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DISCOVERY OF TRACES OF *CRUZIANA SEMIPLICATA* AND *C. RUGOSA* GROUPS (CAMBRO-ORDOVICIAN) FROM THE LESSER HIMALAYA, INDIA AND THEIR STRATIGRAPHIC,TECTONICANDPALAEOBIOGEOGRAPHICIMPLICATIONS

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ABSTRACT

Trace fossils *Arthrophycus* cf. *A. brongniartti, Asterosoma ludwigae, Bergaueria perata, Cruziana semiplicata, Cruziana furcifera, Curvolithus simplex, Diplichnites gouldi, Monomorphichnus lineatus, Phycodes circinatum, Phycodes palmatum, Phycodes rarus, Palaeophycus striatus, Planolites* isp., *Rusophycus leifeirikssoni, Rusophycus petraeus, Rusophycus latus, Rusophycus* isp.-A , *Rusophycus* isp.-B, *Rusophycus* isp.-C, *?Rhabdoglyphus* isp, and *Treptichnus pedum* are reported from the Arkosic Sandstone Member (Koti Dhaman Formation, Tal Group), Nigalidhar syncline, Lesser Himalaya. *Cruziana semiplicata* ranges from Furongian to early Ordovician and the trace fossils of the *Cruziana rugosa* group are considered as typical Ordovician in age; their presence suggests an Ordovician transgression in the Indian Lesser Himalaya and an extension of the sea from Gondwana on to the Indian plate. It implies a hiatus between the Arkosic Sandstone Member and the underlying lower Cambrian Shale Member. The contact between the two shows angular and erosional discordance. The angular discordance is related to the Cambro-Ordovician Kurgiakh orogeny event. The Ordovician trace fossil bearing Arkosic Sandstone together with overlying sequence is being separated from the Tal Group is now designated as the Deona Formation. This contribution introduces a significant facet to the evolution of the Himalaya in general and the Lesser Himalaya in particular.

Keywords: *Cruziana semiplicata*, *Cruziana rugosa* group, Ordovician transgression, Tal Group, Nigalidhar syncline, Lesser Himalaya, Gondwana

INTRODUCTION

The Himalaya is conventionally divided in four thrust-bound lithotectonic zones i.e. the Sub-Himalaya (SH), the Lesser Himalaya (LH), the Higher Himalaya (HH) and the Tethyan Himalaya (TH) (inset, Fig. 1A). The Indian LH preserves Neoproterozoic to lower Cambrian, Permian and Cretaceous marine sequences (Singh, 1979a, 1979b, 1979c, 1981; Srikantia and Bhargava, 1998; Bhargava and Bassi, 1998; Yin, 2006). The Indian TH includes more or less a continuous marine Neoproterozoic to Eocene sequence Srikantia and Bhargava, 1998). The Indian SH consists of Paleogene and Neogene sequences (Srikantia and Bhargava, 1998; Yin, 2006). In Pakistan, the sedimentary rocks north of the Panjal–Khairabad Fault (P-KF) are comparable to those of the Indian TH (DiPietro and Pogue, 2004). The rocks south of the P-KF compare well with those of the Indian LH (DiPietro and Pogue, 2004; Yin, 2006; Hughes *et al*., 2018). The Salt Range (SR) hosts Neoproterozoic to Cambrian, Permian, and Mesozoic-Cenozoic sequences, which have been placed under LH (DiPietro and Pogue, 2004; Yin, 2006) as well as in the SH (Hughes *et al.*, 2018).

There are contentious views regarding the relationship between the Indian LH and TH. Broadly three models exist. One model suggests that these two represent different basins, separated by HH crystalline axis (Saxena, 1971; Aharon *et al.*, 1987). The Indian LH after lower Cambrian witnessed an extensive marine regression (Singh, 1976, 1979a; 1979b, 1979c, 1981; Valdiya, 1995; 1998; Bhargava, 2011, Bhargava *et al.*, 1998); the sea returned only during the early Permian as a consequence of Gondwanan fragmentation (Singh, 1979a, 1981), thereby registering a vast hiatus covering the Ordovician to Carboniferous time span (Singh, 1976, 1981; Valdiya, 1995; 1998). While the sedimentation in the Indian TH was largely uninterrupted during the Palaeozoic only with minor breaks (Bhargava and Bassi, 1998; Srikantia and Bhargava, 1998). Second model suggests that the Indian LH and TH were proximal and the distal parts of a continuous northern margin of the Indian plate (Singh, 1981; Brookfield, 1993; Corfield and Searle, 2000; Myrow *et al.*, 2003; 2006; 2009, 2015; 2016; 2018; Hughes *et al.*, 2005; 2018; Hughes, 2016). According to the third view (DeCelles *et al*., 2000) the Indian HH and TH represent an exotic terrain that accreted to the northern Indian margin during the late Cambrian-early Ordovician.

We, herein, present the first record of trace fossils, globally considered Ordovician (Tremadocian-Arenigian) in age, from the Nigalidhar syncline (Fig. 1B, C), which provides first evidence of Ordovician sedimentation in Indian part of LH. Prior to the present study, the Ordovician strata were unknown in the Indian LH as well as in the Hazara (Pakistan LH) and the Salt Range regions (Pakistan SH), though extensively developed in the TH of India and Pakistan.

This study also documents an angular discordance between the lower Cambrian sequence and the Ordovician sequence in the Nigalidhar syncline of Indian LH, which can be related to the Kurgiakh orogeny in the Indian LH during the Cambro-Ordovician interval.

This record is an important addition to the first order stratigraphic framework of the Indian LH having a seminal bearing on the stratigraphy, tectonics and paleogeography of the LH.

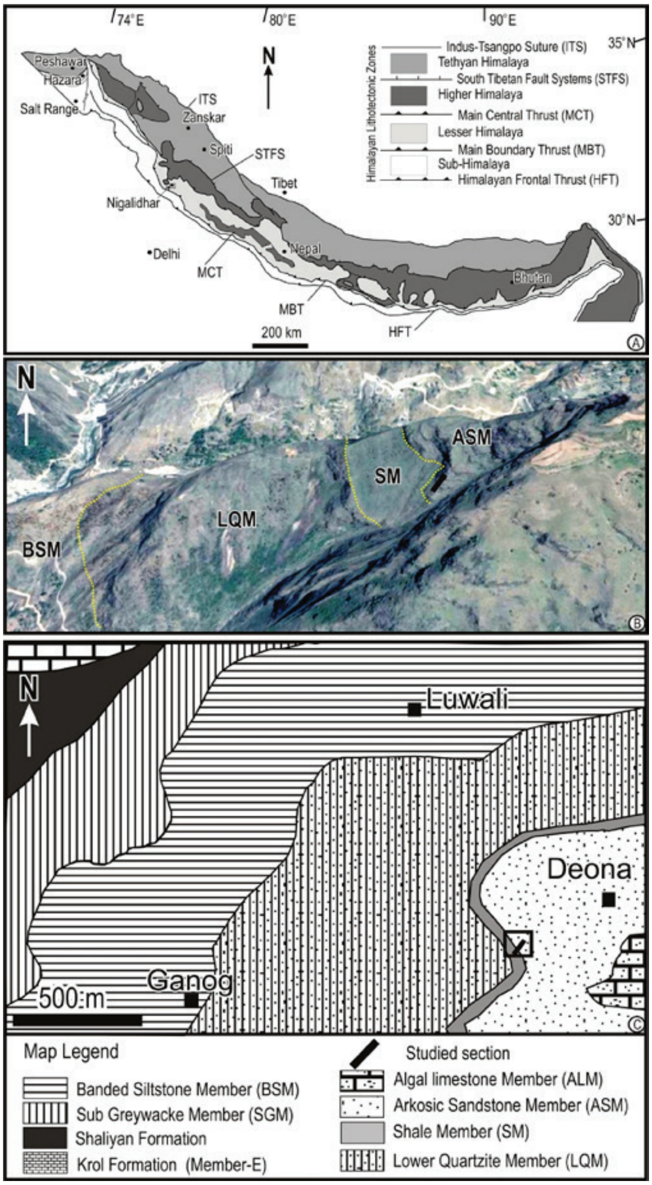

Fig. 1. (A) Lithotectonic subdivision of the Himalaya and respective fault-thrust systems, and location of the Nigalidhar syncline in the Lesser Himalaya, (B) Google-earth image of the Ganog-Deona localities and the distribution of various members of the Tal Group and position of the studied section (black box), Abbreviation BSM=Banded Siltstone Member, LQM=Lower Quartzite Member, SM=Shale Member, and ASM=Arkosic Sandstone Member, (C) Simplified geological map of the Ganog-Deona localities, Nigalidhar syncline (after Bhargava *et al*., 1998).

Geological setting and lithostratigraphy

In the Nigalidhar syncline (Sirmaur district, Himachal Pradesh) (Fig. 1B, C), the ~3300 m thick Tal Group (Bhargava *et al*., 1998; Hughes *et al*., 2005), is divisible into the Shaliyan (393 m), Sankholi (1380 m) and Koti Dhaman (1382 m) formations (Bhargava *et al*., 1998; Hughes *et al*., 2005), further sub-divisible into ten members (Table 1) (Bhargava *et al*., 1998).

The Shaliyan Formation (Tal Group) in the Nigalidhar syncline is Ediacaran-Cambrian in age (Bhargava *et al*., 1998; Tarhan *et al*., 2014). The uppermost part of the Banded Siltstone Member (Sankholi Formation) yielded trilobite fauna of

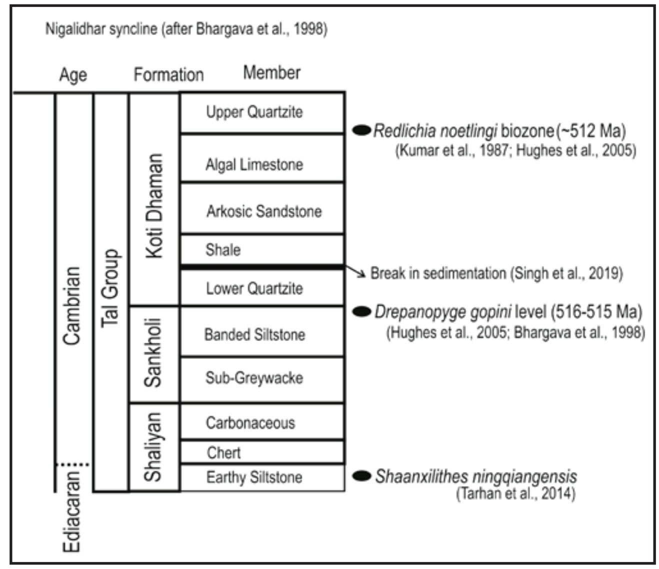

Table 1. Lithostratigraphic classification of the Tal Group in the Nigalidhar syncline and biostratigraphic age control (modified after Bhargava et al., 1998).

