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Supplemental Material for

New Ediacara-type fossils and late Ediacaran stratigraphy from the northern Qaidam Basin (China): paleogeographic implications

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LITHOSTRATIGRAPHY DESCRIPTION

Proterozoic successions in the Qaidam block are represented by the Quanji Group in the Olongbuluke terrane, which is located in the northern margin of the Qaidam block (Figs. 1A–1C) (Lu, 2002; Shen et al., 2007; Sun et al., 2019). The Quanji Group is well exposed at the Quanjishan (37°25′55.2″N, 95°48′0.2″E) and Shihuigou (37°22′21.8″N, 96°03′25.4″E) sections, Qaidam Basin (Fig. 1C; Fig. S1). It is composed of, in ascending order, the Mahuanggou, Kubaimu, Shiyingliang, Hongzaoshan, Heitupo, Hongtiegou, and Zhoujieshan Formations (Fig. 2A) (Bureau of Geology and Mineral Resources of Qinghai Province, 1997; Shen et al., 2007; Shen et al., 2010; Wang et al., 2020a).

The Mahuanggou Formation varies from 457.5 m to 700.8 m in thickness, and unconformably overlies biotite and plagioclase schist of the Paleoproterozoic Dakendaban Group. The lower part of the Mahuanggou Formation consists of purplish-gray to greenish-gray thick-bedded conglomerates. Clasts increase upsection in abundance and size. The middle part of the Mahuanggou Formation is composed of purplish-gray to yellowish-green thick-bedded conglomerates, whereas the upper part is dominated by purplish-gray thick-bedded coarse-grained sandstones.

The Kubaimu Formation, ~97–357 m thick, either conformably overlies the Mahuanggou Formation or sits directly on the metamorphic rocks of the Dakendaban Group in northwestern Quanjishan area where the Mahuanggou Formation is missing. The lower part of the Kubaimu Formation is composed of purplish-gray to grayish-white thick-bedded conglomerates intercalated with medium-grained to coarse-grained sandstones. The middle part of the Kubaimu Formation consists of light red thick-bedded medium-grained to coarse-grained sandstones with small pebbles. The upper part consists of red thick-bedded medium-grained to coarse-grained sandstones.

The Shiyingliang Formation, ~68–395 m thick, disconformably overlies the Kubaimu Formation. The lower part of the Shiyingliang Formation consists of grayish-white thick-bedded sandstones, followed by greenish-gray basaltic and andesitic volcanics, gray to dark gray claystones, shales, and siltstones in the middle part. The upper part of the Shiyingliang Formation is composed of light gray to grayish-white thick-bedded sandstones intercalated with yellowish-green thin-bedded siltstones.

The Hongzaoshan Formation, conformably overlying the Shiyingliang Formation, varies from ~107 to >1700 m in thickness, and is dominated by dolostones which contains stromatolite (Fig. S1H). The lower part of the Hongzaoshan Formation contains two greenish volcanic tuff units with lapilli (Fig. S1I). Two LA-MC-ICPMS zircon U-Pb ages of 1646 ± 20 Ma and 1640 ± 15 Ma were obtained from these volcanic units, respectively (Zhang et al., 2016). More recently, five volcanic samples from the Quanjishan and Shihuigou sections have been dated at 1622 ± 69 Ma, 1650 ± 25 Ma, 1663 ± 22 Ma, 1674 ± 36 Ma, and 1620 ± 15 Ma (LA-ICP-MS zircon weighted mean $^{207}Pb/^{206}Pb$ ages), respectively (Wang et al., 2020a). Fe oxide-bearing paleoweathering crusts were observed in the upper part of the Hongzaoshan Formation (Fig. S1G) or at the top of the Hongzaoshan Formation (Sun et al., 2019; Wang et al., 2015). At the

Shihuigou section, the uppermost Hongzaoshan Formation is composed of yellowish medium- to thin-bedded dolostone intercalated with greenish-gray shales.

The Heitupo Formation, ~10–123 m thick, nonconformably overlies the Hongzaoshan Formation. It is dominated by yellowish-green to greenish-gray siltstones and shales (Fig. S1F). The Heitupo Formation is missing at the Shihuigou section (Sun et al., 2019; Wang et al., 2015), although Bureau of Geology and Mineral Resources of Qinghai Province (1997) described a ca. 10 m thick "Heitupo Formation" with dolostones in its lower part and slates in its upper part. Fragments of *Redkinia* (or tooth-like fossils) reported from the Heitupo Formation (Wang et al., 1980) indicate a likely age of ~555 Ma (Burzin, 1995; Martin et al., 2000; Shen et al., 2010; Vorob'eva et al., 2009), but the reliability of fossil occurrence needs further assessment. A whole-rock Rb-Sr isochron age of 590.03 ± 26 Ma was obtained from the Heitupo Formation (Bureau of Geology and Mineral Resources of Qinghai Province, 1997), but again, this age is not very reliable considering the unpredictable behavior of the Rb-Sr geochronological system.

