

Ichnostratigraphy of the Ediacaran-Cambrian boundary: new insights on lower Cambrian biozonations from the Soltanieh Formation of northern Iran

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Abstract.—Strata in the Central Alborz Mountains, northern Iran, are interpreted to show continuous sedimentation from Ediacaran through Cambrian times. The Soltanieh Formation consists of five members: Lower Dolomite, Lower Shale, Middle Dolomite, Upper Shale and Upper Dolomite members. The clastic units (Lower and Upper Shale members) represent sedimentation in distal marine settings, ranging from the shelf to offshore, and contain abundant trace fossils of biostratigraphic utility. Four ichnozones have been recognized. Ichnozone 1, containing *Helminthoidichnites tenuis*, *Helminthopsis tenuis*, and *Cochlichnus anguineus*, is early Fortunian based on small shelly fossils, and is interpreted as a distal expression of the *Treptichnus pedum* zone. Ichnozone 2, comprising the first occurrence of *T. pedum*, is middle Fortunian, and is best regarded as the upper half of the *Treptichnus pedum* Zone. Ichnozone 3 is late Fortunian–Cambrian Age 2, characterized by a sudden change in abundance and complexity of trace fossils. Main elements in this ichnozone include *Cruziana problematica*, *Curvolithus* isp., *Phycodes* isp., *Treptichnus pedum*, *Treptichnus pollardi*, and *Treptichnus* isp. Ichnozone 4 is of Cambrian Age 2–Age 3 and marked by the first appearances of *Psammichnites gigas*, *Rusophycus avalonensis*, and *Didymaulichnus miettensis*. Integration of trace fossils with small shelly fossils suggests that the Ediacaran–Cambrian boundary should be placed at the base of the Soltanieh Formation or within the Lower Dolomite Member. The delayed appearance of *T. pedum* and the low ichnodiversity in the Lower Shale and lower interval of the Upper Shale reflect limited colonization of settings below storm wave base during the early Fortunian.

Introduction

Defining the Ediacaran-Cambrian boundary and the precise timing of the Cambrian explosion has occupied the attention of paleontologists for decades. A very good measure of this interest is the considerable amount of work performed by the IUGS Cambrian Subcommittee to settle a reference standard for the base of the Cambrian and internationally accepted series and stage subdivisions of the Cambrian system, which still are in progress (Narbonne et al., 1987; Brasier et al., 1994; Terfelt and Ahlberg, 2010; Babcock et al., 2011; Harvey et al., 2011; Peng and Babcock, 2011; Ahlberg and Terfelt, 2012; Ahn et al., 2012; Moczydlowska and Yin, 2012; Peng et al., 2012a, 2012b; Landing et al., 2013). Defining reference standards for the base of Cambrian and its subdivisions has promoted understanding of the successive stages of the Cambrian evolutionary radiation (Landing, 1998; Landing et al., 2013).

A number of biostratigraphic and geochronologic techniques are used for correlation of the Ediacaran-Cambrian boundary and subdivision of pre-trilobitic lower Cambrian. Traditionally, biostratigraphy of the lower Cambrian has been based on small shelly fossils (SSFs) and trace fossils. Small shelly fossils are largely found in carbonates, whereas trace fossils are more common in siliciclastics (Narbonne et al., 1987). Despite that, both groups are common, diverse, and show

rapid changes during this critical time of Earth history (Narbonne et al., 1987). Accordingly, they represent important biostratigraphic tools for the subdivision and correlation of pre-trilobitic strata of the Cambrian (e.g., Steiner et al., 2007).

In spite of the various attempts to settle internationally accepted series and stage subdivisions of the Cambrian system, the Ediacaran-Cambrian boundary and the subdivision of pre-trilobitic lower Cambrian strata require continued attention. In northern Iran, the Ediacaran–Cambrian Soltanieh Formation is well exposed across the Alborz Mountains, and thus has the potential to illuminate some of these issues. In comparison with Ediacaran–Cambrian successions elsewhere, the ichnologic content of the Soltanieh Formation is poorly known. The aims of this study are to: (1) document the Soltanieh Formation ichnofauna, (2) propose a biozonation scheme for the Soltanieh Formation based on trace fossils, (3) suggest the most plausible position for the Ediacaran-Cambrian boundary in northern Iran by using integration of trace fossil and SSF biostratigraphy, and (4) assess the implications of this ichnostratigraphic scheme with respect to global schemes establishing biostratigraphic zonations for the lowermost Cambrian.

Geological setting

The Soltanieh Formation of the Alborz Mountains, northern Iran, regarded as Ediacaran–lower Cambrian, formed in the

Proto-Paleotethys passive margin of northwestern Gondwana (Alavi, 1996). Stöcklin et al. (1964) originally divided the Soltanieh Formation at the type section into three major subdivisions, from bottom to top: the Lower Dolomite Member (123 m), the Chopoghloo Shale Member (247 m), and the Upper Dolomite Member (790 m). This division was later revised by Hamdi et al. (1989), who divided the Soltanieh Formation into five members, in ascending order; the Lower Dolomite (165 m), the Lower Shale (120 m), the Middle Dolomite (180 m), the Upper Shale (90 m), and the Upper Dolomite (580 m) members.

In addition to its type section in the Soltanieh Mountains, the Soltanieh Formation can be traced to several other localities, including Garmab, Vali-Abad, and the Dalir area along the Tehran–Chalous road, north of Tehran (Fig. 1.1). The Soltanieh Formation overlies the Bayandor Formation in the Soltanieh Mountains and the Kahar Formation in the Alborz Mountains. An Ediacaran age is indicated for the Bayandor and Kahar formations based on stratigraphic relationships in the case of the former and the presence of acritarchs in the latter (Hamdi et al., 1989). The Soltanieh Formation is replaced upwards into the overlying Barut Formation (Cambrian Age 3), which is a

succession of greenish and reddish shale and siltstone alternating with dark dolomites and chert (Salehi, 1989).

This study is mainly based on the well-exposed Garmab section, along the Tehran–Chalous road, 97 km northwest of Tehran (36.040900° N 51.310767° E, WGS84) (Fig. 1.1, 1.2), where a more diverse and abundant ichnofauna has been reported. At the Garmab section, the Lower Dolomite Member is a 60 m thick succession of yellowish brown-blue dolomite, the Lower Shale Member is a 192 m thick succession of black shale and silty shale, the Middle Dolomite Member is a 90 m thick succession of well bedded grayish-green dolomite, the Upper Shale Member is a 180 m thick succession of silty shale and sandstone, and the Upper Dolomite Member is a 600 m thick succession light blue dolomite.

Sedimentary facies and depositional environment

Eight facies have been recognized in Soltanieh Formation, which are grouped into siliciclastic-dominated and carbonate-dominated facies associations (Shahkarami et al., 2017). The siliciclastic-dominated Facies Association comprises Facies

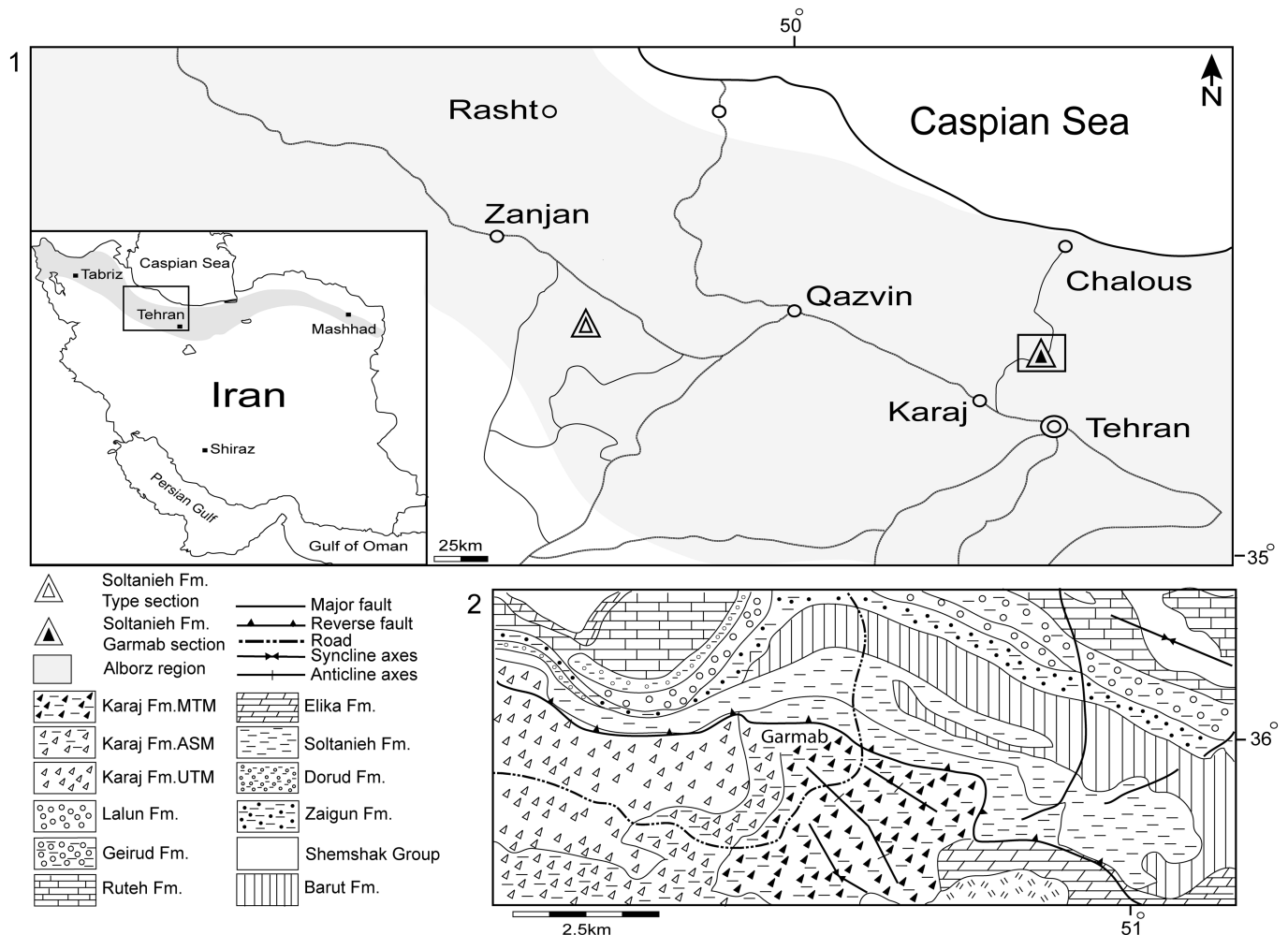


Figure 1. Location of study area and general geology. (1) Map showing the location of the studied section. Insert shows the location of Fig. 1.2; (2), Geological map of Garmab, Tehran–Chalous road, north of Tehran, Iran (modified from Aghanabati et al., 2005). Upper Tuff Member (UTM), Asara Shale Member (ASM), Middle Tuff Member (MTM).

1–4, whereas the carbonate-dominated Facies Association includes Facies 5–8.

Facies 1 consists of coarsening-upward cycles of interbedded greenish-gray silty shale and erosionally based, very fine- to medium-grained sandstone and sandy dolomite. This facies forms a discrete package in the uppermost part of the Upper Shale Member. It records deposition in the upper offshore, reflecting the alternation of suspension fallout during fair-weather times and storm deposition. Facies 2 consists of parallel-laminated, greenish-gray silty shale with mm-scale lenses and laterally discontinuous laminae of erosionally based, very fine-grained sandstone. This facies comprises most of the Upper Shale Member. It records deposition immediately above storm wave base, in the lower offshore. Facies 3 is characterized by parallel-laminated to massive, dark-gray shale and thinly bedded shale-siltstone alternations. This facies is present in the uppermost interval of the Lower Shale Member and the lowermost interval of the Upper Shale Member. It records deposition immediately below storm wave base in the proximal shelf. Facies 4 is characterized by laterally extensive, dark-gray parallel-laminated and massive shale. This facies constitutes most of the Lower Shale Member. It reflects deposition from suspension fallout in the distal shelf.