Drepanopyge gopeni level (516-515 Ma) (Hughes *et al.*, 2005; Bhargava *et al*., 1998). The age of the Tal Group above the Shale Member (SM) (*Redlichia noetlingi* biozone, 512 Ma, Kumar *et al*., 1987; Jell and Hughes, 1997) has been debatable due to the absence of age diagnostic fossils (Myrow *et al*., 2003; Hughes *et al*., 2005). It was surmised that age of the Arkosic Sandstone (ASM), Algal Limestone (ALM) and Upper Quartzite (UQM) members, above the late early Cambrian SM, is Drumian or Furongian or younger (Myrow *et al*., 2003; Hughes *et al*., 2005).

Ganog-Deona section and Trace fossils

The trace fossils come from the ASM exposed along a foot track in a cliff section NE of the Ganog village leading to the Deona village (Figs. 1-4) in the NW part of the Nigalidhar syncline (GPS coordinates: N 30°40’28.51”, E 077°29’3.75”). Along this section, Kumar *et al*. (1987) described the trilobite *Redlichia noetlingi* from the SM. The studied section lies immediately above the SM (Figs. 2-4). We measured ~21 m thick succession of the ASM, which comprises thinly bedded fine-to medium grained sandstone (rippled) alternating with thin shale and siltstone intervals (Figs. 3, 4A, B). The upper interval of this section is marked by conspicuously cross-stratified strata. The lower part of the studied section is highly bioturbated and contains abundant trace fossils. Body fossils are not observed in the present study. The thin couplets of siltstone and sandstone show micro-hummocky cross-beds and rippled surfaces with highly bioturbated base of the sandstone layers (Fig. 4B). In the present study more than 231 specimens of well-preserved trace fossils are collected *in situ* as well as from debris lying just close to the section. The distribution of the recorded trace fossils along the section and their known stratigraphic ranges are shown in Fig. 3 and Table 2 respectively.

Systematic Ichnology

The trace fossil material described herein is deposited at the Department of Geology, Panjab University, Chandigarh, India (Prefix: CAS/NIG). Specimens were photographed using Canon (power shot) SX540HS under low-angle light.

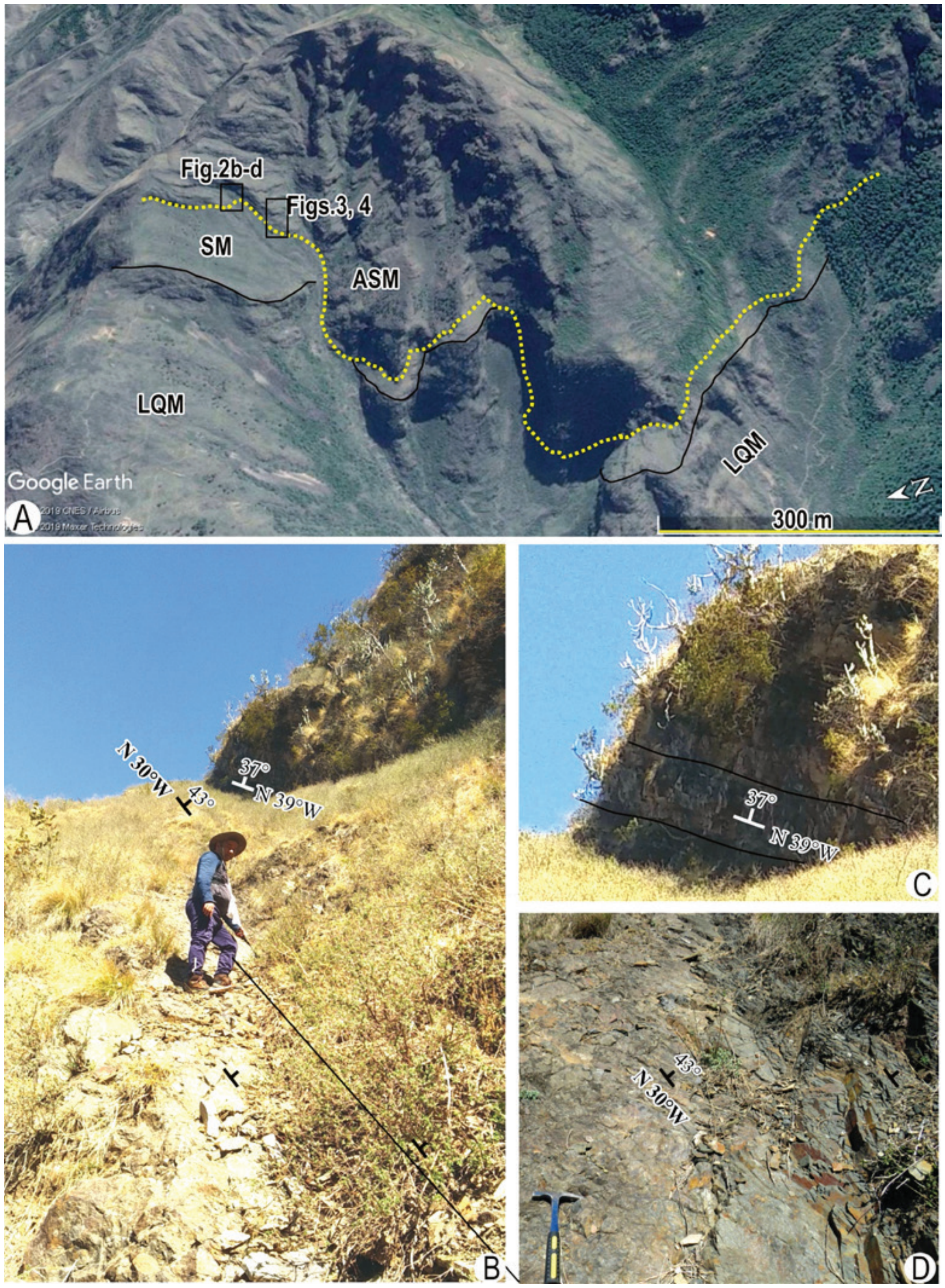

Fig. 2. (A) Google-earth image of the outcrops showing the erosional and angular discordance between the Shale Member (SM) and Arkosic Sandstone Member (ASM) at Ganog-Deona section. Note the variation in thickness of the SM. (B) close-up view of the angular discordance; (C) close-up view of the ASM showing the dip amount/ direction, (D) close-up view of the SM showing the dip amount/ direction.

Ichnogenus Arthrophycus Hall, 1852
Arthrophycus cf. *A. brongniartti* (Harlan, 1832)
(Pl. II, fig. 4)

Material: One slab (CAS/BP-NIG/31) containing one poorly preserved specimen.

Description: Linear-to-slightly-curved, unbranched, horizontal to subhorizontal burrow, parallel to the bedding, exhibiting poorly preserved regularly annulated surface, and preserved as hyporeliefs. Burrow is 2.5 cm long and 10 mm wide; annulations are regularly spaced.

Remarks: Seilacher (2000) included the ichnogenera *Arthrophycus*, *Daedalus* and *Phycodes* within the arthrophycid burrows. Rindsberg and Martin (2003) emended the diagnosis of *Arthrophycus.* Cambrian occurrences of *Arthrophycus* are reinterpreted under *A. minimus* (Mángano *et al*., 2005). *A. brongniartii* (Harlan, 1832) is indicative of Lower Ordovician–Lower Silurian strata (cf. Buatois and Mángano, 2011; Seilacher, 2000; Rindsberg and Martin, 2003; Belaústegui *et al*., 2016). *Arthrophycus* is a feeding trace (fodinichnion) of worms and arthropods (Seilacher, 2000, 2007; Rindsberg and Martin, 2003; Mángano *et al*., 2005).

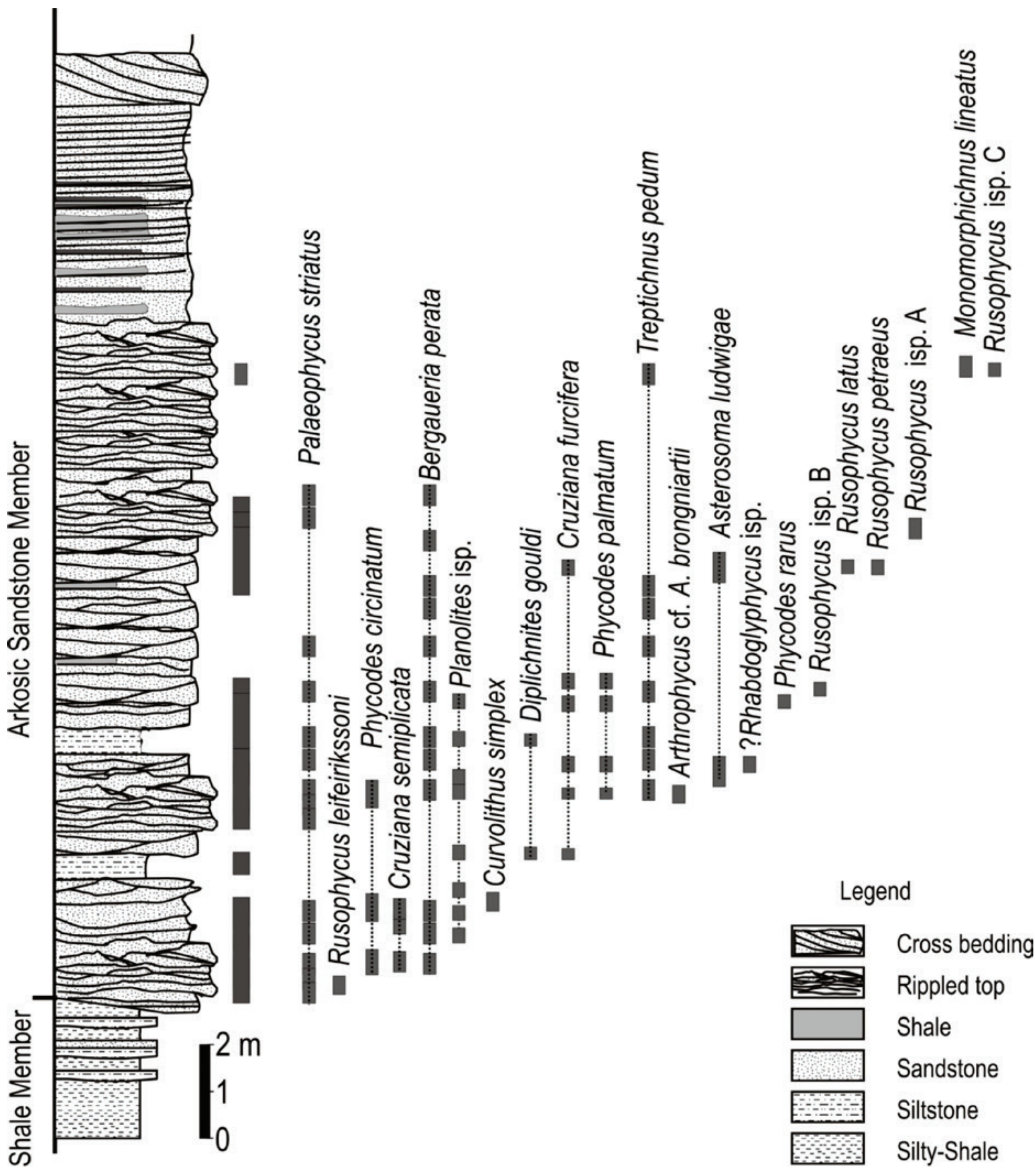

Fig. 3. The litholog of the measured section at Ganog-Deona localities showing the distribution of various recorded trace fossils. Black bars adjoining the lithocolumn indicate densely fossiliferous levels.

