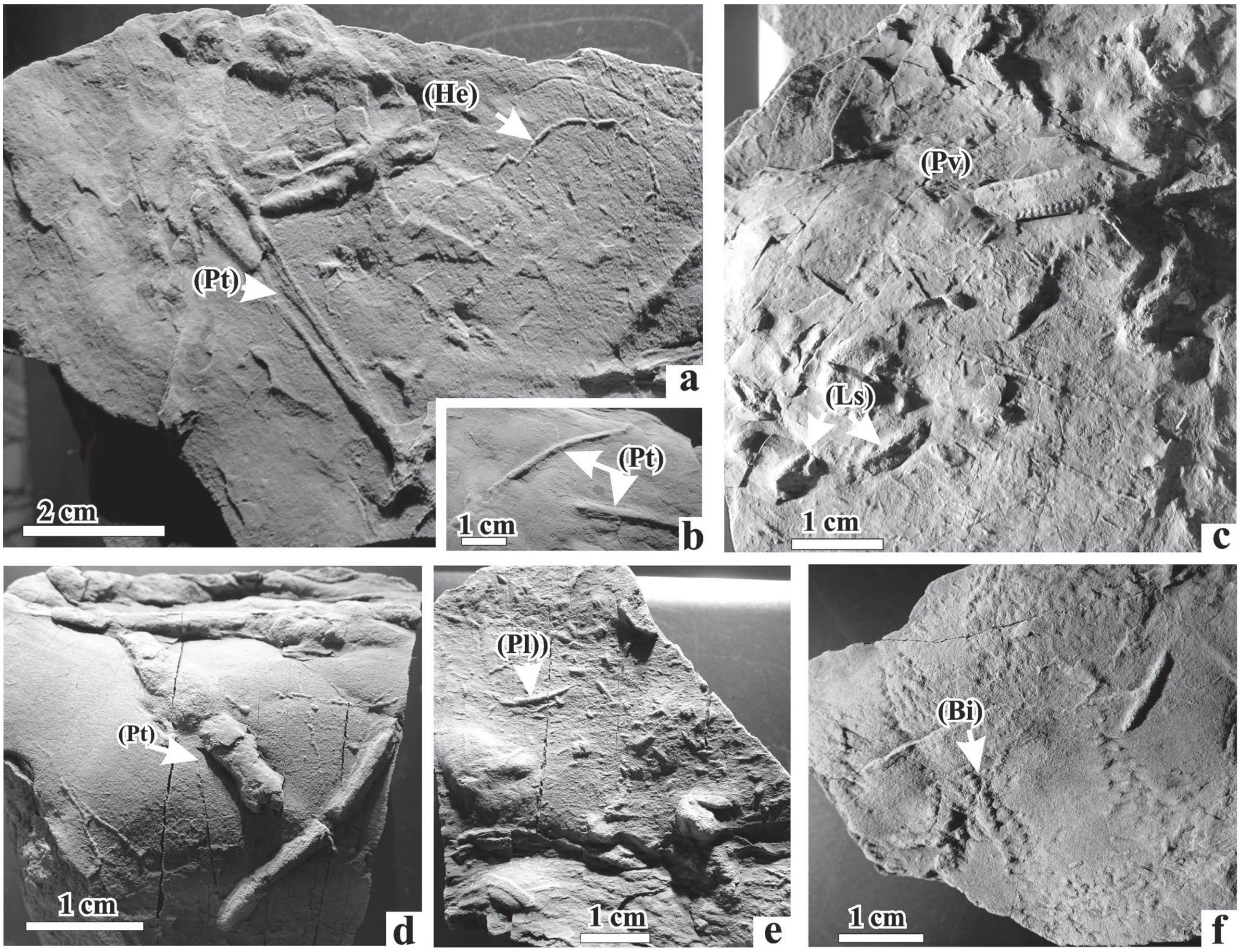

Fig. 8. Trace fossils from basal part of the Po Formation (Visean-Serpukhovian), Spiti Himalaya, India. **a** — (He) *Helminthoidichnites* isp., and (Pt) *Palaeophycus tubularis*, CAS/LO/2016/-PO-24; **b** — (Pal) *Palaeophycus tubularis*, CAS/LO/2016/-PO-25; **c** — (Pv) *Protovirgularia* isp. C, and (Ls) *Lockeia siliquaria,* CAS/LO/2016/-PO-28; **d** — (Pals) *Palaeophycus tubularis*; **e** — (Pl) *Planolites* isp., CAS/LO/2016/-PO-42; **f** — (Bi) *Biformites insolitus,* CAS/LO/2016/-PO-48.