Facies 5 consists of laterally continuous, gray-to-blue dolomite with desiccation cracks, peloids, and fenestral structures. This facies comprises most of the Lower and Upper Dolomite members, and records deposition in the upper intertidal to supratidal zones. Facies 6 is characterized by well-bedded to massive, gray-to-blue, moderately sorted peloidal and intraclastic dolo-grainstone. This facies is present in the Middle Dolomite Member and records deposition in the intertidal to shallow subtidal zones. Facies 7 consists of parallel-laminated,

current-rippled and low-angle cross-laminated limestone (packstone and wackestone) and intercalated dark-gray massive calcareous shale and silty shale. This facies occurs in the lowermost interval of the Lower Shale Member and records deposition in a shallow low-energy subtidal setting. Facies 8 consists of black phosphatic limestone with diverse SSF assemblages, this facies is absent in the Garmab section.

The carbonate-dominated facies association represents deposition in very shallow water (shallow subtidal to peritidal), whereas the siliciclastic-dominated facies association mostly comprises deposition below storm wave base (i.e., shelf), and immediately above storm wave base (i.e., lower and upper offshore) (see environmental subdivisions in Buatois and Mángano, 2011).

Materials and methods

Repository and institutional abbreviation.—The trace fossils described herein were all collected in the Garmab section, Soltanieh Formation, northern Iran. Ichnotaxa are listed alphabetically. Specimens are housed at the Royal Saskatchewan Museum, Regina, Canada.

Systematic paleontology

Ichnogenus *Cochlichnus* Hitchcock, 1858

Cochlichnus anguineus Hitchcock, 1858

Figure 2.1

Materials.—Four slabs (P3309.1, P3311.15, P3311.17, P3311.19) containing four specimens.

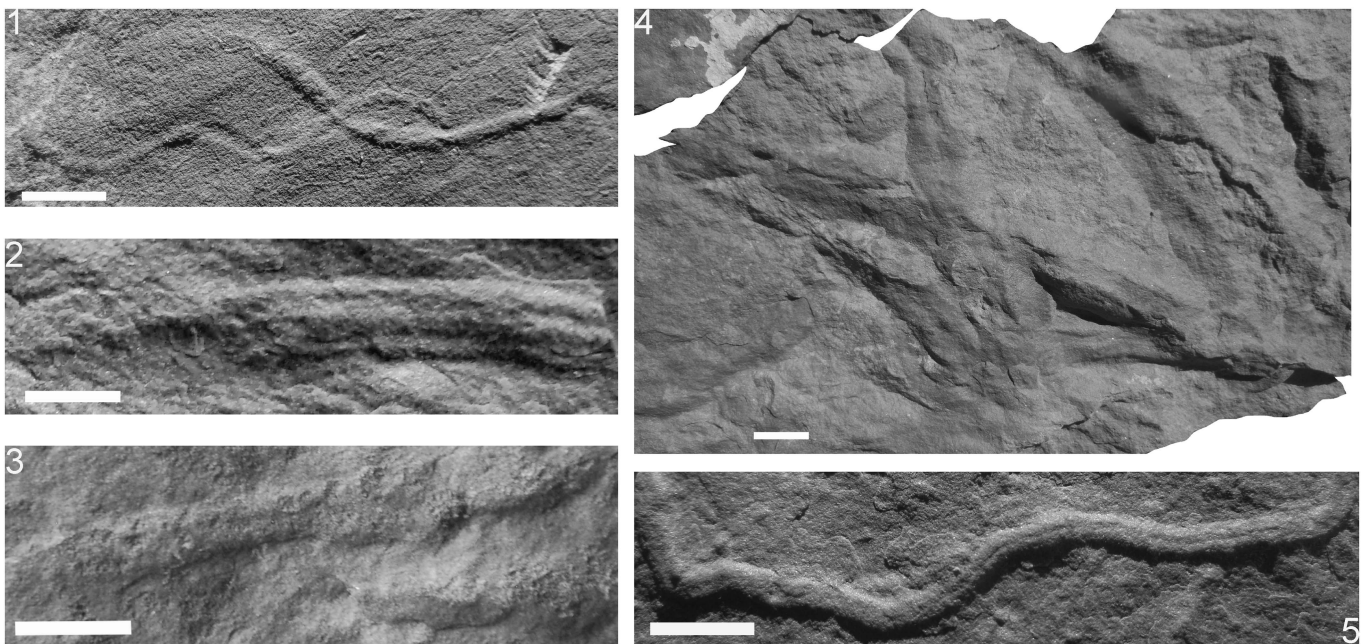


Figure 2. Trace fossils from the Soltanieh Formation, Garmab section. (1) *Cochlichnus anguineus* from the Lower Shale Member (black arrows) (P3309.2) preserved as positive hyporelief; scale bar is 0.5 cm; (2) *Curvolithus* isp. from the Upper Shale Member (P3311.19) preserved as positive epirelief; scale bar is 0.25 cm; (3) *Cruziana* isp., from the Upper Shale Member (P3313.10) preserved as positive hyporelief; scale bar is 0.5 cm; (4) *Didymaulichnus miettensis* from the Upper Shale Member (P3313.8) preserved as positive hyporelief; scale bar is 1 cm; (5) *Cruziana problematica* from the Upper Shale Member (P3311.13) preserved as positive hyporelief; scale bar is 0.5 cm.

Description.—Simple, small unbranched horizontal, sinusoidal trails. Trail width is 1.0–1.7 mm; maximum preserved length is 36.5 mm. Infill is massive. Preserved as positive hyporelief or negative epirelief.

Remarks.—*Cochlichnus anguineus* Hitchcock, 1858 is the type ichnospecies of *Cochlichnus*, and differs from the two other *Cochlichnus* ichnospecies, *C. annulatus* Orłowski, 1989, and *C. antarcticus*, Tasch, 1968, by lack of annulations or lateral markings and having the same filling as the host rock, respectively (Buatois and Mángano, 1993a; Keighley and Pickerill, 1997). *Cochlichnus* is a grazing trail (pascichnion) produced by many different invertebrates, including annelids and nematodes (Fillion and Pickerill, 1990; Lucas et al., 2010). It ranges from the Cambrian to Holocene (Mángano and Buatois, 2014), and occurs in a great variety of marine and non-marine environments (Fillion and Pickerill, 1990).

Occurrence.—Lower and Upper Shale members.

Ichnogenus *Cruziana* d'Orbigny, 1842

Remarks.—The ichnogenus *Cruziana* is mostly represented by a bilobate and elongated trail covered by transverse or herringbone-shaped ridges. Trails may be bounded by lateral outer zones with or without ridges (Häntzschel, 1975; Fillion and Pickerill, 1990). *Cruziana* comprises over 30 ichnospecies mostly separated based on morphologic features resulting from the leg morphology of the producer (Seilacher, 1970, 1992). *Cruziana* is best interpreted as related to combined locomotion and feeding strategy (pascichnia) (Seilacher, 2007). It is widely accepted that the main producers of *Cruziana* in the marine Paleozoic were trilobites or trilobitiforms (Seilacher, 1970, 1985, 1992; Hofmann et al., 2012). *Cruziana* ranges in age from early Cambrian to Holocene (Seilacher, 1970; Muñiz Guinea et al., 2015), and has been reported from a varied spectrum of paleoenvironments, ranging from typical shallow-water marine to freshwater settings (Bromley and Asgaard, 1979; Crimes, 1987).

Cruziana problematica Schindewolf, 1921

Figure 2.5

Materials.—Two slabs (P3311.13, P3313.10) containing two specimens.

Description.—Horizontal, gently winding, strongly convex, small, parallel-sided trails with transverse striation, and central groove dividing the trace longitudinally into two lobes. Width is 2.1–3.5 mm; maximum preserved length is 44.5 mm. Preserved as positive hyporelief.

Remarks.—Relatively small, simple *Cruziana* with transverse to nearly transverse scratch marks are traditionally included in *Cruziana problematica* (e.g., Schindewolf, 1921; Bromley and Asgaard, 1979; Fillion and Pickerill, 1990). Jensen (1997) regarded *C. problematica* as a junior synonym of *Cruziana tenella* (Linnarsson, 1871). However, *C. problematica* is widely reported and is considered the most stable ichnospecies (e.g., Mángano et al., 2002b). The specimens documented here are

very similar to *C. tenella* described by Jensen (1997) from the Mickwitzia Sandstone, south-central Sweden and *C. problematica* described by Keighley and Pickerill (1996) from eastern Canada. The name *C. problematica* is preferred here over *C. tenella* for reasons of nomenclatural stability (Mángano et al., 2002b).

Occurrence.—Upper Shale Member.

Cruziana isp.

Figure 2.3

Materials.—Five slabs (P3310.2, P3311.3, P3311.12, P3311.19, P3313.10) containing six specimens.

Description.—Small, horizontal, slightly oblique, unbranched, trails with bilobate lower surface, and poorly preserved scratch marks. Width is 2.3–5.2 mm; maximum preserved length is 46.50 mm. Preserved as positive hyporelief and negative epirelief.

Remarks.—Poor preservation does not allow determining the pattern of transverse striation, which therefore prevents ichnospecific assessment.

Occurrence.—Lower and Upper Shale members.

Ichnogenus *Curvolithus* Fritsch, 1908

Curvolithus isp.

Figure 2.2

Materials.—Three slabs (P3311.19, P3317.2, P3319.1) containing four specimens.

Description.—Horizontal, straight to slightly oblique, unbranched trails with trilobate upper surface consisting of two outer narrow lobes (each 1.7–2.6 mm wide) and one broad, flat central lobe (4.2–5.6 mm wide). The marginal outer lobes are discontinuous along the structure. Width of the trace is 6.8–10.8 mm; maximum preserved length is 89.0 mm. Preserved as positive epirelief and full relief.

Remarks.—*Curvolithus* comprises two ichnospecies: *Curvolithus multiplex* and *Curvolithus simplex* (Buatois et al., 1998b). *Curvolithus multiplex* has a smooth, trilobate upper surface and a convex, quadra-lobate lower surface; in contrast to *C. multiplex*, *C. simplex* does not have a quadra-lobate lower surface. The specimens documented here are assigned to *Curvolithus* isp. due to uncertainties in the number of lobes on the lower surface. *Curvolithus* has been interpreted as the locomotion trace (Repichnia) of predators, including gastropods, flatworms, or nemertean (Buatois et al., 1998b). *Curvolithus* ranges in age from Cambrian to Miocene and has been recorded from shallow-marine siliciclastic successions (Buatois et al., 1998b; Mángano and Buatois, 2014).

Occurrence.—Upper Shale Member.

Ichnogenus *Didymaulichnus* Young, 1972

Didymaulichnus miittensis Young, 1972

Figure 2.4

Materials.—Four slabs (P3313.4, P3313.8, P3313.10, P3317.1) containing fourteen specimens.

Description.—Horizontal, straight or curving bilobate trails. The trails have a shallow median groove, which divides the trail into two parts, and gently sloping peripheral discontinuous bevels. Overlap among specimens is common. Overall width is 15.2–20.5 mm. The median groove is 2.5–3.4 mm wide. The double-furrow is 10.2–12.7 mm wide. The outer bevels vary in width along the length of the trail, but where well preserved are 2.5–4.4 mm; maximum preserved length is 143.0 mm. Preserved as positive hyporelief and full relief.

Remarks.—There are four accepted ichnospecies of *Didymaulichnus*: *D. lyelli* (Rouault, 1850); *D. tirsasensis* Palij, 1974; *D. miettensis* Young, 1972; and *D. alternatus* Pickerill, Romano, and Melendez, 1984. *Didymaulichnus miettensis* differs from other *Didymaulichnus* ichnospecies by the presence of lateral bevels (Young, 1972; Jensen and Mens, 2001). The specimens from the Soltanieh Formation closely resemble the type material of *D. miettensis* described by Young (1972) from the upper Miette Group, western Canada. *Didymaulichnus* is

interpreted as locomotion traces (Repichnia) of gastropods, bivalves, or arthropods (Hakes, 1977; Bradshaw, 1981), and ranges from Cambrian to Cretaceous (Vossler et al., 1989). *Didymaulichnus miettensis* is restricted to early Cambrian (Jensen and Mens, 2001). A partially preserved specimen from the Soltanieh Formation illustrated by CiabéGhodsí (2007) was referred to *Didymaulichnus miettensis*.