Ichnogenus Asterosoma von Otto, 1854
Asterosoma ludwigae Schlirf, 2000
(Pl. II, fig. 9)

Material: Dozens of specimens observed in the field and one collected and depicted slab (CAS/BP-NIG/78). Description is based on the depicted specimen (Pl. II, Fig. 9).

Description: Cylindrical ramifying burrow structure with three to four short horizontal burrows radiating from a central shaft normal to the bedding surface. Short burrows (2.0-2.7 cm wide and 4.0 to 10 cm long) enlarge with distance from the central shaft (*i.e*., bulbous nature) and show fine striae on surface. Trace is preserved as convex hyporelief.

Remarks: *Asterosoma* is best documented from the Devonian and younger successions (*e.g*., Seilacher, 2007). *Asterosoma ludwigae* is well known from the Carboniferous Atoka shale (Chamberlin, 1971) and Jurassic successions in North of Guincho (Neto de Carvalho and Rodrigues, 2007). *Asterosoma* is distinguished from the ichnogenus *Phycodes* by its bulbous-shaped burrow terminations. *Asterosoma* is attributed to decapod crustacean producer; *e.g*., Altevogt (1968), Häntzschel (1975), Schlirf (2000), Neto de Carvalho and Rodrigues (2001, 2007).

Fig. 4. (A) Field photograph of the outcrop of the Arkosic Sandstone Member (ASM) along the Ganog-Deona section which yielded trace fossil, (B) close-up view of the highly bioturbated thin-interbedded shale-siltstone and fine-to medium-grained rippled sandstone of Arkosic Sandstone Member (ASM), (C) the soft sediment deformation in the ASM.

Ichnogenus Bergaueria Prantl, 1945
Bergaueria perata Prantl, 1945
(Pl. II, fig. 11)

Material: Twenty four slabs (CAS/BP-NIG/37 to CAS/BP-NIG/61) containing thirty seven specimens.

Description: Plug-shaped, cyclindrical to gently conical, smooth burrows with flat wider base. Side of burrows have prominently developed concentric ornamentation, central depression faintly preserved. The burrows are 17 to 21 mm in length; diameter at the top is 21 to 26 mm. The burrows are preserved in full relief.

Remarks: Bergaueria perata was first described from the Upper Ordovician Letná Formation of Czech Republic (Prantl, 1945). Pemberton *et al*. (1988) diagnosed *Bergaueria perata* as bergauerians with smooth walls, faint radial ridges with central depressions. They recognized four distinctive ichnospecies of *Bergaueria*, i.e., *B. perata* Prantl, 1945, *B. langi* Hallam, 1960, *B. radiata* Alpert, 1973 and *B. hemispherica* Crimes *et al.*, 1977. *B. perata* differs from *B. radiata* and *B. hemispherica* by the absence of faint radial ridges (Pemberton *et al*., 1988). *Bergaueria* is regarded as a cubichnion or domichnion structure produced by suspension feeding actinarians (Prantl, 1945; Arai and McGugan, 1968, 1969; Alpert, 1973; Pemberton *et al*., 1988). The ichnogenus *Bergaueria* is known from the earliest Cambrian to the Pleistocene sequences (Crimes and Germs, 1982; Crimes, 1987; Pemberton and Jones, 1988; Pemberton *et al*., 1988; Pemberton and Magwood, 1990; Jensen and Grant, 1998; Pokorny *et al*., 2017; Solórzano *et al*., 2017; Hoşgör and Yilmaz, 2018). *Bergaueria perata* ranges mostly from the early Cambrian to the late Silurian (Ludlow) (Orlowski and Radwanski, 1996; Jensen and Grant, 1998; Seilacher, 2007; Pacześna, 2010; Stachacz, 2016; Hoşgör and Yilmaz, 2018).

Ichnogenus Cruziana d'Orbigny, 1842
Cruziana semiplicata Salter, 1854
(Pl. I, fig. 1; Pl. III, fig. 1)

Material: Two slabs (CAS/BP-NIG/39 to CAS/BP-NIG/61) containing three fragmentary specimens. Additionally, a few poorly preserved specimens observed in field.

Description: Slightly curved to straight *Cruziana* with two well-developed lobes separated by a clear median furrow. Lobes are 8-10 cm in length and 2-2.2 cm wide, and 5-6 mm deep, margin with pleural groove (Pg), and endopodal scratch marks (Sc) are poorly visible in these weathered samples.

Remarks: The preservation of these specimens although does not show the fine morphology of scratch marks properly, but due to the presence of pleural groove (Pg) these specimens can be categorised under *C. semiplicata, C. rouaulti* or *C. goldfussi*. *C. semiplicata* is known from Furongian (late Cambrian) to early Ordovician, *C. goldfussi* and *C. rouaulti* are typical Ordovician forms. However, the presence of scribbling behaviour (crossing-over in Pl. I, fig. 1) and poorly preserved sets of scratches marks (Sc) in our specimens are similar to *C. semiplicata*, hence we grouped them under *C. semiplicata. C. rouaulti* also possesses pleural groove, but it is smaller in size and characterised by very flat lobes lacking the scratch patterns. Our specimens show moderate lobes and faintly preserved scratches which differentiate them from *C. rouaulti*. Our specimens fall under the preservation variant of *C. semiplicata* (Seilacher, 2007) having lateral ridge and faintly preserved scratches on lobes. The specimen (Pl.I, fig. 1) shows the gradual curvature which is a common feature of *Cruziana semiplicata* and it is attributed to the limited capabilities of the producer for lateral bending (Fortey and Seilacher, 1997). *Cruziana semiplicata* is associated with a range of behavioural variants including the scribbling pattern (Fortey and Seilacher, 1997). Although our slab shows incomplete specimens, yet it shows overlapping-pattern of two specimens which may be related to a scribbling behaviour of *C. semiplicata*. Neto de Carvalho (2006) also reported the scribbling behaviour in *Cruziana rugosa* group from the Ordovician Armorican Quartzite. Egenhoff *et al*. (2007) stated that *C. rugosa*, however, seems to be in fact restricted to a middle Tremadocian to Arenig interval throughout Gondwana but *C. rugosa*, *C. furcifera* and *C. goldfussi* do occur in Middle Ordovician successions in the Armorican Massif (Delgado, 1886; Lessertisseur, 1955; Seilacher, 1992) and in North Africa (Desio, 1940; Seilacher, 1992). Magwood and Pemberton (1990) reported *C. rugosa, C. furcifera* and *C. goldfussi* from the early Cambrian Gog Group, Canada which was revised and placed to *C. pectinata* (Seilacher, 1994).

Cruziana furcifera d'Orbigny, 1842
(Pl. I, figs. 2-4; Pl. II, fig. 1)

Material: Four slabs (CAS/BP-NIG/12 to CAS/BP-NIG/15) containing five specimens, and few poorly preserved specimens observed in field.

Description: Straight to slightly curved bilobate ridges (convex hyporeliefs) of uniform or slightly varying width (depending on the depth of the trace maker in the substrate; cf. Buatois and Mángano 2011, p. 257, Fig. 13.5k) ranging from 20 to 23 mm. The lobes of the ridges are rather low (60 to 153 mm), regular (semi-elliptical) in cross section. The lobes meet in a V-shaped furrow or, if the tracemaker moved shallowly or if the substrate was slightly eroded, the furrow may resemble a partly filled V (again, see cf. Buatois and Mángano 2011, p. 257, Fig. 13.5k). Surface of the lobes is densely covered by prominent ridges, which are 0.5 to 0.8 mm wide. The ridges meet in the median furrow at an angle 20º to 30º, forming thereby the pattern of narrow wedged V-letters.

Remarks: Cruziana furcifera (i.e. a key ichnospecies of the *rugosa* group) is by far the most common and best preserved in the present collection. *C. furcifera* described in the present work shows variation in mode of preservation due to preservation in different lithologies *i.e.* in thin medium grained sandstone (Pl.I, fig. 2), in shale (Pl.I, fig. 3), in siltstone (Pl.I, fig. 4) and fine- medium sandstone (Pl. II, fig. 1). The specimen (Pl.I, fig. 3) is preserved in shale (very fragile) and it displays "sets" of striae that seem to be arranged in a non-opposite symmetry due to compaction deformation in the finer lithology. Although this particular specimen also has some similarities with *C. rugosa,* but latter is characterised by steep vertical declining margins which are lacking in our specimen. The specimen is preserved at just interface of reddish siltstone and shale (Pl.I, fig. 4) and partially covered by compact shale (hard to remove) hence the specimen exhibiting the local presence of thicker clusters of striae (see last yellow arrow on the right). This specimen also exhibits wide axial furrow which is not very common in the *C. rugosa* group, however; the grouping of striae are certainly multiple and reminiscent of this group. In this paper, we follow the concept of Egenhoff *et al.* (2007) and many other authors, retaining the members of the of the *rugosa* group at the ichnospecies level, in contrast to Mángano and Buatois (2003) those regarded *C. furcifera*, *C. goldfussi* and *C. rugosa* as subichnospecies of *C. rugosa*. *C. furcifera* has widest palaeogeographic distribution (Seilacher, 1970) and is well known from the Ordovician (Egenhoff *et al.*, 2007).

Ichnogenus Curvolithus Fritsch, 1908
Curvolithus simplex Buatois *et al*., 1998
(Pl. II, fig. 8)

Material: One slab (CAS/BP-NIG/68) containing one specimen, two poorly preserved specimens studied in field.

Description: Endichnial trilobate band-like curved structure, 5–6 mm wide, and 30 mm long. Its central wider part is 4 mm wide and is slightly convex (elevated). It is bordered by two side semicircular steep bevels that are 1.2–1.4 mm wide.