The Hongtiegou Formation varies from ~18 m to >100 m thick. It is characterized by yellowish-green, purplish-gray, to greenish-gray massive diamictites (Fig. S1E). The contact between the Heitupo and Hongtiegou Formations is sharp, suggesting a probable depositional gap between them. However, evident features indicative of sedimentary break have not been observed in the field (Fig. S1F).

The Zhoujieshan Formation of the uppermost Quanji Group, ca. 56 m in thickness at the Quanjishan section, nonconformably underlies dolostones of the Cambrian Xiaogaolu Group (Figs. S1A and S1B). The Zhoujieshan Formation begins with a ~7 m thick cap dolostone in the bottom (Fig. S1D). The lower part (< 1 m thick) of the cap dolostone unit also bears clasts of similar composition to those in the

Hongtiegou diamictite, whereas the middle and upper parts do not. A unit of nearly 50 m thick reddish thin-bedded siltstones and fine sandstones (Fig. S1C) follows the cap dolostone unit, between which lie <1 m thick of thin-bedded yellowish-gray siltstones. The reddish thin-bedded siltstones and fine sandstones contains Ediacara-type fossils such as *Charnia* and tubular fossil *Shaanxilithes*, whose lowest occurrences are ~5 m above the cap dolostone unit (Shen et al., 2007; Wang, 2019; Wang et al., 1980).

In the Helanshan area of Ningxia Hui Autonomous Region, the late Neoproterozoic sequence is represented by the Zhengmuguan and Tuerkeng Formations (Fig. 2B; Bureau of Geology and Mineral Resources of Ningxia Hui Autonomous Region, 1996; Shen et al., 2007; Wang, 2019). The Tuerkeng Formation equals to the upper slate unit of the former Zhengmuguan Formation. At the Suyukou section in the Helanshan area (Fig. 2B), the Zhengmuguan Formation (= the lower diamictite unit of the former Zhengmuguan Formation), ~ 70 m thick, unconformably overlies dolostones of the Mesoproterozoic Wangquankou Formation, whose maximum depositional age is constrained by a LA-MC-ICPMS detrital zircon $^{207}Pb/^{206}Pb$ age of 1608 ± 5.1 Ma (Zhang et al., 2020). The Zhengmuguan Formation is composed of grayish thick- to medium-bedded diamictites. The Tuerkeng Formation, ~80 m thick, unconformably underlies phosphatic pebbly sandstones of the Cambrian Suyukou Formation. The Tuerkeng Formation is dominated by grayish silty slates or slaty siltstones. The transition between the Zhengmuguan and Tuerkeng Formations is gradational (Shen et al., 2007), with clasts in the Zhengmuguan diamictites decreasing upsection in abundance and size. Abundant tubular fossils that can be assigned to *Shaanxilithes* were reported from the Tuerkeng Formation (Shen et al., 2007; Wang, 2019; Yang and Zheng, 1985).

In western Henan, eastern Shaanxi, and southern Shanxi Provinces, the

uppermost Neoproterozoic sequence is represented by the Luoquan and Dongpo Formations (Fig. 2C; Bureau of Geology and Mineral Resources of Henan Province, 1997; Bureau of Geology and Mineral Resources of Shaanxi Province, 1998; Bureau of Geology and Mineral Resources of Shanxi Province, 1997; Guan et al., 1988). At the Jiunvdong section in Lushan, western Henan Province (Fig. 2C), the Paleoproterozoic to early Neoproterozoic succession underlying the Luoquan Formation is composed of, in ascending order, the Sanjiaotang (sandstones), Luoyukou (shales and dolostones), Huanglianduo (conglomerates, dolostones, and cherts), and Dongjia (sandstones and limestones) Formations (Guan et al., 1988). The depositional age of the Luoyukou Formation is constrained by a series of tuff zircon U-Pb ages from the lower part of the Luoyukou Formation, ranging from 1639 ± 13 Ma to 1596 ± 7 Ma (Fig. 2C; Li et al., 2017; Peng et al., 2018; Su et al., 2012; Zhang et al., 2019). The depositional ages of the Huanglianduo and Dongjia Formations are less well constrained. The youngest detrital zircon ages from the Huanglianduo Formation are 1690 ± 66 Ma (Wang et al., 2020b) or 1625 ± 100.5 Ma and 1687 ± 53.5 Ma (Zuo et al., 2019), whereas the youngest detrital zircon age from the Dongjia Formation is 1661 ± 64.5 Ma (Zuo et al., 2019). It is thought that the Huanglianduo Formation was deposited in Mesoproterozoic by lithostratigraphic comparison and stromatolite assemblage (Xu et al., 2015; Yue et al., 2020) and the Dongjia Formation was deposited in early Neoproterozoic by organic-walled microfossil assemblage (Yin and Guan, 1999). However, the Dongjia Formation could also be Mesoproterozoic in age because taxa of the Dongjia microfossil assemblage are common in other middle Mesoproterozoic to early Neoproterozoic (Tonian) assemblages (Baludikay et al., 2016; Li et al., 2019), particularly considering that the occurrence of the diagnostic genus *Trachyhystrichosphaera* from the Dongjia Formation could be as early as ~1100 Ma or 1070 Ma (Beghin et al., 2017; Loron et al.,