Occurrence.—Upper Shale Member.

Ichnogenus *Gordia* Emmons, 1844

Gordia marina Emmons, 1844

Figure 3.2

Materials.—One slab (P3311.5) containing a single specimen.

Description.—Horizontal, non-branching, winding and curving, small trail with self-overcrossing. Width is 2.7 mm; maximum preserved length is 44.0 mm. Preserved as positive hyporelief.

Remarks.—There are five recognized ichnospecies of *Gordia*: the type ichnospecies *G. marina* Emmons, 1844; *G. arcuata*

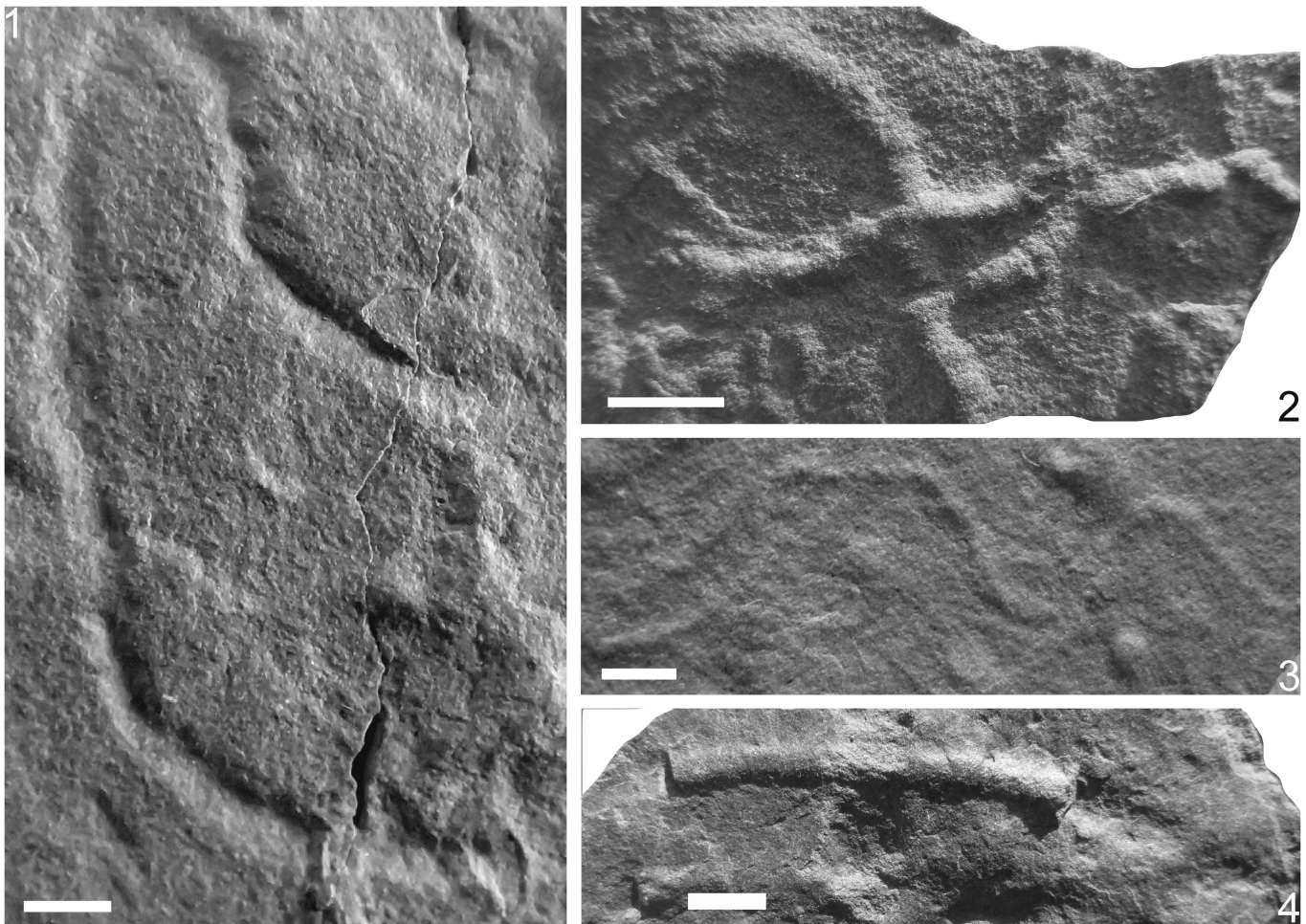


Figure 3. Trace fossils from the Soltanieh Formation, Garmab section. (1) *Helminthoidichnites tenuis* from Upper Shale Member (P3311.5) preserved as negative epirelief; scale bar is 0.25 cm; (2) *Gordia marina* from the Upper Shale Member (P3311.5) preserved as positive hyporelief; scale bar is 0.25 cm; (3) *Helminthopsis tenuis* from Upper Shale Member (P3311.18) preserved as positive hyporelief; scale bar is 0.25 cm; (4) *Palaephyucus tubularis* from the Upper Shale Member (P3319.3) preserved as positive hyporelief; scale bar is 0.5 cm.

Książkiewicz, 1977; *G. maeandria* Jiang in Jiang, Luo, and Zhang, 1982; *G. nodosa* Pickerill and Peel, 1991; and *G. indianaensis* (Miller, 1889). *Gordia marina* can be easily differentiated from the other ichnospecies of *Gordia* because it lacks the annulations of *G. nodosa*, the angled turns of *G. indianaensis*, the apical arcuate bends of *G. arcuata*, and the guided meanders of *G. maeandria* (Fillion and Pickerill, 1990; Buatois et al., 1998a). Fillion and Pickerill (1990) questioned the validity of *G. maeandria* in that guided meander is not typical of *Gordia*. *Gordia* differs from *Helminthopsis* in its looped form, having overcrossing and never showing meanders (Pickerill and Peel, 1991). The ethology of *Gordia* and its possible producers are not well constrained. Książkiewicz (1977) suggested that it might be a feeding burrow or trail produced by polychaetes. Yang (1984) considered it as a locomotion trace produced by worms or gastropods. Other authors (e.g., Aceñolaza and Buatois, 1993; McCann, 1993; Geyer and Uchman, 1995) have considered this ichnogenus as a pascichnia produced by worms or worm-like organisms. The ichnogenus *Gordia* ranges in age from Ediacaran to Holocene (Fillion and Pickerill 1990; Mángano and Buatois, 2014), and is known from non-marine, and shallow- to deep-marine deposits (Narbonne, 1984; Fillion and Pickerill, 1990; Norman, 1996). The ichnospecies *Gordia arcuata* has been documented in the Soltanieh Formation by CiabeGhodsí (2007).

Occurrence.—Upper Shale Member.

Ichnogenus *Helminthoidichnites* Fitch, 1850
Helminthoidichnites tenuis Fitch, 1850
 Figure 3.1

Materials.—Seven slabs (P3309.1, P3309.2, P3311.5, P3311.9, P3311.11, P3311.15, P3311.19) containing ten specimens.

Description.—Simple, unbranched, horizontal, mostly straight to slightly bent, nonmeandering trails. Diameter is 0.9–1.9 mm and may slightly vary along the course of individual trails. Maximum observed length is 83.8 mm. Overlapping among different individuals is common, but there is no self over crossing. Trace fill is identical to the host rock. Preserved as positive hyporelief and negative epirelief.

Remarks.—*Helminthoidichnites tenuis* is interpreted as a grazing trace, most likely produced by vermiform animals (Buatois et al., 1998a). *Helminthoidichnites* comprises only one ichnospecies, *H. tenuis*, although the case may be made that a review of this ichnogenus may result in recognition of additional ichnospecies. *Helminthoidichnites* differs from *Gordia* by lacking self-overcrossing and from *Helminthopsis* by having a non-meandering course (Hofmann and Patel, 1989; Buatois et al., 1998a). The ichnogenus ranges in age from Ediacaran to Holocene (Mángano and Buatois, 2014).

Occurrence.—Lower and Upper Shale members.

Ichnogenus *Helminthopsis* Heer, 1877
Helminthopsis tenuis Książkiewicz, 1968
 Figure 3.3

Materials.—Four slabs (P3309.1, P3309.2, P3311.17, P3311.18) containing eight specimens.

Description.—Horizontal, smooth, unbranched, unlined, irregular, high-amplitude meandering trails. Width is 1.0–1.8 mm; maximum preserved length is 49.0 mm. Preserved as positive hyporelief and negative epirelief.

Remarks.—There are three ichnospecies of *Helminthopsis*, separated based on their geometrical pattern (Wetzel and Bromley, 1996): *H. abeli* Książkiewicz, 1977; *H. hieroglyphica* Wetzel and Bromley, 1996; and *H. tenuis* Książkiewicz, 1968. *Helminthopsis tenuis* is distinguished from *H. abeli* and *H. hieroglyphica* by the lack of horseshoe-like turns and its high-amplitude winding (Wetzel and Bromley, 1996), and from *Helminthoidichnites* by its meandering course (Hofmann and Patel, 1989). *Helminthopsis* is thought to be a grazing trace (pascichnion) produced by deposit-feeding organisms in brackish to fully marine environments; polychaete annelids are regarded as potential tracemakers (Książkiewicz, 1977). *Helminthopsis* ranges in age from Ediacaran to Holocene (Buatois et al., 1998a).

Occurrence.—Lower and Upper Shale members.

Ichnogenus *Palaeophycus* Hall, 1847
Palaeophycus tubularis Hall, 1847
 Figure 3.4

Materials.—Seventeen slabs (P3311.1, P3311.4, P3311.7, P3311.10, P3311.12, P3311.14, P3311.19, P3311.20, P3312.1, P3313.1, P3313.3, P3313.9, P3313.10, P3314.1, P3315.1, P3316.1, P3318.1) containing thirty five specimens.

Description.—Horizontal, branched and unbranched, straight to slightly curved, unornamented, thinly lined cylindrical burrows. Burrow-fill is similar to the host rock. Width is 2.6–13.4 mm; maximum preserved length is 172.5 mm. Preserved as positive hyporelief.

Remarks.—*Palaeophycus* is distinguished from *Planolites* primarily by the presence of wall linings and a burrow-fill identical to the host rock. Infills of *Palaeophycus* represent passive, gravity-induced sedimentation within open, lined burrows; collapse features show that some segments were incompletely filled by this process. The fillings, therefore, tend to be of the same composition as the surrounding matrix (Pemberton and Frey, 1982). Seven ichnospecies of *Palaeophycus* are currently accepted: *P. tubularis* Hall, 1847; *P. heberti* (Saporta, 1872); *P. striatus* Hall, 1852; *P. sulcatus* (Miller and Dyer, 1878); *P. alternatus* Pemberton and Frey, 1982; *P. bolbitermilus* Kim, Pickerill, and Wilson, 2000; and *P. imbricatus* (Torell, 1870). *Palaeophycus tubularis* is distinguished from the other *Palaeophycus* ichnospecies by its thin wall and the absence of striations (Pemberton and Frey, 1982). *Palaeophycus* is interpreted as dwelling burrows (dominichnia) of suspension feeders or predators, such as polychaetes (Osgood, 1970; Pemberton and Frey, 1982), and ranges in age from Ediacaran to Holocene (Häntzschel, 1975). *Palaeophycus* is a facies-crossing

ichnotaxon found in almost every depositional environment (Pemberton and Frey, 1982).

Occurrence.—Lower and Upper Shale members.

Ichnogenus *Phycodes* Richter, 1850

Phycodes isp.

Figure 4.4

Materials.—Two slabs (P3311.1, P3319.3) containing two specimens.

Description.—Horizontal, broomlike structure without spreite, consisting of four branches originated from the same point of a thick, slightly curved single stem. Width of the branches is 4.2–8.2 mm, whereas the main tube is 7.1–9.0 mm in diameter. Maximum length preserved is 79.9 mm. Preserved as full relief.