Remarks: Curvolithus was first described from the Bohemian Upper Ordovician (Fritsch, 1908) on the basis of fragmentary specimens. Later on, Buatois *et al*. (1998) revised the ichnogenus *Curvolithus* and discussed the morphology and defined a new ichnospecies *Curvolithus simplex*. Seilacher (2007) provided the detailed morphology of *Curvolithus. Curvolithus* is distinguished from other similar forms (*e.g*., *Aulichnites*, *Psammichnites*) by its trilobate upper surface. Fritsch (1908) interpreted *Curvolithus* as a locomotion trace (repichnion). Seilacher (1990, 2007) suggested the flat worms (tubellarians) as trace makers of *Curvolithus*. Buatois *et al*. (1998) stated that it is made by scavenging gastropods as well as carnivorous forms and also tubellarian or nemertean worms cannot be excluded. In all, *Curvolithus* ranges in age from Precambrian (Webby, 1970) to Miocene (Keij, 1965). It occurs in various shallow marine settings, i.e., brackish, distal fan deltas, tidal flats and offshore settings (Buatois *et al*., 1998; Henken *et al*., 2016).

Ichnogenus Diplichnites Dawson, 1873
Diplichnites gouldi Gevers (in Gevers *et al.*), 1971
(Pl. IV, fig. 5)

Material: Five slabs collected and described; one slab (CAS/BP-NIG/32) containing several specimens is depicted in Pl. IV, Fig. 5.

Description: Highly crowded slab, showing the randomly oriented eight to nine sets of trackways; sets comprise 3 to 8 thick, straight to slightly curved, conical to elongate ridges. Lengths of trackways varies from 30 mm to 80 mm. Trackways also show as a single, broad central drag mark (lower part of the Pl. IV, Fig. 5).

Remarks: Seilacher (1985) defined *Diplichnites* as an undertrack of *Cruziana*; it is attributed to digging action by the organism into a mud–sand interface (Seilacher, 1955, 1970; Goldring and Seilacher, 1971; Seilacher, 1983, 1985, 2007). Crimes (1970) interpreted it as a result of faster speed of locomotion of the tracemaker of *Diplichnites*. Crimes (1970), Young (1972) and Gibb *et al.* (2017) illustrated that some *Cruziana* to *Diplichnites* trackways are transitional. The ichnogenus *Diplichnites* is known from Cambrian to Mesozoic (Lucas *et al*., 2006); however, *Diplichnites gouldi* has a stratigraphic range from Ordovician to Permian (Gevers

EXPLANATION OF PLATE I

Ordovician trace fossils from the Arkosic Sandstone Member (Deona Formation), Nigalidhar syncline. Fig. 1. ***Cruziana* cf. *semiplicata*** showing pleural groove (Pg) and faintly preserved scratch marks (Sc) and crossing over (Cg) pattern. Figs. 2-4. ***Cruziana furcifera,*** variable mode of preservation in sole of thin quartzite (2, 4) and silty-shale (3) beds.

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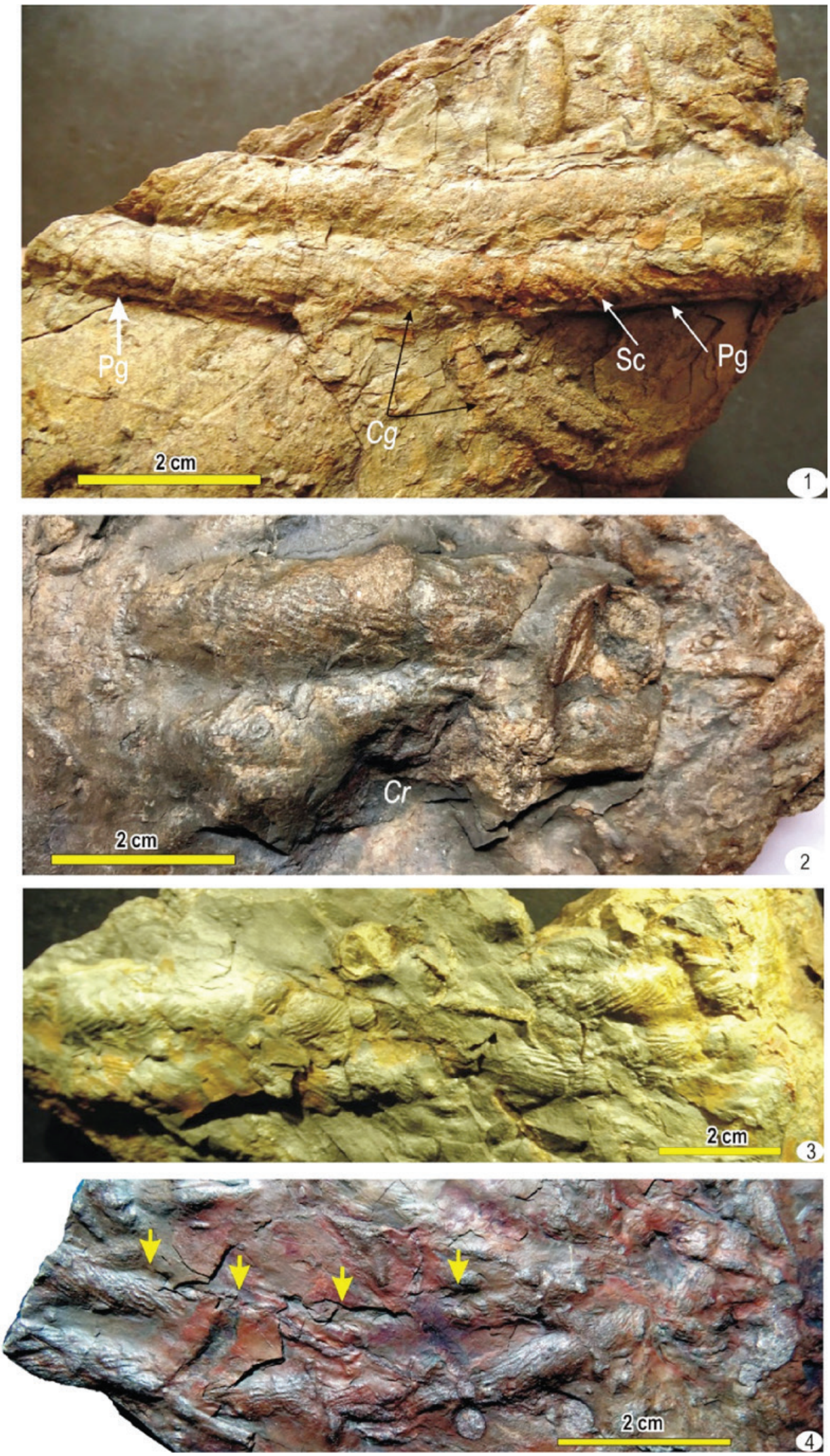
Plate I



*et al.*1971; Bradshaw, 1981; Wright *et al.*, 1995; Trewin and McNamara, 1994; Draganits *et al.*, 1998, 2001; Iasky *et al.*, 1998; Hunt and Lucas, 2005; Myrow *et al.*, 2016; Smith *et al.*, 2003). Myriapods are considered as the most likely producers of *Diplichnites gouldi* (Bradshaw, 1981; Johnson *et al.*1994; Trewin and McNamara 1994). In Himalaya, it is known from the Ordovician (Myrow *et al.*, 2016) and Devonian (Draganits *et al.*, 1998, 2001).

Ichnogenus Monomorphichnus Crimes, 1970

Monomorphichnus lineatus Crimes *et al*., 1977
(Pl. II, fig. 6)

Material: One slab (CAS/BP-NIG/17) containing one specimen.

Description: Six parallel straight to slightly curved ridges, each is 14 to 21 mm long, 1.1-1.2 mm wide and 1.6 mm high, with an interval of 1.4 mm between each ridge. The trace is preserved as convex hyporelief. Lower ridges are overlapping with small *Planolites*.

Remarks: Crimes (1970) erected *Monomorphichnus* for traces made by trilobites raking the sediments. *M. lineatus* differs from *M. bilinearis* (type ichnospecies) by its seires of single ridges. It differs from *M. multilineatus* in latter the central ridges are deeper than outer ridges. Our specimens closely show the characters of *M. lineatus*. *Monomorphichnus* is a wide ranging ichnogenus, known from Cambrian (Crimes *et al.*, 1977) to Triassic (Shone, 1979; Fillion and Pickerill, 1990; Gibb *et al.*, 2009).

Ichnogenus Phycodes Richter, 1850
Phycodes circinatum Magdefrau, 1934
(Pl. II, fig. 5)

Material: One slab (CAS/BP-NIG/98) containing one specimen.

Description: Tightly packed bundles of five retrusive spreite burrows, which curve back distally in a palmate fashion. Burrows are 38 mm to 60 mm in length and 8 to 18 mm wide. Preserved as convex hyporelief on sole of thin quartzite bed.

Remarks: In Gondwana, *Phycodes circinatus* is apparently restricted to the Lower Ordovician (MacNaughton, 2007); in Laurentia, it is known from lower Cambrian (Magwood and Pemberton, 1990) to middle Ordovician (Fillion and Pickerill, 1990). *Phycodes circinatus* in the Himalaya is known from the Ordovician of Kinnaur (Bhargava *et al.*, 1983; Bhargava and Bassi, 1998).

Phycodes palmatum Hall, 1852
(Pl. III, fig. 5; Pl. IV, figs. 2, 4)

Material: Dozens of slabs observed in field, and two slabs (CAS/BP-NIG/19 and CAS/BP-NIG/20) is described.

Descriptions: The specimen (Pl. IV, fig. 2) comprises bundle of three sand filled endogenic burrows, originating from a single horizontal burrow. Each burrow is 50 to 78 mm long, and 11 to 12 mm wide, and preserved as convex hyporelief on sole of quartzite beds. The specimen (Pl. IV, fig. 4) shows palmate type of arrangement of burrows, proximal part covered, distally branching into three distinctive, non-uniform branches. Individual burrows are mostly 50-100 mm in length and 11 to 17 mm wide.

Remarks: Phycodes palmatus is characterised by the small number of burrows branching from a single point. It is known from Cambrian to Jurassic (Seilacher, 1955; Glaessner, 1969; Daily, 1972; Banks, 1970; Germs, 1972; Crimes and Germs, 1982; Crimes *et al.*, 1977; Fritz and Crimes, 1983; Joseph *et al.*, 2012). In the Himalaya, it is known from the Ordovician of Kinnaur (Bhargava *et al.*, 1983)

Phycodes rarus Hanken, Uchman, Nielsen, Olaussen, Eggebø and Steinsland, 2016
(Pl. IV, fig. 1)

*Material: One slab (*CAS/BP-NIG/27) of quartzite.