This slightly curved, unbranched, horizontal structure consists of a central furrow flanked by regular closely spaced oval lobes or pads, which are well-preserved only on one side of the trace (Fig. 9b). The outer margins of some lobes show fine striations. The specimen is grouped here under a common epirelief preservational variant of *Protovirgularia*. A similar trace from the Vallès-Penedès Basin in NE Spain was described as *Protovirgularia dichotoma* (Gibert & Domènech 2008).

Protovirgularia **isp. B**
Fig. 9h

An elongated and slightly curved trace, 85 mm long and 5–6 mm wide, preserved as a positive hyporelief. Chevron-like lamellar ornamentation is developed but reduced towards one of the extremes where *Protovirgularia* is terminated by a *Lockeia*-like body. *Lockeia siliquaria* is almond-shaped, smooth, and lacks a well-developed keel and ornamentation. It shows a compound trace fossil of the resting trace of *Lockeia siliquaria* and the locomotion trace of *Protovirgularia* (cf. Han & Pickerill 1994). *Protovirgularia* specimens that terminate with *Lockeia siliquaria* are assigned to *Protovirgularia rugosa*. Ekdale & Bromley (2001) stated that *L. siliquaria* represents the place where the bivalve temporarily stopped for feeding.

Protovirgularia **isp. C**
Fig. 8c

A poorly preserved *Protovirgularia* isp. with effaced upper surface of the specimen. The trace is 13 mm long and 8 mm wide, with prominent chevron markings on one side.

Psammichnites **Torell, 1870**

The ichnogenus *Psammichnites* Torell 1870 includes a wide variety of predominantly horizontal, sinuous to looped, back-filled traces, characterized by a distinctive median dorsal