Remarks.—Thirteen ichnospecies of *Phycodes* have been described in the literature, based on their overall pattern and size, nature, style, disposition and degree of branching, and presence or absence of spreite (Han and Pickerill, 1994): *P. antecedens* Webby, 1970; *P. auduni* Dam, 1990; *P. bromleyi*

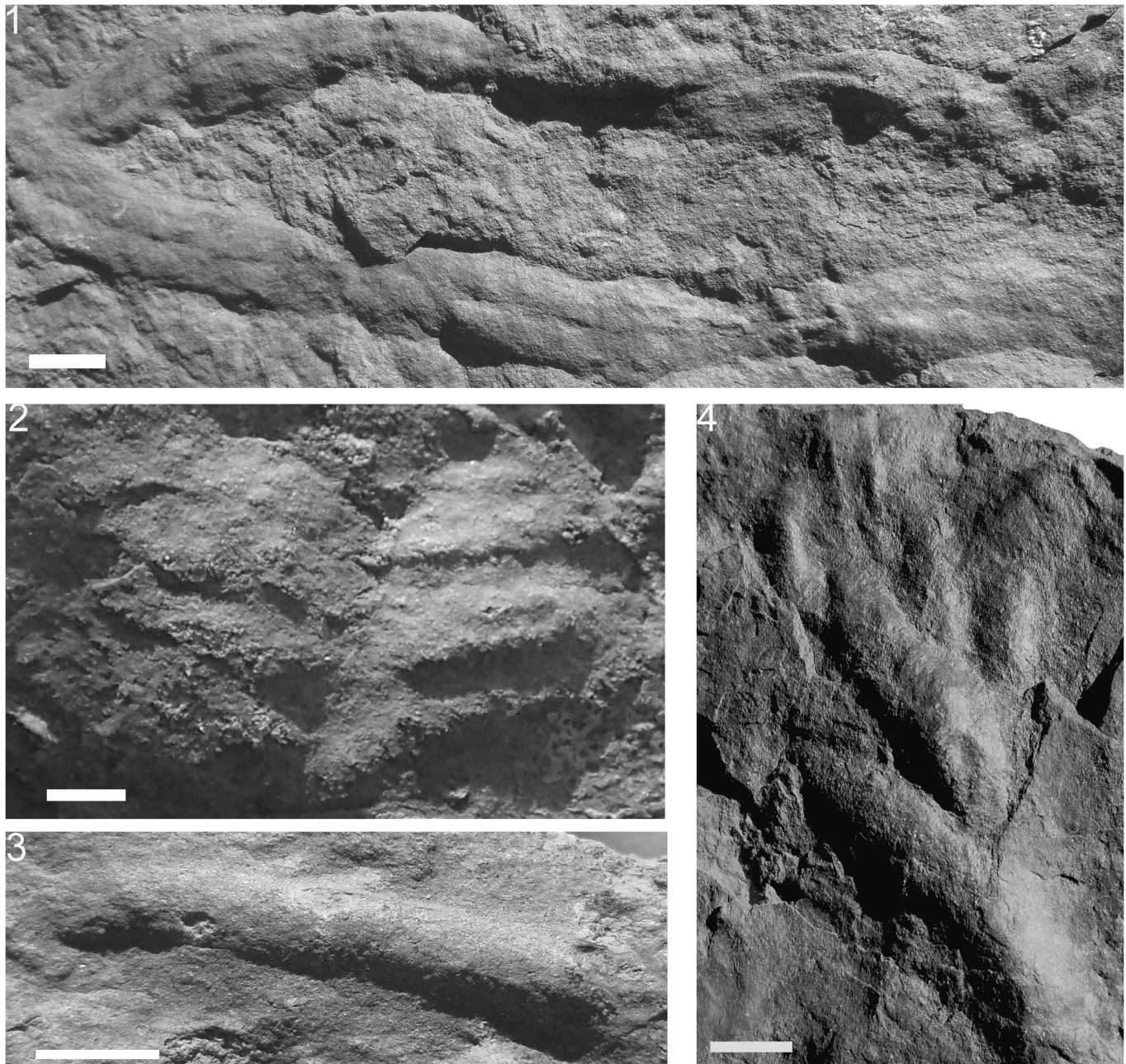


Figure 4. Trace fossils from the Soltanieh Formation, Garmab section. (1) *Psammichnites gigas* from the Upper Shale Member (P3317.1) preserved as positive epirelief; scale bar is 0.5 cm; (2) *Rusophycus avalonensis* from the Upper Shale Member (P3313.9) preserved as positive hyporelief; scale bar is 0.25 cm; (3) *Planolites montanus* from the Upper Shale Member (P3313.8) preserved as positive hyporelief; scale bar is 0.25 cm; (4) *Phycodes* isp. from the Upper Shale Member (P3319.3) preserved as full relief; scale bar is 0.5 cm.

Dam, 1990; *P. circinatum* Richter, 1853; *P. coronatum* Crimes and Anderson, 1985; *P. curvipalmatum* Pollard, 1981; *P. flabellum* (Miller and Dyer, 1878); *P. fusiforme* Seilacher, 2000; *P. templus* Han and Pickerill, 1994; *P. parallelum* Seilacher, 2000; *P. reniforme* Hofmann, 1979; *P. unguatus* Fillion and Pickerill, 1990; and *P. wabanensis* Fillion and Pickerill, 1990. Some forms of *Phycodes* consist of a few main branches showing a spreite-like structure, which distally give rise to numerous free branches. In other forms, the spreite are lacking, and branches tend to be more random (Osgood, 1970). *Phycodes* reflects a variety of behavioral activities by the tracemaker (Han and Pickerill, 1994), but two basic interpretations are a feeding trace (fodinichnion) produced by an organism that systematically mines a nutrient-rich layer along a silt-mud surface, most likely annelids (Seilacher, 1955), or a structure produced by an organism that burrowed outwards from a single point and then withdrew to a 'home-case' only to re-burrow outwards again through the previously excavated tunnel (Marintsch and Finks, 1982; Singh et al., 2008). *Phycodes* ranges in age from Cambrian (Crimes and Anderson, 1985) to Miocene (Bradley, 1981). *Phycodes* has been reported from shallow-marine, deep-marine (Crimes et al., 1977; Bradley, 1981; Narbonne, 1984), and brackish-water (Hakes, 1985) environments. Non-marine examples are in need of re-evaluation (Pollard, 1985). Although the Soltanieh specimen supports placement in *Phycodes*, poor preservation prevents an ichnospecific assessment.

Occurrence.—Upper Shale Member.

Ichnogenus *Planolites* Nicholson, 1873
Planolites montanus Richter, 1937
 Figure 4.3

Materials.—Five slabs (P3311.8, P3311.11, P3311.17, P3311.19, P3313.8) containing thirteen specimens.

Description.—Horizontal, unbranched, straight to slightly curved, unornamented, cylindrical burrows. Burrow-fill similar to the host rock. Width is 0.6–2.8 mm; maximum preserved length is 47.1 mm. Preserved as positive and negative hyporelief.

Remarks.—Four ichnospecies of *Planolites* are currently recognized based on size, curvature, and wall characteristics: *P. beverleyensis* (Billings, 1862); *P. annularis* Walcott, 1890; *P. montanus* Richter, 1937; and *P. constriannulatus* Stanley and Pickerill, 1994. *Planolites montanus* comprises small, curved to tortuous burrows. *Planolites beverleyensis* comprises large, straight to gently curved burrows. *Planolites annularis* consists of transversely annulated burrows, and *Planolites constriannulatus* is comprised of a burrow with both longitudinal striations and transverse annulation. *Planolites* is interpreted as feeding burrows (fodinichnia) of deposit-feeders (Pemberton and Frey, 1982), and ranges in age from Cambrian to Holocene (Häntzschel, 1975; Mángano and Buatois, 2014). *Planolites* is found in almost every depositional environment (Pemberton and Frey, 1982).

Occurrence.—Upper Shale Member.

Ichnogenus *Psammichnites* Torell, 1870
Psammichnites gigas (Torell, 1868)
 Figure 4.1

Materials.—Six slabs (P3313.2, P3313.5, P3313.6, P3313.7, P3317.1, P3317.2) containing fifteen specimens.

Description.—Large, unbranched, horizontal, straight to slightly curved bilobate trails. The burrow-fill is finer-grained and darker in color compared to the host sediment. Width is 6.7–20.0 mm; maximum length preserved is 148.8 mm. Overlap among specimens is locally common. Preserved as negative hyporelief and positive epirelief. Negative hyporeliefs are gently concave, with a median ridge. Positive epireliefs are gently convex with a shallow, straight median groove of variable width and depth.

Remarks.—There is general agreement that the ichnogenus *Olivellites* Fenton and Fenton, 1937 is a junior synonym of *Psammichnites* (Chamberlain, 1971; D'Alessandro and Bromley, 1987; Maples and Suttner, 1990; Seilacher, 1997; Zhu, 1997; Mángano et al., 2002a). The ichnotaxonomic status of the lower Cambrian ichnospecies *Taphrhelminthopsis circularis* Crimes et al., 1977 is more uncertain. Uchman (1995a) demonstrated that the ichnogenus *Taphrhelminthopsis* is a preservational variant of *Scolicia* and, therefore, its junior synonym. *Taphrhelminthopsis circularis* is most likely a preservational variant of *Psammichnites* (Mángano and Buatois, 2016). *Psammichnites* is distinguished from *Didymaulichnus* by lack of median groove on the lower side and by its overall more complex internal structure (Seilacher, 2007). *Psammichnites gigas* Torell, 1870 is the type ichnospecies of *Psammichnites*; other ichnospecies include *P. plummeri* (Fenton and Fenton, 1937); *P. grumula* (Romano and Meléndez, 1979); *P. implexus* (Rindsberg, 1994); and *P. saltensis* (Aceñolaza and Durand, 1973). The Soltanieh specimens are very similar in overall shape and size to *Psammichnites gigas*, as described and illustrated by Hofmann and Patel (1989) from the lower Cambrian of New Brunswick, Canada. *Psammichnites* is interpreted as a back-filled structure representing the feeding activities of a subsurface vagile animal using a siphon-like device (Mángano et al., 2002a; Jago and Gatehouse, 2007). The ichnogenus *Psammichnites* ranges in age from early Cambrian to Permian (Mángano et al., 2002a), and the type ichnospecies, *Psammichnites gigas*, is of early Cambrian age (Jago and Gatehouse, 2007). *Psammichnites gigas* was first recorded in the Soltanieh Formation by CiabeGhodsi (2007).

Occurrence.—Upper Shale Member.

Ichnogenus *Rusophycus* Hall, 1852
Rusophycus avalonensis Crimes and Anderson, 1985
 Figure 4.2

Materials.—One slab containing one specimen (P3313.9).

Description.—Short, horizontal, bilobate trace consisting of few scratch marks (6–7) arranged transversely to the median furrow. Width is 23.8 mm; maximum length preserved is 17.6 mm. Preserved as positive hyporelief.

Remarks.—*Rusophycus* comprises several ichnospecies, including 21 listed just for the lower Cambrian (Mángano and Buatois, 2016); its type ichnospecies is *Rusophycus biloba* (Fillion and Pickerill, 1990). *Rusophycus* is distinguished from *Cruziana* by its length-to-width ratio; only specimens with the length-to-width ratio less than two are placed in *Rusophycus* (Keighley and Pickerill, 1996). The specimens analyzed here are similar to *Rusophycus avalonensis* Crimes and Anderson, 1985 because of the overall shape and the divided ridges, but the ridges are not arranged in bundles. Paleozoic marine *Rusophycus* are widely accepted as resting traces (cubichnia) made by trilobites (Osgood, 1970; Crimes, 1975).

Occurrence.—Upper Shale Member.