Description: Hypichnial, sparsely distributed, long, curved to slightly winding, successively branching cylinders converging in a stem (Pl. IV, fig. 1). Branches are smooth; a few branches exhibit finer granulation; few branches plunge gently in the bed, and some overlaps at different levels. It occurs in association with the a few specimens of *Phycodes pedum* on the same slab.

Remarks: Hanken *et al.* (2016) erected *Phycodes rarus* from the upper Ordovician of Norway for the *Phycodes* having long, winding, sparse tubes, converging in a proximal stem. Although, they pointed out that if *Phycodes* is formally confined to tightly-spaced bundles (Seilacher, 2007), *Phycodes rarus* should be transferred to another ichnogenus. We follow Hanken *et al.* (2016) and assign our specimen to *Phycodes rarus* based on the diagnosis characters described for the ichnospecies. *Phycodes rarus* is known from the Ordovician (Hanken *et al.*, 2016).

Ichnogenus Palaeophycus Hall, 1847
Palaeophycus striatus Hall, 1852
(Pl. II, fig. 6; Pl. IV, fig. 3)

Material: Dozens of slabs observed in field, and two were collected (CAS/BP-NIG/28 and CAS/BP-NIG/29).

Description: Horizontal, branched or unbranched, straight to slightly curved burrows, covered with longitudinal striae (Pl. IV, Fig. 3), preserved as convex hyporelief. Burrow-fill is massive and same as of the host rock. Burrows are 8 to 16 mm in diameter, and up to 100 mm long.

Remarks: Palaeophycus striatus is defined as thinly lined *Palaeophycus*, sculpted by continuous, parallel, longitudinal striae (after Pemberton and Frey, 1982; Fillion and Pickerill, 1990). Our specimens clearly show continuous, parallel, longitudinal striae (Pl. IV, Fig. 3). *Palaeophycus* has long stratigraphic range from Cambrian to Pleistocene (Pemberton and Frey, 1982; Narbonne *et al.*, 1987; DÁlessandro and Bromley, 1986).

Ichnogenus Planolites Nicholson, 1873
Planolites isp.
(Pl. III, fig. 4)

EXPLANATION OF PLATE II

Ordovician trace fossils from the Arkosic Sandstone Member (Deona Formation), Nigalidhar syncline. Fig. 1. ***Cruziana furcifera*** exhibiting cross-over pattern (arrow head). Fig. 2. ***Rusophycus leifeirikssoni***. Fig. 3. ***Rusophycus*** isp.-A. Fig. 4. ***Arthrophycus brongniartii***. Fig. 5. ***Phycodes circinatum***. Fig. 6. ***Palaeophycus striatus***. Fig. 7. ***Rusophycus petraeus***. Fig. 8. ***Curvolithus simplex***. Fig. 9. ***Asterosoma ludwigae***. Fig. 10. *?**Rhabdoglyphus*** isp. Fig. 11. ***Bergaueria perata***.

Plate II

Material: Dozens of specimens observed in field, one slab collected (CAS/BP-NIG/07).

Descriptions: Simple, unlined, unbranched, 5 to 46 mm long, cylindrical or subcylindrical infilled burrows, straight to gently curved, horizontal to oblique to bedding planes, and a few burrows seem to intersect in different planes and have wider ends. Burrows filled by material slightly coarser than the host rocks.

Remarks: The specimen is strongly bioturbated and contains abundant *Planolites* isp., ?*Helminthopsis* isp., and *Treptichnus pedum*. *Planolites* is interpreted as dwelling and deposit feeding structures. It is a long ranging ichnogenus known from a wide variety of shallow marine settings (Häntzschel, 1975; Pemberton and Frey, 1982; Fillion and Pickerill, 1990; Keighley and Pickerill, 1995; Uchman, 1998; Ekdale *et al.*, 2007).

Ichnogenus Rusophycus Hall, 1852
Rusophycus leifeirikssoni Bergström, 1976
(Pl. II, fig. 2)

Material: One slab (CAS/BP-NIG/79) of quartzite bearing the sole trace fossil.

Description: Deep bilobate structure with apple shaped outline, preserved as positive hyporelief. Length is 50 mm; width is 40 mm; depth is 27 mm. Lobes are almost vertical, perpendicular to bedding plane. Anterior part is deeper and narrower than posterior part. Lobes with poorly preserved scratch marks are perpendicular to the axis.

Remarks: Bergström (1976) and Seilacher (1985, 1992, 2007) consider *Rusophycus leifeirikssoni* an opisthocline (tail down) structure made by trilobite. However, Fillion and Pickerill (1990) and Mángano and Buatois (2003, 2004) consider as a prosocline (head-down) structure. *Rusophycus leifeirikssoni* is known from the lower Cambrian to Tremadocian of Gondwana.

Rusophycus petraeus (Seilacher, 1970)
(Pl. II, fig. 7)

Material: Two slabs collected, one depicted and described (CAS/BP-NIG/82).

Description: A series of equal, evenly curved, rather broad, 1-2 mm wide and 10 to 29 mm long scratch marks. The trace (or a series of traces) is rather irregular in the longitudinal direction (right – left in the figure).

Remarks: The *petraea* group is characterized by rounded, sub-equal scratch marks (Buatois and Mángano, 2011, p. 258). In our material, the sub-equal or rather equal scratch marks reach usually a series of 5 to 7 (these are equally slightly curved; they do not cross or even touch one another; their length is equal or changes fluently towards one of ends of a series). The *Cruziana petraea* as figured by Buatois and Mángano, 2011, Fig. 13.6a is a very short structure compared, e.g., by *C. furcifera* (herein Pl. II, fig. 1). Thereby, it is an objective problem to define the boundary between *Cruziana petraea* and *Rusophycus petraeus sensu* Seilacher (1992; 2007). Also among the material found and depicted herein (Pl. II, fig. 7), it is difficult to decide between *Cruziana* and *Rusophycus*. The ichnospecies *Cruziana petraea* Seilacher, 1970 and *Rusophycus petraeus* (Seilacher, 1970) are known from the Ordovician (Caradocian) of Jordan, Benin, Libya and Chad (Seilacher, 1970, 2007). Vintaned and Carls (2011) reported *Rusophycus petraeus* from the Middle-Upper Ordovician interval of the Cadena Ibérica Oriental (NE Spain). We follow the Vintaned and Carls (2011) and keep our specimen under *Rusophycus petraeus.*

Rusophycus latus Webby, 1983
(Pl. III, fig. 7)

Material: One slab (CAS/BP-NIG/86) with one specimen (depicted),

Descriptions: Heart-shaped *Rusophycus* with two well-defined asymmetrical lobes, separated by narrow axial furrows. Length is 40 mm and width is 50 mm. Depth is 21 mm. Lobe surface marked by poorly preserved transverse, coarse (thick) bifid scratch marks, which are parallel close to axial furrow. Genal spine ridge is preserved (base of left lobe).

Remarks: Rusophycus latus is characterised by the length/width ratio less than 1.0, bifid scratch marks running fully to margin and genal spine ridges may occur (Fillion and Pickerill, 1990). Our specimen, although partially weathered, exhibits genal spine ridge and length/width ratio aspects of *R. latus. Rusophycus latus* is known from the lower Cambrian to the Ordovician (Alpert, 1976; Webby, 1983; Fillion and Pickerill, 1990; Mángano *et al.*, 1996: Buatois and Mángano, 2011).

Rusophycus isp. A
(Pl. II, fig. 3)

Material: One slab (CAS/BP-NIG/103).

Descriptions: Elongate, posteriorly tapering bilobate hyporelief occurring at sole of a quartzite bed. Overall length is 25 mm and maximum width is 22 mm, and length / width ratio is nearly 1.2. Lobes are widest anteriorly and gradually taper to rear. Well-defined median furrow, widest anteriorly. Scratch marks are not preserved and lobes are covered with fine granular ornamentation.

Remarks: The lack of scratch marks prevents assignment of this specimen to a known ichnospecies, though, the length/width ratio is suggestive of *Rusophycus* Ichnogenus.

Rusophycus isp. B
(Pl. III, fig. 6)

Material: One slab (CAS/BP-NIG/17)

Descriptions: Small, bilobate hyporelief, 10 mm in length and 8 mm in width, with two lobes that taper posteriorly and gape anteriorly.

EXPLANATION OF PLATE III

Ordovician trace fossils from the Arkosic Sandstone Member (Deona Formation), Nigalidhar syncline. Fig. 1. ***Cruziana semiplicata***, showing pleural groove (Pg) and faintly preserved scratch marks (Sc), ***Cruziana*** is twin cross-cut by **?*Helminthopsis*** isp.; the subsequent trace fossil definitely appeared as a furrow (not as a tunnel), because it closely tracks the surface of ***Cruziana***. Below centre, a set of probably mechanic scratch marks occurs; below left, oval bulges may represent ***Lockeia*** isp. in convex hyporelief. Fig. 2. ***Treptichnus pedum***. Fig. 3. ***Rusophycus*** isp.-C, strongly bioturbated lower bedding plane with a small *Rusophycus* isp-C., in low-right part of the sample; other preserved fragments of traces belong to ichnogenera *Planolites*, *Lockeia* and ?*Skolithos* (broken-off casts of vertical shafts). Fig. 4. ***Planolites*** isp., in strongly bioturbated lower bedding plane along with several specimens of ?***Helminthopsis*** isp. (small grooves in the center and in lower-left part of the sample) and ***Treptichnus*** isp. along the upper edge of the figure. Fig. 5. ?***Phycodes palmatus***. Fig. 6. ***Monomorphichnus lineatus*** and small ***Rusophycus*** isp-B. Fig. 7. ***Rusophycus latus***, Figs. 8-10. ***Treptichnus pedum***.