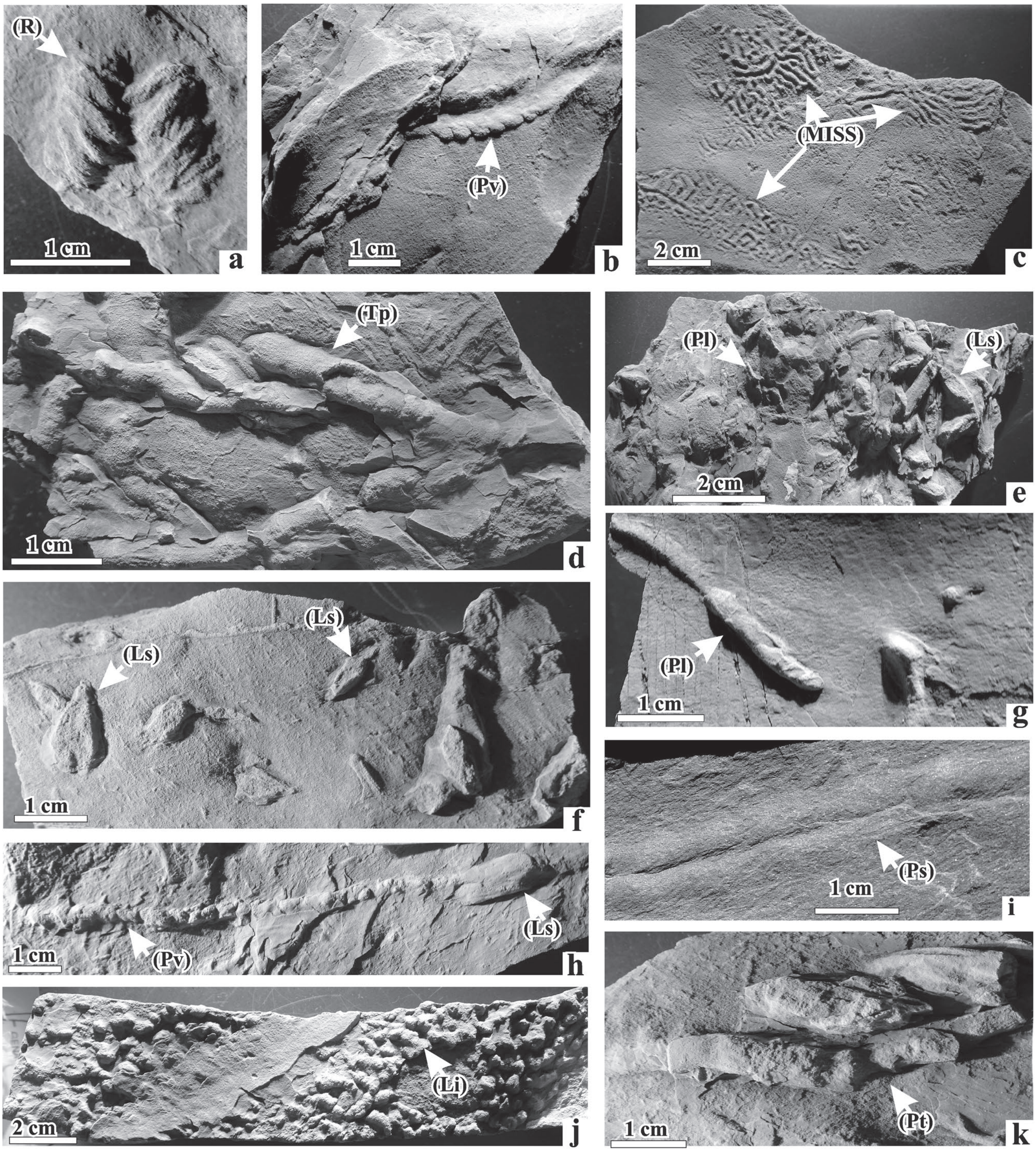

Fig. 9. Trace fossils from basal part of the Po Formation (Visean-Serpukhovian), Spiti Himalaya, India. **a** — *Rusophycus* isp., CAS/LO/2016/-PO-20; **b** — *Protovirgularia* isp. A, a preservational variant of *Protovirgularia*, CAS/LO/2016/-PO-21; **c** — Microbially Induced Sedimentary Structures (MISS), probably algal mat, CAS/LO/2016/-PO-33; **d** — *Treptichnus* isp., CAS/LO/2016/-PO-29; **e** — (Pl) *Planolites* isp., and (Ls) *Lockeia siliquaria,* CAS/LO/2016/-PO-30; **f** — (Ls) *Lockeia siliquaria;* **g** — (Pl) *Planolites* isp., CAS/LO/2016/-PO-31; **h** — *Protovirgularia* isp. B, temporary resting site *Lockeia siliquaria* (Ls) and locomotion trace *Protovirgularia* (Pv), CAS/LO/2016/-PO-37; **i** — (Ps) *Psammichnites* isp., CAS/LO/2016/-PO-39; **j** — (Li) *Lingulichnus* isp., CAS/LO/2016/-PO-22; **k** — (Pt) *Palaeophycus tubularis,* CAS/LO/2016/-PO-23.

structure (Mángano et al. 2002b). Mángano et al. (2002b) revised the Carboniferous *Psammichnites* and stated that Carboniferous *Olivellites* Fenton and Fenton 1937a and *Aulichnites* Fenton and Fenton 1937b are junior synonyms of *Psammichnites*. Based on taxonomic revision they further stated that Carboniferous *Psammichnites* specimens can be attributed to three ichnospecies, namely, *P. plummeri* (Fenton & Fenton 1937a), *P. grumula* (Romano & Meléndez 1985), and *P. implexus* (Rindsberg 1994). *Psammichnites plummeri* is the most common Carboniferous ichnospecies and is characterized by a relatively straight, continuous dorsal ridge/groove, fine transverse ridges, a wider size range, and a non-looping geometric pattern (Mangano et al. 2002b). *Psammichnites grumula* differs from the other ichnospecies of *Psammichnites* by having median dorsal holes or protruding mounds. *Psammichnites implexus* is characterized by its consistently narrower size range, subtle backfill structure, and tendency to scribble. *Psammichnites* records the feeding activities of a subsurface animal using a siphon-like device.

Psammichnites **isp.**
Fig. 9i

Material: Two specimens observed in the field; one of them was collected and measured.

A poorly preserved, nearly straight, smooth, unbranched, bilobed ridge with a faintly developed median furrow, preserved as a convex epirelief. The trace is 5.1 cm long and 1.0 cm wide. The specimen is weathered and shows a faint meniscate structure; however, the median furrow is clearly visible along one part of the specimen. No internal backfill structural pattern is visible. The specimen morphologically closely resembles *Psammichnites plummeri* (Fenton & Fenton 1937c) in its pattern of straight ridges but lacks fine, closely spaced transverse ridges (Mángano et al. 2002b). The specimen differs from the other bilobate trace of *Archaeonassa* in lacking a broad central flat area between the lobes (Jensen 1997).

Rusophycus **Hall, 1852**

The ichnogenus of *Rusophycus* Hall, 1852 refers to a short, bilobate, coffee-bean shaped trace fossil, usually with a median furrow. The lobes are transversely wrinkled by anterolaterally orientated fine striae (Häntzschel 1975). Paleozoic *Rusophycus* indicates nesting or resting behaviours of trilobites (Osgood 1970). *Rusophycus* is furthermore interpreted as resting traces of arthropods (Bergström 1973; Jensen 1990) and notostracan branchiopods (Bromley & Asgaard 1979).

Rusophycus **isp.**
Fig. 9a

Material: Three specimens observed in the field; two of them were collected.

A butterfly-shaped (anterior and posterior, broad openings), relatively shallow, horizontal, bilobate structure with a distinct cleft separating two strongly striated lobes. The bilobate structure is 10 mm wide and 14 mm long, and preserved as positive hyporelief in fine- to very fine-grained sandstone. Lobes are strongly convex; median furrow deepens and widens towards the anterior end of the trace. The scratchings seem to be clearly clustered in groups and these groups open (or expand) towards the axial area.