Ichnogenus *Treptichnus* Miller, 1889

Remarks.—*Treptichnus* is a burrow consisting of segments connected at their ends, each one to the next, characteristically but not invariably in a zigzag pattern. At present, there are ten ichnospecies of *Treptichnus*: the type ichnospecies, *T. bifurcus* Miller, 1889; *T. pedum* (Seilacher, 1955); *T. triplex* Palij, 1976; *T. coronatum* (Crimes and Anderson, 1985); *T. lublinensis* Paczesna, 1986; *T. pollardi* Buatois and Mángano, 1993b; *T. tripleurum* (Geyer and Uchman, 1995); *T. rectangularis* Orłowski and Zylińska, 1996; *T. meandrinus* Uchman, Bromley, and Leszczyński, 1998; and *T. apsorium* Rindsberg and Kopaska-Merkel, 2005. *Treptichnus* is interpreted as feeding structures (fodinichnia) produced by vermiform animals or insect larvae, the latter in the case of non-marine occurrences (Uchman, 2005). *Treptichnus* has been recorded from non-marine (Buatois and Mángano, 1993a, 1993b; Buatois et al., 2000), marginal-marine (Archer and Maples, 1984; Buatois et al., 1998a), shallow-marine (Fedonkin, 1977; Geyer and Uchman, 1995), and deep-marine (Crimes et al., 1981; Uchman et al., 1998) environments. *Treptichnus* is considered to range in age from Cambrian to Holocene (Crimes, 1987; Geyer and Uchman, 1995; Muñiz-Guinea et al., 2014). However, reports of treptichnid trace fossils from terminal Ediacaran rocks in the Nama Group of Namibia and the GSSP section in Newfoundland suggest that *Treptichnus* may extend back into the late Ediacaran (Jensen et al., 2000; Gehling et al., 2001; Högström et al., 2013). Further work on the relationship between the so-called treptichnids and *Treptichnus* is pending.

Treptichnus pedum (Seilacher, 1955)

Figure 5.1

Materials.—Five slabs (P3310.2, P3311.2, P3311.8, P3311.11, P3311.15,) containing nine specimens.

Description.—Straight or curved sets of individual burrows of similar length connected to one another at their lower parts. The burrows alternate in direction, forming a zigzag pattern; where

the burrows are arranged in a nearly straight succession, the segments generally are aligned, and the zigzag pattern is rarely developed. In curved portions of the burrow, the segments generally project outwards. Width is 2.9–6.7 mm; maximum preserved length is 25.2 mm. Preserved as positive hyporelief.

Remarks.—*Treptichnus pedum* was originally described as *Phycodes pedum*, but Osgood (1970) noted that *P. pedum* differs from other ichnospecies of *Phycodes*, such as the type ichnospecies *Phycodes circinatum* Richter, 1853, and that it merited a new ichnogenetic designation. *Treptichnus pedum*, as described by Seilacher (2007), includes straight, sinusoidal, curved, or looping burrows constructed from upward curving segments. *Treptichnus pedum* is a feeding burrow (Crimes et al., 1977) with several morphological variants (Seilacher, 2007), ranges in age from the early Cambrian to Holocene (Crimes et al., 1977; Muñiz Guinea et al., 2014), and is restricted to normal-marine salinity conditions (Buatois et al., 2013). There is general agreement that the *T. pedum* tracemaker was a motile bilaterian animal that lived below the sediment-water interface, propelling itself forward in upward curving projections that breached the sediment surface (Seilacher, 1955; Geyer and Uchman, 1995; Jensen, 1997; Dzik, 2005). Dzik (2005) argued that the *T. pedum* animal was a priapulid worm, a conclusion supported by Vannier et al. (2010) based on neoichnologic experiments. Although it is sometimes referred to as *Trichophycus pedum* (e.g., Geyer and Uchman, 1995; Peng et al., 2012a), the overall morphology of *Trichophycus* is remarkably different, consisting of a U-shaped burrow with a retrusive spreite (Mángano and Buatois, 2011). *Treptichnus pedum* has been reported as *Trichophycus pedum* from the Soltanieh Formation by CiabeGhodsí et al. (2006) and CiabeGhodsí (2007).

Occurrence.—Lower and Upper Shale members.

Treptichnus pollardi Buatois and Mángano, 1993b

Figure 5.3

Materials.—Six slabs (P3318.1, P3311.6, P3311.16, P3311.18, P3311.20, P3313.01) containing ten specimens.

Description.—Horizontal, simple, straight burrows with knots or shafts at semi-regular intervals. Width is 1.3–4.6 mm; individual segments length is 2.6 mm. Spacing between segments is 7.5–15.9 mm. The maximum number of burrow segments is six. Preserved as positive hyporelief.

Remarks.—*Treptichnus pollardi* is distinguished from *T. bifurcus* by the presence of surficial pits, absence of twiglike projections, more irregular pattern, and longer individual segments. *Treptichnus pollard* differs from *T. lublinensis* and *T. triplex* by the absence of terminations projecting past the zigzags, the presence of pits associated with the horizontal burrow segment, and its thinner segments (Buatois and Mángano, 1993b). Although distinction from the ichnogenera *Saerichnites* and *Ctenopholeus* may be unclear depending on preservation (e.g., Buatois and Mángano, 2004; Fürsich et al., 2006), the overall morphology of the Soltanieh Formation

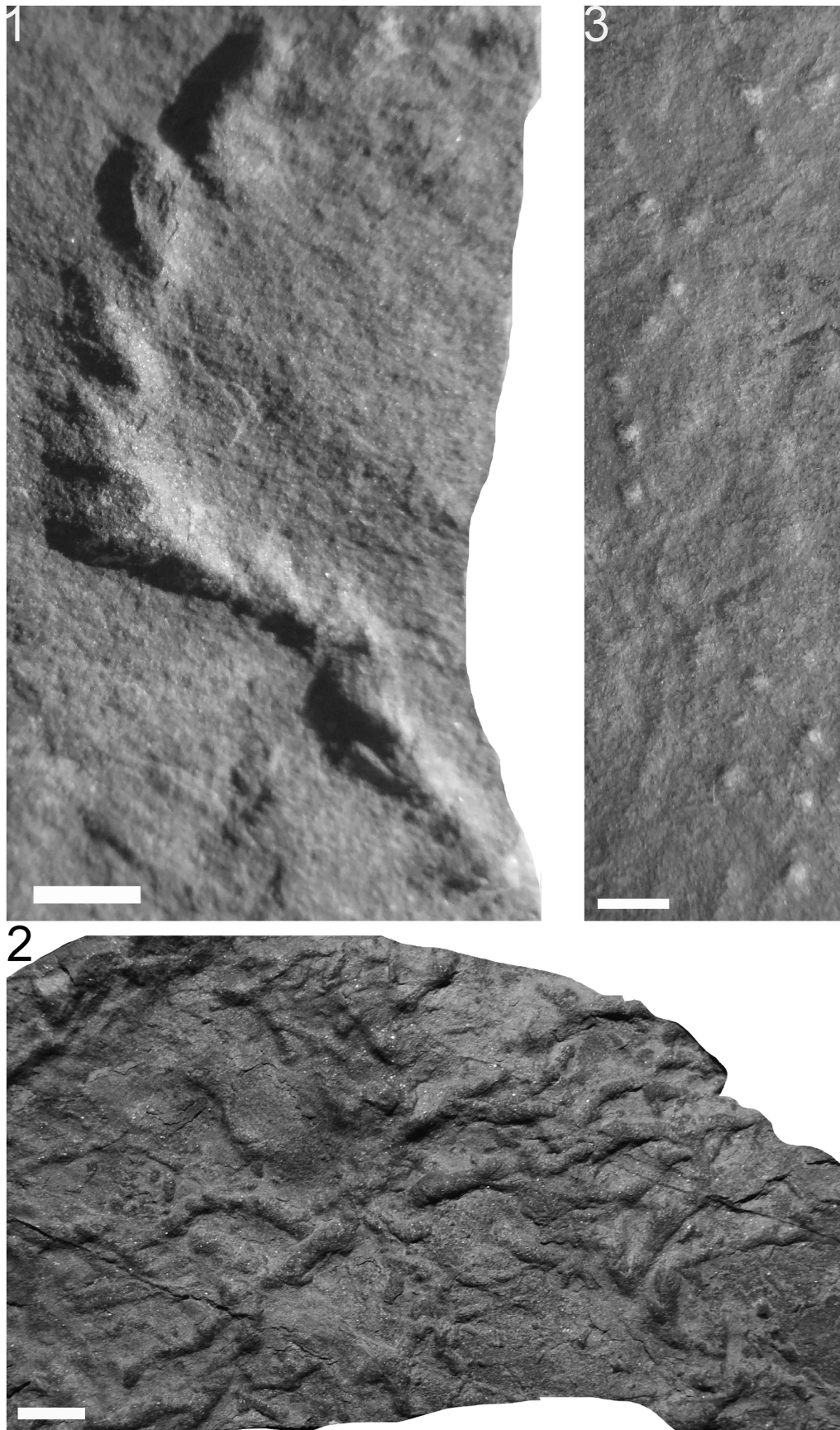


Figure 5. Trace fossils from the Soltanieh Formation, Garmab section. (1) *Treptichnus pedum* from the Upper Shale Member (P3311.11); scale bar is 0.25 cm; (2) *Treptichnus* isp. from the Upper Shale Member (P3319.2); scale bar is 0.5 cm; (3) *Treptichnus pollardi* from the Upper Shale Member (P3311.20); scale bar is 0.5 cm. All specimens preserved as positive hyporelief.

favors inclusion in *T. pollardi*. *Treptichnus pollardi* has been typically, though not exclusively (e.g., Geyer and Uchman, 1995), recorded from freshwater environments (Buatois and Mángano, 1993a, 1993b; Fregenal-Martinez et al., 1995; Metz, 1995; Buatois et al., 2000).

Occurrence.—Upper Shale Member.

Treptichnus isp.
Figure 5.2

Materials.—Four slabs (P3310.1, P3310.2, P3311.9, P3319.2) containing seven specimens.

Description.—Horizontal, gently curved, branching burrows. The burrows occasionally exhibit a short projection. Width is 1.1–2.6 mm. Preserved as positive hyporelief.

Remarks.—Lack of zigzag pattern and regular projection does not allow ichnospecific assignment.

Occurrence.—Upper Shale Member.

Previous work

In order to contextualize the new trace-fossil data reported here and to define a biozonation for the Soltanieh Formation, previously published reports of trace fossils and SSFs from this unit are briefly reviewed and critically re-evaluated.

Lower Dolomite Member.—Hamdi et al. (1989) reported phosphatic tubes, including *Hyolithellus* sp. along with others resembling *Rugatotheca* sp., fragments of the protoconodont *Protohertzina* sp., and globomorphs of the *Olivoooides multisulcatus* Qian, 1977 group in the upper part of the Lower Dolomite Member in the Vali-Abad area.

Lower Shale Member.—Hamdi et al. (1989) and CiabeGhodsi (2007) recorded large discoidal algal vesicles assigned to *Chuarina* sp. from the lower interval of the Lower Shale Member in the Vali-Abad area, and the type section, respectively. Hamdi et al. (1989) compared their material with larger ellipsoidal vesicles of *Shouhsienia* sp. from the Sinian System in China. CiabeGhodsi (2007) reported *Diplocraterion* isp., *Planolites vulgaris*, *Skolithos* isp., and *Treptichnus pedum* from the upper interval of the Lower Shale Member. *Planolites vulgaris* needs re-evaluation because the type specimen of this ichnospecies has been regarded as inorganic (Pemberton and Frey, 1982). Based on the illustration provided, an affinity with *Helminthoidichnites* cannot be disregarded. In addition, specimens attributed to *Diplocraterion* isp. and *Skolithos* isp. are based on bedding-plane expressions, so their true morphology cannot be confirmed.