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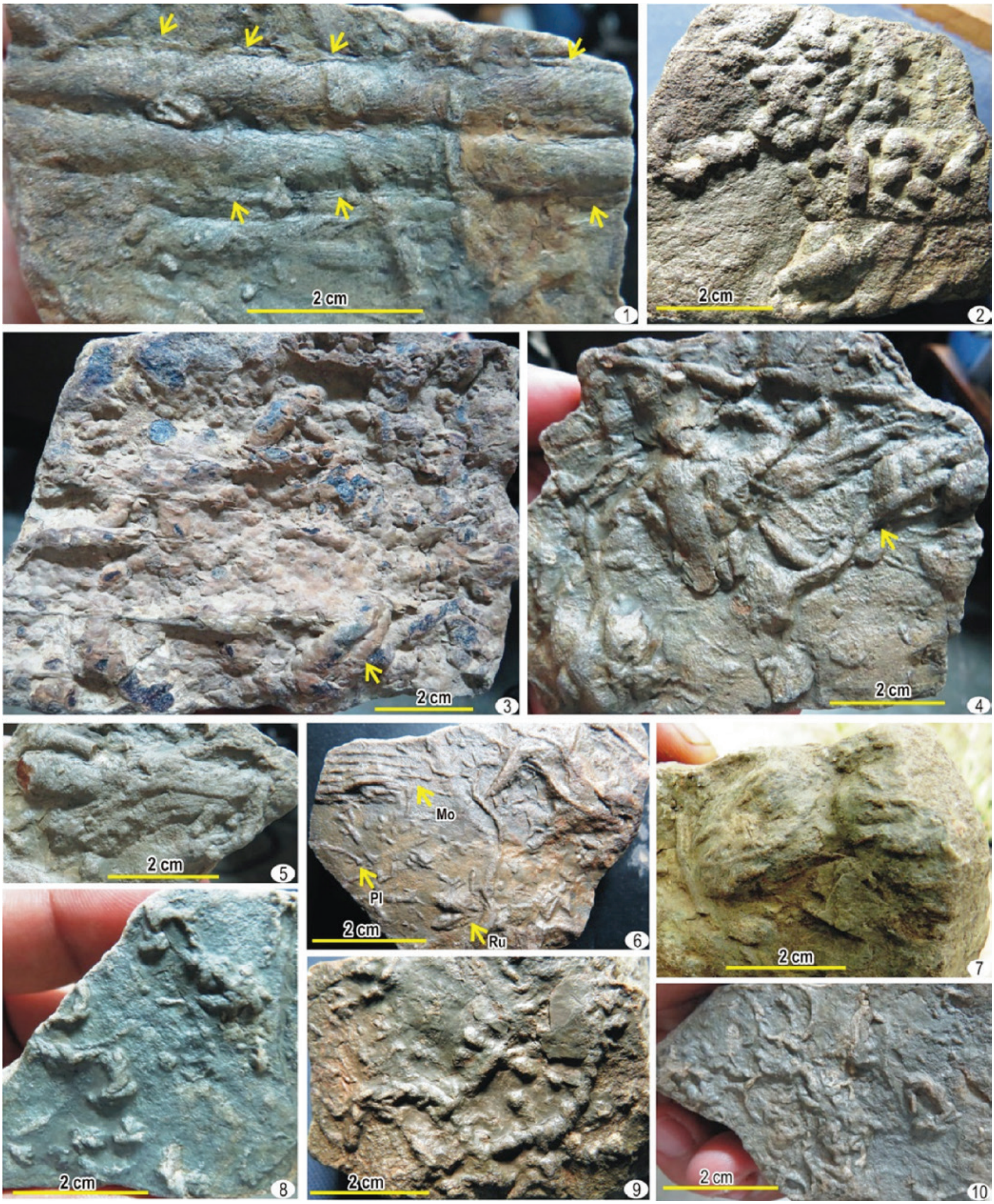
Plate III



Remarks: The small size and lack of prominent scratch marks prevent assignment to ichnospecies level.

Rusophycus isp. C
(Pl. III, fig. 3)

Material: One slab (CAS/BP-NIG/105)

Descriptions: Elongate, bilobate hyporelief, overall length is 26 mm and maximum width is 14 mm, with prominent median furrow with two lobes widest anteriorly and gradually taper to rear. One lobe is slightly wider. No scratch marks are preserved.

Remarks: The lack of prominent scratch marks prevents assignment to ichnospecies level.

Ichnogenus Rhabdoglyphus Vassoevich, 1951
?Rhabdoglyphus isp.
(Pl. II, fig. 10)

Material: One slab containing one specimen (CAS/BP-NIG/76)

Descriptions: Curved, cylindrical non-uniform, unbranched burrow with short invaginated segments, spacing of the segments not regular, preserved as positive hyporelief.

Remarks: Stanley and Pickerill, (1993) described the distinguishing features of *Rhabdoglyphus* and *Fustiglyphus*. According to them, *Rhabdoglyphus* has invaginated segments while *Fustiglyphus* has well-defined rings or knots with no invagination on. Our specimen more or less weathered shows invaginated segments, therefore doubtfully assigned to *Rhabdoglyphus*.

Ichnogenus Treptichnus Miller, 1889
Treptichnus pedum (Seilacher, 1955)
(Pl. III, figs. 2, 8-10)

Material: Dozens of slabs observed in field, and collected seven slabs and described three (CAS/BP-NIG/107, CAS/BP-NIG/112; CAS/BP-NIG/113).

Descriptions: The specimen (Pl. III, fig. 2) shows mutually touching short, prominent bulges forming a row and a cluster. The trace can be understood as several crosscutting specimens of *Treptichnus pedum.* The specimen (Pl. III, Fig. 8) is small (<2 cm), consists of small eight to nine curved burrows, oriented obliquely to the curved trace axis, preserved as a hyporelief structure. The specimen (Pl. III, fig. 9) shows convex hyporelief, short "bars" oriented obliquely to the curved trace axis and also exhibits single-sided addition of small curves. The specimen (Pl. III, fig. 10) shows short bars, tapering towards their ends, preserved in convex hyporelief; these are mostly curved. Center right, a nearly closed elliptical structure composed of bars oriented obliquely to the trace axis.

Remarks: A wide variety of preservation mode of *Treptichnus pedum* is recorded in studied material but generally they are smaller in size compared to those recorded so far from the Himalaya. *Treptichnus* is interpreted as a systematic feeding structure with each segment reaching up to the sediment surface (Seilacher and Hemleben, 1966; Jensen, 1997) and known from earliest Cambrian to Triassic (Rindsberg and Kopaska-Markel, 2005; Metz, 2000). *Treptichnus pedum* is used to demarcate the Ediacaran-Cambrian boundary (Narbonne *et al.*, 1987; Landing *et al.* 2013; Geyer and Landing, 2016). In the Himalaya its distribution is discussed by Singh *et al.* (2017) and inferred that it is not useful in demarcation of the Ediacaran-Cambrian boundary.

Importance of the recorded trace fossils

According to the latest global stratigraphic distribution of trace fossils, the elements of *Cruziana* ichnofacies in the Arkosic Sandstone Member *i.e. Arthrophycus* cf. *A. brongniartti, Asterosoma ludwigae, Bergaueria perata, Cruziana semiplicata, Cruziana furcifera, Curvolithus simplex, Diplichnites gouldi, Monomorphichnus lineatus, Phycodes circinatus, Phycodes palmatum, Phycodes rarus, Palaeophycus striatus, Planolites* isp., *Rusophycus leifeirikssoni, Rusophycus petraeus, Rusophycus latus, Rusophycus* isp.-A , *Rusophycus* isp.-B, *Rusophycus* isp.-C, *?Rhabdoglyphus* isp, and *Treptichnus pedum* are assigned to early-middle Ordovician (Table 2). The age assignment is based on the *Cruziana* and *Arthrophycus* ichnostratigraphic schemes which have been extensively used for dating the Gondwanan lower Paleozoic successions that lack body fossils (Seilacher, 1970, 1990, 1992, 1994, 2000, 2007, Buatois and Mángano, 2011; Jensen *et al.*, 2011; Sadlok, 2014; Crimes 1970; Bergström, 1976; Baldwin, 1977; Fillion and Pickerill, 1990; MacNaughton, 2007; Egenhoff *et al.*, 2007). In adjoining Pakistan TH, the Misri Banda Quartzite too has been assigned an Ordovician age on the basis similar trace fossils (Pogue and Hussain, 1986). The presently reported trace fossils and the stratigraphic relationship of SM and the ASM is suggestive of a hiatus between the ASM and underlying lower Cambrian SM. The hiatus is supported by following evidences:

1. *Uneven thickness of the Shale Member and erosional contact*: The stratigraphic thickness of the SM varies along the strike of the member in the Ganog-Deona section with undulatory and erosional contact (Fig. 2A). The rocks of the ASM at the Deona cliff section occur as a valley-fill, suggesting an aerial exposure and erosion prior to the deposition of ASM.
2. *Angular discordance between the Shale Member and the Arkosic Sandstone Member*: The SM in the Ganog-Deona section strikes N330°W with a dip of 43°, while the overlying ASM strikes N321°W and dips at 37° showing an angular discordance of 6° (Fig. 2B-D).
3. *Soft sediment deformation in the Arkosic Sandstone Member*: The soft sediment deformation, reminiscent of paleosiesimites (Fig. 4C), indicate extension of post-orogenic tectonics. These features are similar to those observed in post-orogenic sediments of Himalaya.

Lithostratigraphic implications of the hiatus

Consequent to the recognition of an angular unconformity, the successions above the SM (~512 Ma) i.e. the ASM, ALM and UQM need to be delinked from the Tal Group (Table 3). We propose the name Deona Formation (Bhargava *et al.*, *in preparation*) to include the ASM, ALM and UQM. Nearly 400

EXPLANATION OF PLATE IV

Ordovician trace fossils from the Arkosic Sandstone Member (Deona Formation), Nigalidhar syncline. Fig. 1. ***Phycodes rarus***. Fig. 2. ***Phycodes palmatum***. Fig. 3. ***Palaeophycus striatus***. Fig. 4. ***Phycodes palmatum***. Fig. 5. ***Diplichnites gouldi***.