Treptichnus **Miller, 1889**

Treptichnus Miller, 1889 is a burrow consisting of segments connected at their ends, each to the next one, characteristically but not invariably in a zigzag pattern. Ichnotaxonomy of *Treptichnus* has been discussed in detail by Maples & Archer (1987), and Buatois & Mángano (1993). The ichnogenera of *Plangtichnus* and *Haplotichnus* are junior synonyms of *Treptichnus* (Buatois & Mángano 1993; Getty & Bush 2017). *Treptichnus* is interpreted as feeding structures (fodinichnia) produced by vermiform animals or insect larvae (Buatois & Mángano 1993; Getty & Bush 2017).

Treptichnus **isp.**
Fig. 9d

Material: A depicted and described specimen only.

A burrow system consisting of more-or-less straight six to seven segments, joined to each other at very blunt angles (approximately 160°); other segments are orientated at an oblique angle, namely, 20–40°, to the main axis of the trace. The trace is 87 mm long; segments are 10–22 mm long and 4–6 mm wide, preserved in hyporelief. The fill is identical to the host rock.

Microbially induced sedimentary structures (MISS)

Wrinkle structures consisting of ridges surrounding elongated depressions (Fig. 9c) were recorded on the upper bedding plane of a fine-grained sandstone bed in the lower part of the section. The ridges are flat and horizontal, slightly curved, and interconnected at some places. Microbially induced sedimentary structures (MISS) result from the response of microbial mats to physical sediment dynamics (Lowe 1980; Walter et al. 1980; Byerly et al. 1986; Hofmann et al. 1999; Allwood et al. 2006, 2007, 2009; Noffke 2009). Wrinkle structures (MISS) are found primarily in wave-dominated, low-energy shoreface settings (Calner & Eriksson 2011) but also occur in a wide range of environmental settings (Hagadorn & Bottjer 1997, 1999; Pflüger 1999; Bottjer et al. 2000; Noffke et al. 2002, 2006; Noffke 2009).

Paleoenvironmental significance

The recorded trace fossils of *Asteriacites stelliformis*, *A. quinquefolius*, *Biformites insolitus*, *Helminthoidichnites*? isp., *Lingulichnus* isp., *Lockeia siliquaria*, *Palaeophycus tubularis*, *Planolites* isp., *Protovirgularia* isp. A, *Protovirgularia* isp. B, *Protovirgularia* isp. C, *Psammichnites* isp., *Rusophycus* isp., and *Treptichnus* isp. are characteristic for the *Cruziana* ichnofacies.

This ichnofacies is characterized by the dominance of horizontal traces of mobile organisms and subordinate presence of vertical and inclined permanent structures, a wide variety of ethologic categories, the dominance of deposit- and detritus-feeding traces, a limited participation of suspension feeders and predators, and a high ichnodiversity and abundance (cf. MacEachern & Pemberton 1992; MacEachern et al. 1999; Buatois & Mángano 2011). The shallowing-upward, heterolithic interval of interbedded fine-grained sandstone and siltstone of the parasequences, highly bioturbated in the lower part of the section, is interpreted as deposits from a lower shoreface environment. The heterolithic successions of fine-grained sandstone and siltstone provided a favourable setting for the preservation of trace fossils. The dark shale interval at the base of the parasequences indicates a transgressive phase (offshore setting), followed by a deposition of heterolithic successions of fine-grained siltstone and sandstone (lower shoreface). Higher up in the section, it is followed by coarser, thick-bedded sandstone beds indicating an upper shoreface setting. The high sediment supply can be related to tectonic uplift in adjacent areas.

Baucon & Carvalho (2016) suggested that *Asteriacites*-bearing beds may be considered ichnological proxies for marine settings, low bioturbation intensity, shallow tiering, high sedimentation rate and/or event-bed deposition, significant levels of hydraulic energy, and low predation pressure. The presence of hummocky cross stratification, planar and trough cross bedding, and traces of *Cruziana* ichnofacies indicate a paleoenvironment slightly above the fair-weather wave base to the storm wave base, in a zone ranging from the lower shoreface to the lower offshore setting.

Acknowledgements: BPS is thankful to the University Grant Commission (UGC, New Delhi) for providing financial support within grant No. F.20-1/2012(BSR)/20-8(12)/2012(BSR). ONB acknowledges the Indian National Science Academy (No. 567-3. 2015) for its financial assistance. The work of RM was supported by the RVO67985831 Project of the Institute of Geology of the Czech Academy of Sciences. We are thankful to the reviewers Gabriela Mángano, Alfred Uchman and Lothar Vallon for constructive reviews of the manuscript.

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