Middle Dolomite Member.—Hamdi et al. (1989) reported the tubular fossil *Hyolithellus vladimirovae* and protoconodonts of the *Protohertzina anabarica* Missarzhevsky, 1969 group from the lower interval of the Middle Dolomite Member. Less common elements include the tubular fossils *Anabarites trisulcatus*

Missarzhevsky in Voronova and Missarzhevsky, 1969; *Cambrotubulus decurvatus* Missarzhevsky in Rozanov et al., 1969; siphogonuchitids; *Palaeosulcachites* sp.; *Siphogonuchites* sp.; and globomorphs. These authors mentioned that beds near the top of the Middle Dolomite Member contain a similar assemblage, but with more abundant *A. trisulcatus*, *C. decurvatus*, and *Siphogonuchites* sp., in addition to the primitive mollusks *Maikhanella multa* and *Purella* sp., and the tubular fossils *Tiksitheca licis* Missarzhevsky in Rozanov et al., 1969; *Circotheca* sp.; and *Ladatheca* isp.; as well as hyolithids. Tashayoe et al. (2012) recently reported *Anabarites latus* Val'kov and Sysoev, 1970; *A. rectus* Vasil'eva in Rudavskaya and Vasil'eva, 1984; *A. tripartitus* Missarzhevsky in Rozanov et al., 1969; *A. trisulcatus*; *Cambrotubulus* isp.; *Conotheca subcurvata* Yu, 1974; *Drepanochites dilatatus* Qian and Jiang in Luo et al., 1982; *Hyolithellus vladimirovae* Missarzhevsky in Rozanov and Missarzhevsky, 1966; *Jakutiochrea lenta* Val'kov, 1987; *Protohertzina anabarica* Missarzhevsky, 1969; *P. siciformis* Missarzhevsky, 1973; *P. unguiformis* Missarzhevsky, 1973; *Siphogonuchites triangularis* Qian, 1977; *Siphogonuchites* sp.; and *Yunnanodus dolerus* Wang and Jiang in Jiang, 1980 from the Garmab section. CiabeGhodsi (2007) documented the ichnotaxa *Bergaueria perata* Prantl, 1945; *Circulichnus montanus* (Vyalov, 1971); and *Gordia arcuata* from the lower interval of the Middle Dolomite Member at the type section. However, specimens assigned to *Bergaueria perata* and *Circulichnus montanus* are unconvincing based on the available material.

Upper Shale Member.—Hamdi et al. (1989) mentioned that at the Vali-Abad section the lower interval of the Upper Shale Member contains abundant and diverse phosphatized mollusks comparable with those found in the upper interval of the Middle Dolomite Member. These authors also reported *Anabarites* cf. *trisulcatus* Missarzhevsky, 1969; allathecidae hyoliths; and pelagiellids from the Dalir section. The upper interval in the Vali-Abad section contains specimens of the *Latouchella korobkovi* (Vostokova, 1962) group of monoplacophorans, including 'close-coiled' *Yangtzespira* sp., 'lax coiled' *Bemella* sp., 'uncoiled' *Ceratoconus* sp., and *Obtusoconus* sp., which appear approximately 20 m from the top of the unit. Other typical elements at this level include *Purella tianzhushanensis* Yu, 1979 and broad monoplacophorans resembling *Protowenella* sp.; pelagiellids of the *Pelagiella lorenzi* (Kobayashi, 1939) occur in the top 10 m. CiabeGhodsi (2007) added *Lopochites latazonalis* Qian, 1977; *Igorella emeiensis* (Yu, 1987); *Igorella* sp.; *Purella squamulosa* Qian and Bengtson, 1989; *Bemella simplex* Yu, 1979; and *Lapworthella* sp. to this group. CiabeGhodsi (2007) described several trace fossils from the Garmab section, namely *Chondrites furcatus* Sternberg, 1833; *Didymaulichnus miettensis*; *Diplichnites* isp.; *Diplocraterion* isp.; *Hormosiroidea* isp.?; *Monomorphichnus lineatus* Crimes et al., 1977; *Neonereites uniserialis* Seilacher, 1960; *Palaeophycus alternatus*; *Paleodictyon croaticum* Uchman, 1995b; *Plagiogmus arcuatus* Glaessner, 1969; *Psammichnites gigas*; and *Protovirgularia dichotoma*? M'Coy, 1850. However, many of these ichnotaxa lack diagnostic features and have been excluded from the list of trace fossils used in this study. Structures assigned to *Chondrites furcatus* do not display the classic

dichotomic branching of this ichnogenus (Fu, 1991). The specimen attributed to *Diplichnites* isp. appears to consist of a string of pits rather than appendage imprints and in fact, a second string of pits is apparent on the same slab, which may suggest an affinity with *Saerichnites*. The specimen attributed to *Diplocraterion* is only seen on bedding-plane view, so their U-shaped morphology cannot be confirmed. The ichnotaxonomy of *Hormosiroidea* is in need of revision (Gaillard and Olivero, 2009). In addition, the specimen illustrated lacks the morphologic features typically present in this ichnogenus. Based on the illustrations provided, the presence of scratch marks cannot be confirmed in the specimens assigned to *Monomorphichnus lineatus*. *Neonereites uniserialis* has been regarded as a preservation variant of *Nereites* (Uchman, 1995a). However, the specimen illustrated from the Soltanieh Formation lacks the diagnostic features of *Nereites*, actually resembling a simple grazing trail, such as *Helminthoidichnites*. The specimen figured as *Paleodictyon croaticum* does not display the typical morphology of this ichnotaxon; an affinity with *Multina* cannot be disregarded. *Plagiogmus arcuatus* is now considered a preservational variant of *Psammichnites gigas* by some (McIlroy and Heys, 1997; Mángano et al., 2002a). The structures figured as *Protovirgularia dichotoma?* do not show the diagnostic chevronate pattern characteristic of *Protovirgularia* (e.g., Seilacher and Seilacher, 1994; Mángano et al., 1998).

Upper Dolomite Member.—Meyer (1967) noted that the stromatolites *Collenia spissa* Fenton and Fenton, 1939 and *Hadrophyucus inmanis* Fenton and Fenton, 1939 are moderately common in the upper interval of this member. Problematic records of *Salterella* have also been reported (Assereto, 1963; Stöcklin et al., 1964). CiabeGhodsi (2007) and Tashayoe et al. (2012) also reported *Hyolithellus filiformis* Bengtson in Bengtson et al., 1990; *Conotheca subcurvata* (Yu, 1974); *Igorella* sp.; *Latouchella krobkovi* Vostokova, 1962; *Latouchella maidipingensis* (Yu, 1974); and *Obtusoconus rostriptutea* Qian in Qian et al., 1978 from this unit.

Ichnostratigraphy of the Soltanieh Formation

Several ichnostratigraphic schemes have been proposed for the Ediacaran–Cambrian boundary (Alpert, 1977; Crimes, 1987, 1992; MacNaughton and Narbonne, 1999; Jensen, 2003). The latter two schemes have been recently adapted (Buatois and Mángano, 2011; Mángano et al., 2012), and two Ediacaran zones and three early Cambrian zones are considered. The lower Ediacaran zone includes simple grazing trails, such as *Helminthoidichnites*, *Helminthopsis*, *Gordia*, and *Archaeonassa*, together with *Epibaion* and *Kimberichnus*. The age of this interval is ca. 560–550 Myr (Jensen et al., 2006). The upper Ediacaran zone includes the oldest branching-burrow systems, represented by treptichnids. The age of this zone is 550–541 Myr (Grotzinger et al., 1995; Jensen et al., 2006; Schmitz, 2012). The lowermost early Cambrian zone, or the *Treptichnus pedum* Zone, is of Fortunian age and defined by the first appearance of *T. pedum*, as well as other complex forms (Narbonne et al., 1987; Landing et al., 2013, 2015). The *Rusophycus avalonensis* Zone contains the oldest bilobate, trilobite-type resting traces (*R. avalonensis*) and the bilobate

epichnial trail *Taphrelminthopsis circularis* (Narbonne et al., 1987; Jensen et al., 2006). The age of this zone ranges from Fortunian to Cambrian Age 2. The *Cruziana problematica* Zone (= *C. tenella* Zone), which contains the oldest bilobate, trilobite-like trails (*Cruziana problematica*) associated with *Psammichnites gigas*, is Cambrian Age 2.

The application of the lowest appearance of SSFs for global correlation of Ediacaran–Cambrian boundary was first proposed at the Bristol plenary session in 1983 (Narbonne et al., 1987). Biozonations based on SSFs are available in Siberia and South China (Peng et al., 2012a). In Siberia, SSF zonation comprises, in ascending order, the *Anabarites trisulcatus* and *Purella antiqua* assemblage zones of the Fortunian, and *Watsonella crosbyi* and *Aldanella operosa* assemblage zones of Cambrian Age 2–Age 3 (Khomontovsky and Karlova, 1993, 2002; Peng et al., 2012a). The SSF zonation of south China comprises the assemblage zones *Anabarites trisulcatus*–*Protohertzina anabarica* (SSF1) of the lower Meishucunian Stage (= Fortunian), *Paragloborilus subglobosus*–*Purella squamulosa* (SSF2), and *Watsonella crosbyi* (SSF3) of the middle Meishucunian Stage (= lower part of Cambrian Age 2). The upper Meishucunian (= upper part of Cambrian Age 2) strata comprise the *Sinosachites flabelliformis*–*Tannuolina zhangwentangi* Assemblage Zone (SSF4) (Steiner et al., 2007), which directly underlies the trilobitic interval of the Cambrian in the shallow-water realm of the Yangtze Platform.

Non-biostratigraphic techniques used for correlation of the Ediacaran–Cambrian boundary include chemostratigraphic techniques, such as the measurement of carbon and sulfur isotopes (Magaritz et al., 1986; Tucker, 1986; Magaritz, 1989; Brasier et al., 1992; Brasier, 1993; Shen and Schidlowski, 2000; Ru et al., 2011). The carbon isotopic curve emerges as an increasingly important tool for intercontinental and intracontinental correlation, especially in regions where the primary biologic marker for a key horizon is absent. The results obtained by applying chemostratigraphic techniques, however, may be influenced by provenance and diagenetic alteration, and most importantly they still require biostratigraphy for final calibration (Rozanov et al., 2008). In any case, biostratigraphy remains a cost-effective means of correlating the Ediacaran–Cambrian transition.

The biostratigraphy of the Soltanieh Formation is poorly known and largely based on shelly fossils (Hamdi et al., 1989; Tashayoe et al., 2012) with very little published on ichnostratigraphy (CiabeGhodsi et al., 2006; Tashayoe et al., 2012). Small shelly fossils reported from the Soltanieh Formation are comparable with skeletal assemblages recorded in China and northern Siberia (Hamdi et al., 1989), containing elements of *A. trisulcatus*–*P. anabarica* and *W. crosbyi* assemblage zones of Meishucunian Stage, and the *Pelagiella subangulata* Taxon Zone of Qiongzhusian Stage (Steiner et al., 2007).

Although the carbonate intervals (Lower, Middle and Upper Dolomite members) do not contain trace fossils, the clastic deposits of the Soltanieh Formation (Lower and Upper Shale members) are host to trace fossils of biostratigraphic utility, which have largely been overlooked. The Lower Shale Member contains ichnotaxa that are known from both Ediacaran and early Cambrian rocks and those that are only known from the Phanerozoic. The former group includes the simple grazing

trail, namely *Helminthoidichnites tenuis* and *Helminthopsis tenuis*, whereas the second group consists of the grazing trail *Cochlichnus anguineus*, and the bilobate trail *Cruziana* isp. The latter occurs on the same bed as the branching burrow *Treptichnus pedum*. The Upper Shale Member contains fifteen ichnospecies, including *Cochlichnus anguineus*, *Cruziana problematica*, *Curvolithus* isp., *Didymaulichnus miettensis*, *Gordia marina*, *Helminthoidichnites tenuis*, *Helminthopsis tenuis*, *Palaeophycus tubularis*, *Phycodes* isp., *Planolites montanus*, *Psammichnites gigas*, *Rusophycus avalonensis*, *Treptichnus pedum*, *Treptichnus pollardi*, and *Treptichnus* isp.

Our study indicates that four distinctive trace-fossil zones can be recognized in the Soltanieh Formation, all belonging to the early Cambrian (Fig. 6). Ichnozone 1 characterizes the middle interval of the Lower Shale Member (157–171 m above its base). This ichnozone is of low ichnodiversity, containing only three ichnotaxa of simple horizontal trails, namely *Helminthoidichnites tenuis*, *Helminthopsis tenuis*, and *Cochlichnus anguineus*, collected 157 m above the base of the Lower Shale Member (Fig. 7). A wrinkled surface associated with these specimens suggests the presence of microbial mats (Fig. 2.1), which allowed the superb preservation of these delicate structures. *Cochlichnus anguineus*, *Helminthoidichnites tenuis*, and *Helminthopsis tenuis* commonly occur in direct association with the microbial mat and record microbial grazing as one of the most widespread feeding strategies across the Ediacaran-Cambrian boundary (Buatois et al., 2014).