Plate IV

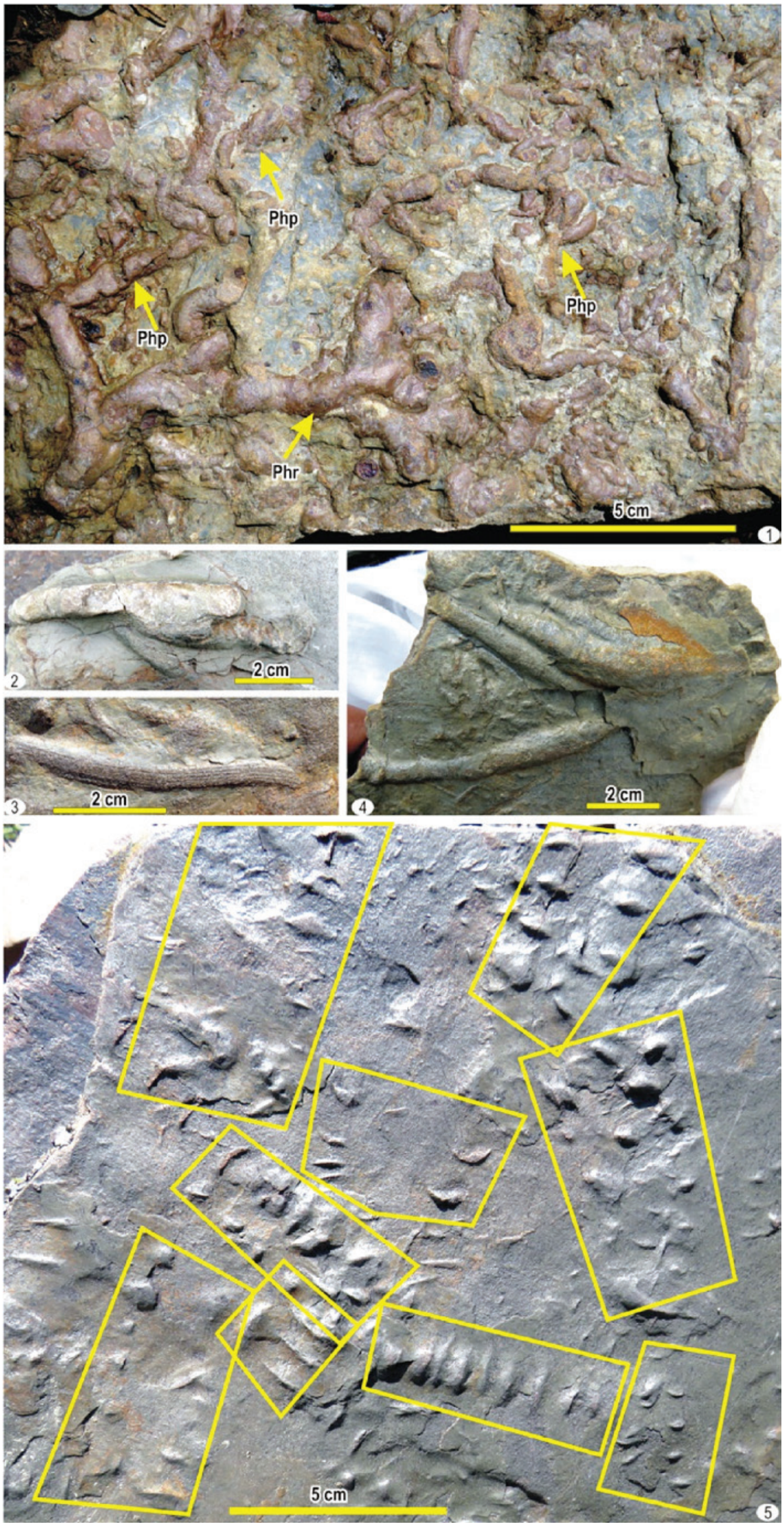
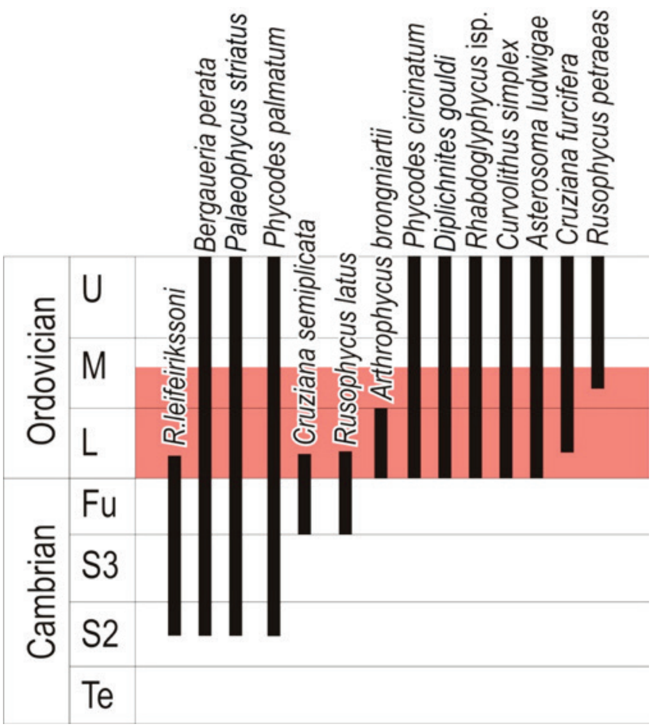


Table 2. Stratigraphic range of various ichnospecies of the *Cruziana*, *Rusophycus* and other important trace fossils recorded in the present study. Stratigraphic range is according to Buatois and Mángano (2011).



m of the sequence, above these trace fossils bearing succession, is yet to be evaluated for constraining the upper age limit of the Deona Formation in the Nigalidhar syncline. This is second dismemberment of the Tal Group; earlier Singh (1979b) had delinked the Nilkanth Formation (Cretaceous) from the Tal Group.

Tectonic significance

Singh (1979a, 1979b, 1979c) suggested a major break in sedimentation between the Cambrian (Tal Group) and the Nilkanth Formation (Cretaceous) within the LH. Singh (1979a, 1981) stated that after deposition of the Tal Group (lower Cambrian), the LH received short-lived transgressions of early Permian (Boulder Slate Formation), late Cretaceous (Nilkanth Formation) and late Paleocene-Eocene (Subathu Formation) along a narrow zone. According to Hughes *et al.* (2005), there is no firm age constraint on cessation of the pre-Permian sedimentation within the LH. Previous workers suggested that the LH formed a positive area after the lower Cambrian (Singh, 1979a, 1981; Valdiya, 1995, 1998; Bhargava, 2008, 2011). In the TH, there is a conclusive evidence of a late Cambrian–early Ordovician deformational event leading to a hiatus (Hayden, 1904; Bhargava and Bassi, 1998; Wiesmayr and Grassemann, 2002; Myrow *et al.*, 2016). It was followed by deposition of more or less complete Palaeozoic sequence commencing from the early Ordovician onwards with minor interruptions (Bhargava and Bassi, 1998). The lack of record of Ordovician-Carboniferous strata in the LH and the spectacular contrasts in the Palaeozoic facies between the TH and the LH have been widely used to propound various models of development of the Indian northern margin prior to the Cenozoic deformation (Gansser, 1964; Saxena, 1971; Bhargava, 1976; Searle, 1986; Aharon *et al.*, 1987; Brookfield, 1993; Corfield and Searle, 2000; DeCelles *et al.*, 2000; Myrow *et al.*, 2003; 2016; 2018 Yin, 2006; Bhargava, 2011; Yu *et al.*, 2015; Hughes *et al.*, 2018; Martin, 2017; Singh *et al.*, 2019).

The present discovery of the Ordovician trace fossils and strata in the Indian LH bridges the gap in the early Paleozoic geological history. The recorded angular discordance between the lower Cambrian Tal Group and Ordovician Deona Formation in the LH is interpreted as a manifestation of the late Cambrian-early Ordovician Kurgiakh orogeny (Srikantia *et al.*, 1980; Bhargava *et al.*, 2011; Myrow *et al.*, 2016). The Kurgiakh orogeny is mostly recognised in the TH (Srikantia *et al.*, 1980; Myrow *et al.*, 2016). Prior to the present report Bhargava *et al.* (2011) provided definite evidence pertaining to this orogeny in the LH. According to them, in the Tons valley, the Paleoproterozoic Dharagad Group, overlain by the Mesoproterozoic Deoban and Neoproterozoic Simla groups rests as a thrust sheet over the Chilar Formation, which occurs as windows and also as tectonic slivers within the overriding thrust sheet designated as the Dharagad Thrust Sheet. The present contribution makes the Kurgiakh orogeny an important event in the entire Himalaya, which was considered as a phase of the protracted Pan-African Orogeny (Valdiya, 1995, 1998).

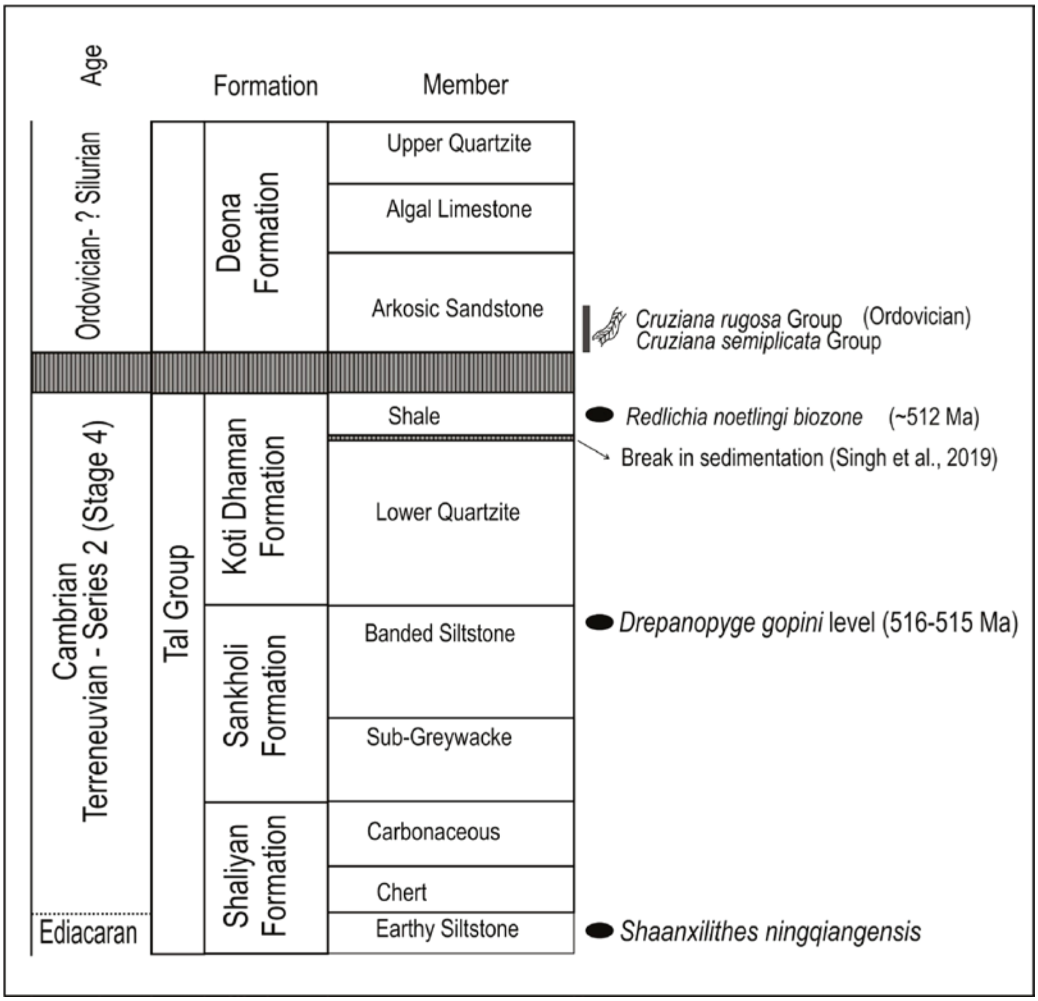
The present record of the Ordovician strata would prove valuable in postulating tectonic models and hypotheses regarding the stratigraphic architecture of the northern margin of the Indian plate during the early Palaeozoic. The Ordovician occurrence could not be isolated and restricted to a small area of the Inner Krol Belt and it may be also present in other parts of LH. Indirect evidence of the presence of an Ordovician sequence is provided by zircons in the Baxa Group in Bhutan (McQuarrie *et al.*, 2008). Presumably, the Ordovician basin could be widespread; its sediments due to intense tectonics in the LH are truncated and possibly occur as tectonic slivers interlayered with older formations and have, thus remained unrecognised. The present study emphasizes the necessity for a thorough search for the Ordovician faunal elements in so-called unfossiliferous sequences of the LH.

Paleobiogeographic implications

Worldwide, the trace fossil *Cruziana* and its various ichnospecies are widely known from the Ordovician of Algeria and Jordan (Seilacher, 1970, 1992, 2007), Turkey (Seilacher, 1992; 2007), Oman (Seilacher, 1992; Fortey and Seilacher, 1997); Libya (Seilacher, 1992, 2007; Seilacher *et al.*, 2002; Gibert *et al.*, 2011), Newfoundland (Bergstrom, 1976; Fillion and Pickerill, 1990), Wales (Crimes, 1970; 1975), Spain (Baldwin, 1977), Bolivia (Egenhoff *et al.*, 2007), Argentina (Buatois and Mángano, 2011; Aceñolaza, 1978; Aceñolaza and Durand, 1978; Aceñolaza and Fernández, 1978; 1984; Aceñolaza and Manca, 1982; Aceñolaza and Aceñolaza, 2003; Mángano *et al.*, 1996; 2001; Mángano and Buatois, 2003), France (Knaust, 2004, Neto de Carvalho, 2006; Neto de Carvalho and Baucon, 2016), Iran (Bruton *et al.*, 2004; Bayet-Goll and Neto de Carvalho, 2016), China (Yin, 1932; Yang and Fu, 1985; Yang, 1990) and Australia (Wells *et al.*, 1970; Ritche and Gilbert-Tomlinson, 1977; Gibb *et al.*, 2009) forming part of the Gondwana supercontinent. Outside the Gondwanan realm, the *Cruziana rugosa* group is also known from Russia (Jensen *et al.*, 2011; Kushlina and Dronov, 2011) and Baltica (Sadlok, 2014; Orlowski *et al.*, 1970; 1971).

The discovery of Ordovician ichnospecies of *Cruziana* from the Indian LH extends their palaeobiogeographic dispersal

Table 3. Revised lithostratigraphic classification of the Tal Group in the Nigalidhar syncline. Highlighted portion indicates hiatus.



to the Indian plate and underscores an important aspect in the geological evolution of the lower Palaeozoic of the Himalaya. The discovery shall enable finer modification in the palaeobiogeographic reconstruction during the Ordovician.

Geochronological and Bisotratigraphic ages

Myrow *et al.*, (2010, 2016) provided detrital zircon age from the Tal Group in the Nigalidhar syncline. Their sample KD-1 is from the Koti Dhaman Formation, just south of the Koti Dhaman village in the Pirtari-Dochi section, Nigalidhar syncline. The stratigraphic position of their sample is above the carbonates of the Algal Limestone Member (see fig. 2, Myrow *et al.*, 2016). However, at the Pritari-Dochi section, the contact of Banded Siltstone Member (Sankholi Formation) and the Lower Quartzite Member (Koti Dhaman Formation) is exposed, and south of the Koti Dhaman village only the Lower Quartzite Member is exposed. The Algal Limestone Member is exposed only in extreme North-west of the Koti Dhaman village above the Ganog, Chou and the Drabil villages. Hence, the collected sample KD-1 (Myrow *et al.*, 2010, 2016) certainly belongs to the Lower Quartzite Member (Koti Dhaman Formation), which is overlain by the *Redlichia noetlingi* bearing SM (~512 Ma). The KD-1 sample contains zircons from ca. 510 Ma to 3300 Ma (Myrow *et al.*, 2010, 2016) and lacks grains younger than 510 Ma. In the Mussoorie syncline the youngest zircon in the Tal Group is ~525 Ma (Myrow *et al.* 2010, Table 1, p.1664). Recent work in the Mussoorie syncline (Singh *et al.*, *under preparation*) suggests revision of the Tal stratigraphy.

We suggest that detrital zircons from the ASM (Deona Formation) should be dated. However, it will prove fruitful only if latest Cambrian-early Ordovician granites are exposed in the provenance area. However, more work is required to discover the body fossils from the ASM (Deona Formation). The level equivalent to the ASM (Deona Formation) in the Korgai and Mussoorie synclines also requires a thorough paleontological investigation.

REGIONAL CORRELATION

Myrow *et al.* (2003) suggested late Cambrian or younger age for the top of the Tal Group in LH. Subsequently, Hughes *et al.* (2005) and Hughes (2016) considered the top of the Tal Group to be Drumian or Furongian based on the lithological correlations with the TH strata. The present discovery of the Ordovician trace fossils from ASM contradicts these age assignments. Table 4 depicts the Cambro-Ordovician and younger stratigraphic correlations among the Bikaner (craton India), the Nigalidhar (LH, India), the Salt Range (SH, Pakistan), the Peshawar basin (TH, Pakistan) and the Zanskar-Spiti regions (TH, India). The ASM (Deona Formation) can be correlated to the Misri Banda Quartzite (Peshawar Basin, Pakistan) (Pogue *et al.*, 1991) based

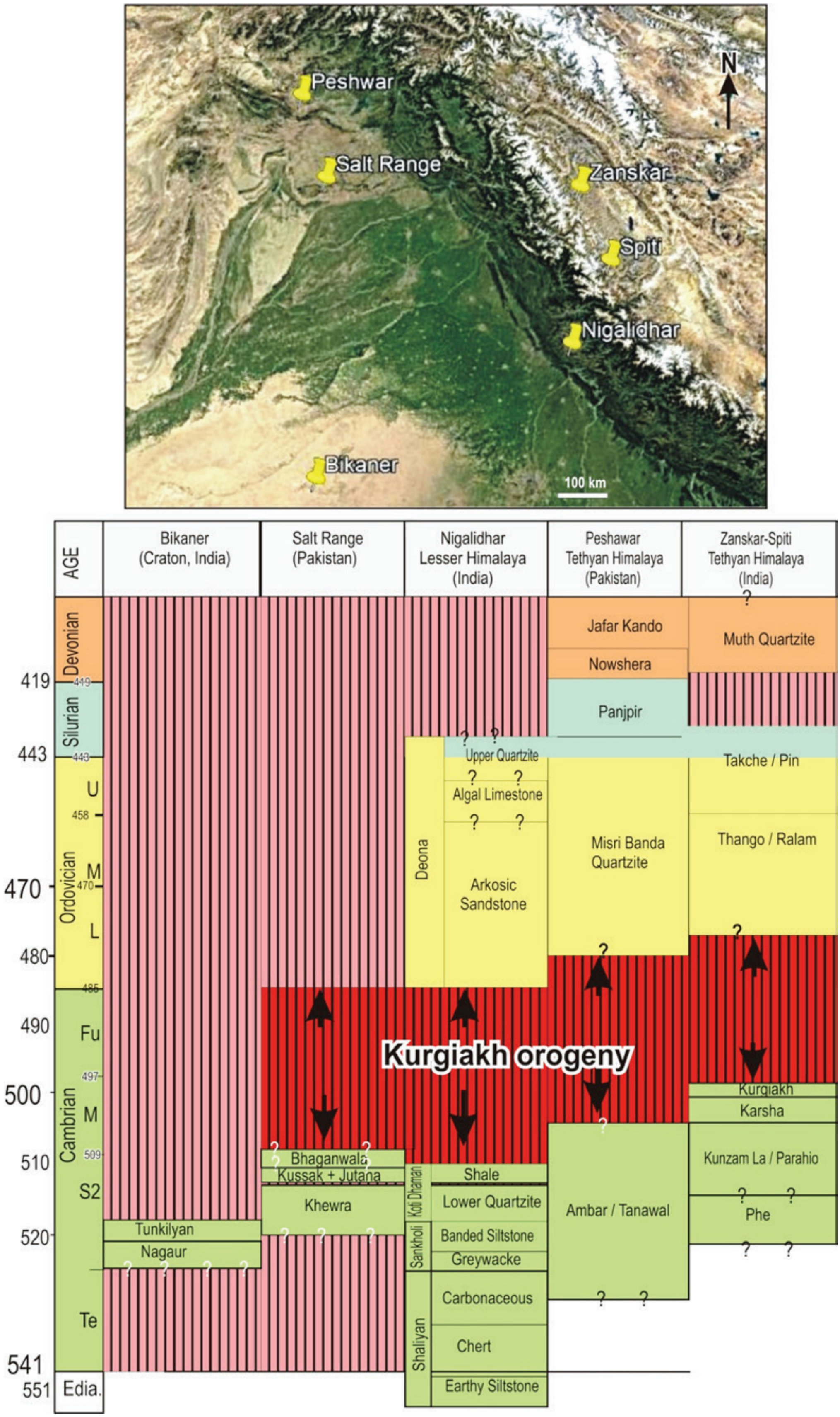


Table 4. Stratigraphic correlation of various formations of the Rajasthan basin (Peninsular part of India), Salt Range (Sub-Himalaya), Krol-Tal belt (Lesser Himalaya, India), Peshawar basin (Tethyan Himalaya, Pakistan) to Zanskar-Spiti region (Tethyan Himalayan, India) and proposed age range of Kurgiakh orogeny.

on the occurrence of traces of the *C. rugosa* group (Pogue and Hussain, 1986) and to the Thango / Ralam Formation (TH of Zanskar-Spiti-Kinnaur and Kumaun-Garhwal regions), which has yielded the Ordovician trace fossil *Phycodes circinatum* (Bhargava and Bassi, 1998) and also possibly to the basal part of the overlying Takche / Pin Formation, which yielded abundant traces of *Cruziana rugosa* group (Singh *et al.*, *unpublished collections*). The ALM and UQM (Deona Formation) could be homotaxial with the upper part of the late Ordovician-middle Silurian Takche Formation (Srikantia, 1981) of the Zanskar-Spiti region. The Bhaganwala and part of the Jutana formations (Salt Range) are likely to represent an early Ordovician age, but no age constraints yet available.

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This is a contribution to the IGCP- 668: Equatorial Gondwana History and Early Paleozoic Evolutionary Dynamics.

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