Although this ichnofauna shows similarities with that of the Ediacaran (Fedonkin, 1985; Narbonne et al., 1987; Jensen, 1997; MacNaughton and Narbonne, 1999; Gehling et al., 2005;

Buatois and Mángano, 2011; Mángano et al., 2012), the presence of the *Anabarites trisulcatus*-*Protohertzina anabarica* Zone (Hamdi et al., 1989) in the dolomites below and above the Lower Shale indicates a Fortunian age. Also, uncontroversial examples of *Cochlichnus* have not been recorded in the Ediacaran (Buatois and Mángano, 2016). The most likely interpretation is to consider this ichnofauna as the distal expression of those that characterize the *Treptichnus pedum* Zone (see Discussion). Previous reports of *Chuarina* sp. from the lower interval of the Lower Shale Member at Vali-Abad and Soltanieh Mountains (Hamdi et al., 1989; CiabeGhods, 2007) indicate that *Chuarina* persisted into the lowermost Cambrian. A similar situation has been observed in the Heziao and Jijiapo sections, Hubei province, southern China, where *Chuarina* sp. has been reported from siltstone and chert from the lower Cambrian Yanjahe Formation (Steiner, 1994). Amard (1997) also suggested an early Cambrian age for *Chuarina* from the Pendjari Formation of West Africa. These findings question the utility of *Chuarina* for global correlation of Proterozoic successions. If this is the case, then either the whole Soltanieh Formation is of early Cambrian age, or the Ediacaran-Cambrian boundary is placed within the Lower Dolomite Member below the oldest occurrence of SSF.

Ichnozone 2 represents the uppermost interval of the Lower Shale Member, the Middle Dolomite Member, and the lower interval of the Upper Shale Member (171 m above the base of the Lower Shale Member to 80 m above the base of the Upper Shale Member). A total of six ichnospecies occur in this zone including, *Cruziana* isp., *Gordia arcuata*, *Helminthoidichnites tenuis*, *Helminthopsis tenuis*, *Palaeophycus tubularis*, and

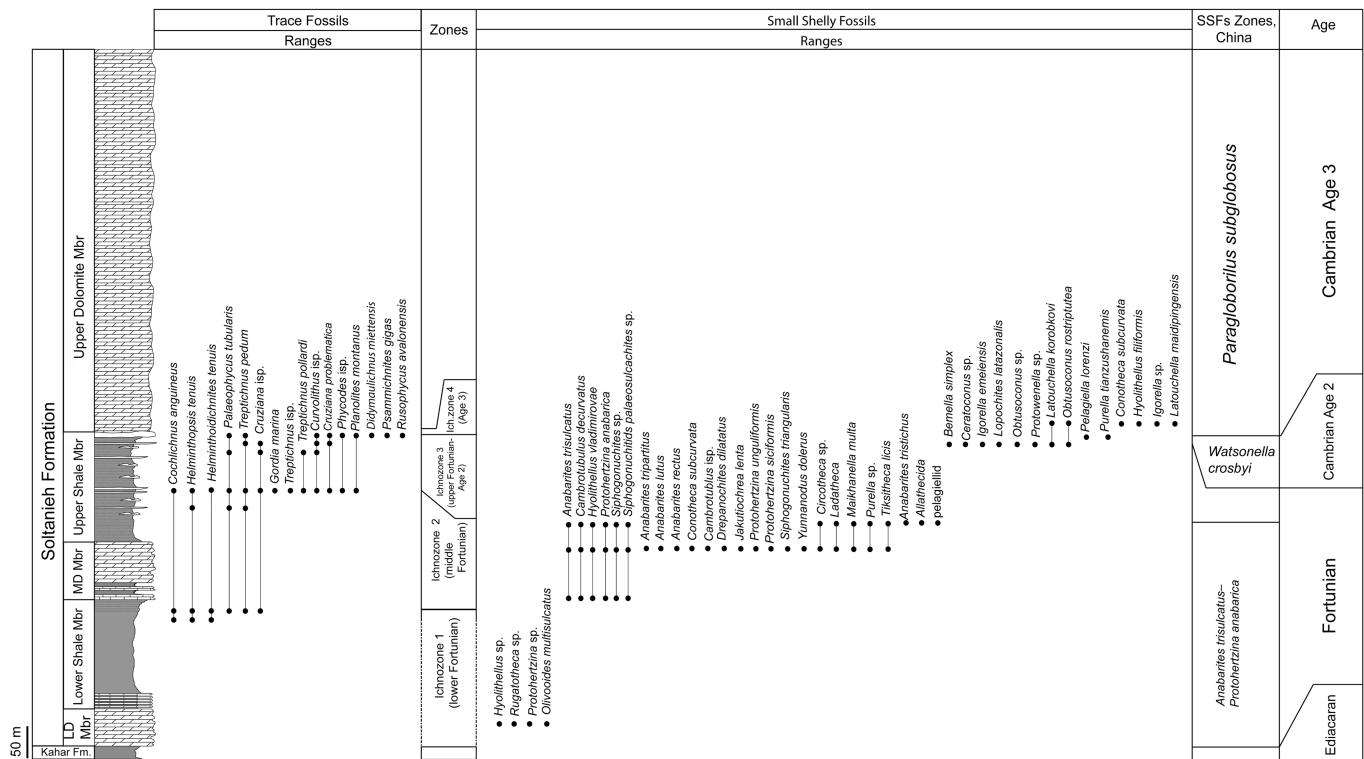


Figure 6. Stratigraphic column of the Soltanieh Formation, showing distribution of trace fossils, small shelly fossils, biozonation based on trace fossils and small shelly fossils, and correlation in relation to the Yangtze platform, China. Small shelly fossil data based on Hamdi et al. (1989), CiabeGhods (2007), and Tashayoe et al. (2012).

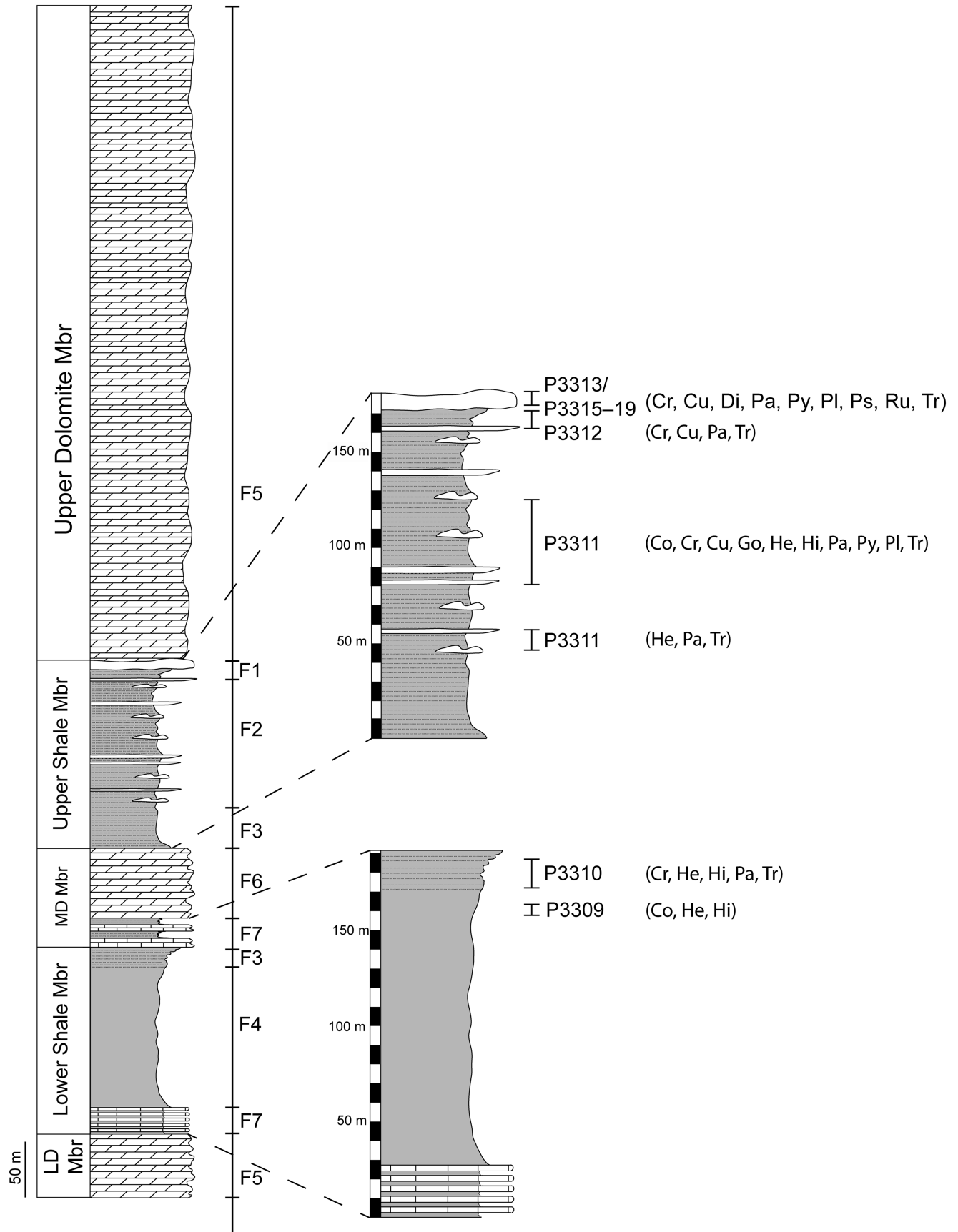


Figure 7. Distribution of sedimentary facies in the Soltanieh Formation, with a detail on trace-fossil distribution in the siliciclastic units indicating the location where the ichnofossiliferous samples were collected. *Cochlichnus* (Co), *Cruziana* (Cr), *Curvolithus* (Cu), *Didymaulichnus* (Di), *Gordia* (Go), *Helminthoidichnites* (Hi), *Helminthopsis* (He), *Palaeophycus* (Pa), *Planolites* (Pl), *Phycodes* (Py), *Psammichnites* (Ps), *Rusophycus* (Ru), *Treptichnus* (Tr).

Treptichnus pedum, indicating higher ichnodiversity than in the underlying ichnozone 1. The presence of *Cruziana* isp. in these strata is particularly significant because it reinforces evidence for the presence of arthropod-produced trace fossils in the *Treptichnus pedum* Zone. Most of the trace fossils appear in the lowermost interval of the zone (171–173 m above the base of Lower Shale Member) (Fig. 7). This ichnozone is defined by the first appearance of *T. pedum*, and is regarded as Fortunian in age (Jensen, 2003; Buatois and Mángano, 2011), being referred to as Ichnozone II in the global ichnostratigraphic scheme or *T. pedum* Zone (Narbonne et al., 1987; MacNaughton and Narbonne, 1999; Jensen, 2003). This is consistent with the presence of the *Anabarites trisulcatus*-*Protohertzina anabarica* Zone (Hamdi et al., 1989). In strict ichnologic terms, the first occurrence of *Treptichnus pedum* together with the first bilobate trace *Cruziana* isp. may be taken as evidence that the Ediacaran-Cambrian boundary is placed within the Lower Shale Member, 171 m above its base. As discussed above, however, integration with small shelly fossils and evaluation of environmental constraints suggest placing the Ediacaran-Cambrian boundary at the base of the Soltanieh Formation or within the Lower Dolomite Member, rather than within the Lower Shale Member.

Ichnozone 3 characterizes the middle interval of the Upper Shale Member (80–178 m above its base; Fig. 7). This ichnozone is defined by a sudden increase in the abundance of trace fossils and the occurrence of more complex burrows, including *Cruziana problematica*, *Phycodes* isp., and *Treptichnus pollardi*. The other elements of this ichnozone are *Cochlichnus anguineus*, *Curvolithus* isp., *Gordia marina*, *Helminthoidichnites tenuis*, *Helminthopsis tenuis*, *Palaeophycus tubularis*, *Planolites montanus*, *Treptichnus pedum*, and *Treptichnus* isp. This ichnozone corresponds to ichnozone III of the global ichnofossil scheme, encompassing the lower half of the *Rusophycus avalonensis* Zone of the Chapel Island Formation, which represents the upper half of Member 2 and higher strata of the Chapel Island Formation, Burin Peninsula (Narbonne et al., 1987), and the lower half of the *Rusophycus avalonensis* Zone of the Mackenzie Mountains, which characterizes the Backbone Ranges Formation and the lower interval of the Vampire Formation (MacNaughton and Narbonne, 1999). However, *R. avalonensis* has not been found at comparable levels in the Soltanieh Formation. Ichnozone 3 is interpreted as late Fortunian–Cambrian Age 2 (Buatois and Mángano, 2011).

Ichnozone 4 represents the uppermost interval of the Upper Shale Member (178 m above its base to the base of the Upper Dolomite Member; Fig. 7). This zone is based on the first appearance of large back-filled trace fossils (*Psammichnites gigas*), together with bilobate, trilobite-like resting trace fossils (*Rusophycus avalonensis*), and large locomotion trace fossils (*Didymaulichnus miettensis*). The other elements of this ichnozone are *Cruziana* isp., *Curvolithus* isp., *Palaeophycus tubularis*, *Phycodes* isp., *Planolites montanus*, and *Treptichnus pedum*. Ichnozone 4 corresponds to ichnozones III and IV of the global scheme, encompassing both the upper half of the *Rusophycus avalonensis* Zone of Burin Peninsula (Narbonne et al., 1987) and the Mackenzie Mountains (MacNaughton and Narbonne, 1999), and the *Cruziana tenella* Zone of the latter region, which characterizes the upper interval of the Vampire Formation (MacNaughton and Narbonne, 1999). This zone is

regarded as Cambrian Age 2–3 (Buatois and Mángano, 2011). This is supported by the presence of *Pelagiella lorenzi* (*Pelagiella subangulata*; Steiner et al., 2007).

Discussion

The Ediacaran-Cambrian boundary is globally defined by a point placed with specific reference to the first appearance of *T. pedum* in the global stratotype section in Newfoundland (Narbonne et al., 1987) and in other regions, including the Mackenzie Mountains of Canada (MacNaughton and Narbonne, 1999; Carbone and Narbonne, 2014), the Flinders Ranges of South Australia (Jensen et al., 1998), eastern Finnmark, Norway (Føyn and Glaessner, 1979; Högström et al., 2013), Sonora, Mexico (Stewart et al., 1984; Sour-Tovar et al., 2007), and Death Valley, Eastern California (Jensen et al., 2002), among many other areas. In the Alborz Mountains of northern Iran, however, the first appearance datum of *Treptichnus pedum* occurs stratigraphically higher in the section. Although ichnozone 1 consists of grazing trails, which are common in Ediacaran strata elsewhere, these trace fossils are also abundant in Fortunian deposits in Burin Peninsula, in connection with microbially stabilized surfaces (Buatois et al., 2014). In contrast to the Fortunian of Burin Peninsula, arthropod trackways are absent in ichnozone 1 in the Soltanieh Formation. We hypothesize that the presence of an ichnofauna of “Ediacaran aspect” and the late appearance of *Treptichnus pedum* in the Soltanieh Formation is due to environmental constraints. Buatois et al. (2013) noted that this ichnotaxon has a broad environmental tolerance, albeit displaying a preference for sandy substrates. The shelf shales of the Soltanieh Formation may have represented the seaward limit of the *T. pedum* producer. Alternatively, because *T. pedum* is typically preserved along lithologic interfaces, its absence in the shelfal shale may simply reflect a taphonomic constraint. Therefore, ichnozone 1 in the Alborz Mountains may be understood as a distal expression of the *Treptichnus pedum* Zone, which is commonly recognized in settings above storm wave base (Buatois et al., 2013). A similar situation has been noted in the Ediacaran–Cambrian succession of eastern Yunnan Province, South China (Zhu, 1997), western Mongolia (Smith et al., 2015), Lesser Himalaya, India (Singh et al., 2014), and southeastern Kazakhstan (Weber et al., 2013), where the first appearance of the trace-fossil *T. pedum* postdates the Ediacaran–Cambrian transition.

Ichnozone 2 of the Soltanieh Formation corresponds in part to ichnozone III of global ichnofossil zones and the *Treptichnus pedum* Zone of the Chapel Island Formation, Burin Peninsula, which characterizes the lower part of Member 2, from 2.4 to 133 m above its base (Narbonne et al., 1987; Landing, 1996). This ichnozone is also represented in the upper interval of the Ingta Formation in the Mackenzie Mountains (MacNaughton and Narbonne, 1999) and the Nomtsas Formation of Namibia (Crimes and Germs, 1982; Geyer and Uchman, 1995), among other areas. Integration of trace fossils and small shelly faunas suggests that ichnozone 2 of the Soltanieh Formation is best regarded as the upper half of the global *Treptichnus pedum* Zone to accommodate the shelf deposits of early Fortunian age that make up the lower interval of the Lower Shale Member.

| Chronostratigraphy | Northern Iran | | | | South China | | | Southeast Kazakhstan | | Western Mongolia | | Northern, India | | Northern Pakistan | |
|--------------------------|--|---------|---|---------|---------------------|---|--------------|--|----------------------------|--|----------------------------|--|----------------------------|------------------------|-------------------------------------|
| | Lithostratigraphy | | Biozonation /Trace fossils | | Lithostratigraphy | Biozonation /Trace fossils | | Lithostratigraphy | Biozonation /Trace fossils | Lithostratigraphy | Biozonation /Trace fossils | Lithostratigraphy | Biozonation /Trace fossils | Lithostratigraphy | SSFs |
| | Age 2 | | | | | | | | | | | | | | |
| Precambrian Ediacaran | Fortunian | | Soltanieh Fm. | | Xiaowaitoushan Mbr. | Kurgan Fm. | | Zuun-Arts Fm. | | Krol Group | | Tanawal Fm. | | | |
| | LD Mbr. | LS Mbr. | MD Mbr. | US Mbr. | L-Ph Mbr. | U-Ph Mbr. | Berkuty Mbr. | BG2 | Chert-Phosphate Mbr. | Abbottabad Fm. | Upper quartzite unit | Middle dolomitic unit | Lower arenaceous unit | | |
| | Anabarites trisulcatus–Protohertzina anabarica | | Watsonella crosbyi | | Zhongyicun Mbr. | Paragloborilus subglobosus–Purella squamulosa | | Anabarites trisulcatus–Protohertzina anabarica | | Deo Ka Tiba Fm. | | Anabarites trisulcatus - Protohertzina anabarica | | Hazirad Fm. | Hyalolithes sp. Chencelloria sp. |
| | Trepitichnus pedum | | Rusophycus avalonensis Cruziana problematica | | Trepitichnus pedum | Rusophycus avalonensis | | Trepitichnus pedum | | Rusophycus avalonensis Trepitichnus pedum | | Arenaceous Mbr. | | Dimidia-Allonia | Rusophycus avalonensis |
| | Soltanieh Fm. | | Shiyantou Fm. | | Kyrshabakty Fm. | Chulaktai Fm. | | Bayangol Fm. | | Bayangol Fm. | | Argillaceous Mbr. | | Rusophycus avalonensis | |
| | Kahar Fm. | | Dahai Mbr. | | Aksai Mbr. | Karatau Mbr. | | BG3 | | BG4 | | Arenaceous Mbr. | | | |

Figure 8. Stratigraphic column of the Soltanieh Formation, showing distribution of trace fossils, small shelly fossils, biozonation based on trace fossils and small shelly fossils, and correlation in relation to the Yangtze platform, China. Sources: Latif (1972), Hasan (1986), Hamdi et al. (1989), Zhu (1997), Steiner et al. (2007), Desai et al. (2010), Weber et al. (2013), and Smith et al. (2015).

In sections worldwide, *Cruziana* and *Rusophycus* commonly occur stratigraphically below the first occurrence of trilobite body fossils, and above the first appearance of *Trepitichnus pedum* (Crimes, 1987). In the Chapel Island Formation in Newfoundland, for example, *Rusophycus avalonensis* appears ~250 meters up-section from *T. pedum*, and in current global ichnostratigraphic schemes this ichnotaxon first appears below the *Cruziana problematica* Zone. In the Soltanieh Formation, however, *R. avalonensis* has been collected above *Cruziana problematica* and together with *Psammichnites gigas* within ichnozone 4. In this formation, the first appearance of bilobate cruzianid traces occurs at the base of the ichnozone 2, whereas *Cruziana problematica* first appears in ichnozone 3, considerably above (172 m) the first appearance of *T. pedum*. In strict sense, because *Cruziana* and *Rusophycus* are both produced by trilobites or trilobitiform arthropods, there is no a priori reason why *Cruziana* should occur stratigraphically above *Rusophycus*.

Finally, Hamdi et al. (1989) noted that the phosphatic layers near the base of the Upper Shale Member might be part of a contemporaneous event across the Palaeotethyan belt, underscoring similarities with successions in China, India, Pakistan, Kazakhstan, and Mongolia. However, correlations suggest a more complicated pattern. In South China, the phosphate layers of the Upper Phosphate Member occur within the *R. avalonensis* and *Paragloborilus subglobosus–Purella squamulosa* biozones (Zhu, 1997; Steiner et al., 2007). In southeastern Kazakhstan, the phosphate deposits of the Aksai Member occur below the *R. avalonensis* Zone, and within the *Purella antiqua* assemblage zone (Weber et al., 2013). In western Mongolia, the phosphate layers at the base of Member 2 of the Bayangol Formation occur

within the *Anabarites trisulcatus–Protohertzina anabarica* Assemblage Zone and below the *R. avalonensis* Zone (Smith et al., 2015). The Chert-Phosphate Member of Northern India occurs within the *Anabarites trisulcatus–Protohertzina anabarica* Assemblage Zone, below the *R. avalonensis* Zone (Desai et al., 2010). In northern Pakistan, the phosphate-bearing deposits at the top of Abbottabad Formation are believed to be of earliest early Cambrian age (Latif, 1972; Hasan, 1986). However, due to lack of biostratigraphic and geochronological constraints, the age of the Abbottabad Formation is in dispute.

Therefore, the phosphatic layers of the Upper Shale Member are most likely coeval with those in the Upper Phosphate Member in Yunnan and the Karatau Member in Southeastern Kazakhstan, whereas Member 2 of the Bayangol Formation of western Mongolia, the Chert-Phosphate Member in India, and the upper Abbottabad Formation in Pakistan seem to be older (Fig. 8). To summarize, the integration of stratigraphic, sedimentologic, and biostratigraphic data suggests two phosphatic events (early Fortunian and late Fortunian) rather than one.

Conclusion

Trace-fossil assemblages recorded from the Soltanieh Formation in northern Iran are characterized by low to moderate diversity, dominance of very simple forms, and a combination of locomotion, grazing, and dwelling structures. Ichnodiversity increases towards the top of the unit. An analysis of the Soltanieh ichnofauna indicates that four ichnozones may be recognized. Ichnozone 1 is of early Fortunian age and is characterized by low diversity of simple grazing traces. Ichnozone 2

is of middle Fortunian age, and is defined based on the first appearance of *Treptichnus pedum* and the earliest bilobate trace *Cruziana* isp. Ichnozone 3 is late Fortunian–Cambrian Age 2, and is marked by sudden change in abundance and complexity of trace fossils and the first appearance of *Cruziana problematica*. Ichnozone 4 is Cambrian Ages 2–3, and is characterized by the first appearance of *Psammichnites gigas*, *Rusophycus avalonensis*, and *Didymaulichnus miettensis*. An integration of trace fossils with small shelly fossils and evaluation suggest that the Ediacaran–Cambrian boundary should be placed at the base of the Soltanieh Formation or within the Lower Dolomite Member.

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