2019; Pang et al., 2020; Rainbird et al., 2020). The Luoquan Formation, ~13 m thick, unconformably overlies dolomitic limestones of the Dongjia Formation at the Jiunvdong section. It consists of, in ascending order, the lower ~1.4 m thick purplish diamictites, the middle ~9.3 m thick greenish-gray diamictites, and the upper ~2.3 m thick light red diamictites. The Dongpo Formation begins with a ~3.8 m thick light red silty shales, overlain by ~39 m thick greenish-gray shales intercalated with thin-bedded siltstones. The Dongpo Formation is unconformably overlain by phosphatic pebbly sandstones of the Cambrian Xinji Formation. Abundant *Shaanxilithes* fossils have been reported from the Dongpo Formation in several sections in Shaanxi and Henan Provinces recently (Wang, 2019).

The upper Quanji Group in the Olongbuluke terrane is quite similar to the general characteristics of upper Neoproterozoic successions in the western and southern margins of the North China block, e.g., the Suyukou and Jiunvdong sections (Figs. 1A and 2), which are also composed of an underlying diamictite unit and overlying finer-grained siliciclastic rocks (Qi, 2017; Shen et al., 2007; Wang et al., 2020a; Wang, 2019). Specifically, the Hongtiegou Formation in the Olongbuluke terrane is comparable to the Zhengmuguan Formation in the Helanshan area of Ningxia Hui Autonomous Region and the Luoquan Formation in Shaanxi and Henan Provinces. These three Formations are all characterized by post-Gaskiers glacial depositions overlying Paleo-Mesoproterozoic to early Neoproterozoic carbonates and siliciclastics. Meanwhile, The Zhoujieshan Formation overlying the Hongtiegou diamictite in the Olongbuluke terrane is comparable to the Tuerkeng Formation overlying the Zhengmuguan diamictite in the Helanshan area and the Dongpo Formation overlying the Luoquan diamictite in Shaanxi and Henan Provinces. These three Formations are all dominated by finer-grained siliciclastics that contain the potential terminal Ediacaran index tubular fossil

Shaanxilithes. They also share transitional boundaries with the underlying diamictite units.

FOSSIL DESCRIPTION

All illustrated specimens from the Quanjishan assemblage are deposited at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences (NIGPAS, Nanjing, China), with NIGPAS museum catalog numbers (prefix NIGP-) given for illustrated specimens.

Charnia. Thirteen frondose specimens, three with parts and counterparts, are described under the genus *Charnia* (Figs. 3A–3C; Figs. S2A–S2E). Although most specimens were collected as floats with their stratigraphic orientation undetermined, a few specimens which were excavated freshly from the Quanjishan section show that the petaloids are preserved as negative reliefs on bed tops (Figs. S2C and S2D). The Quanjishan *C. masoni* specimens are characterized by a uniterminal frond with two rows of primary branches emanating alternately from the central midline at 12–45°, forming a slightly zig-zag central suture. Holdfast is not preserved, whereas sometimes possible stem is preserved (Fig. 3A). Petalodium is oblanceolate in shape, 21.4–44.6 mm in length and 4.7–13.4 mm in width (n = 6), with length/width ratio 2.5–6.1 for nearly completely preserved ones. Primary branches are sigmoidal to rectangular, and usually less than 10 on each petaloid. The largest primary branch of petalodium is 6.4–29.8 mm in length and 1.4–5.4 mm in width (n = 10), with length/width ratio 2.9–5.9. Secondary branches can be discernable in well-preserved specimens (Figs. 3B and 3C; Figs. S2C and S2D), ca. 0.5–2.0 mm in length. Tertiary branches are barely discernable (Fig. 3C). A particular incomplete frondose fossil without more diagnostic features appears to have a central stalk (Fig. S2F), different

from specimens assigned to *C. masoni*.

***Shaanxilithes*.** More than six hundred specimens of annulated tubular fossils, many with parts and counterparts, are described under the genus *Shaanxilithes* (Figs. 3E–3G; Fig. S3). Specimens of tubular fossils are classified as different taphomorphs of *Shaanxilithes ningqiangensis* in this study (Meyer et al., 2012; Wang, 2019). They consist of ribbons ornamented with densely packed annulations (Fig. 3E; Figs. S3A–S3C), ribbons composed of slightly to severely disarticulated segments resembling *Palaeopascichnus* (Fig. 3F; Figs. S3D–S3G), as well as ribbons without distinct surface ornamentations (Fig. 3G). Specimens of *S. ningqiangensis* are unbranched and uniseriated, usually with uniform width along the length. Ribbons can be straight, bent, or highly curved, with a diameter of 0.6–5.0 mm (mean = 1.9 mm; SD = 0.8 mm; n = 612) and a length up to ~10 cm. The size frequency distribution of tubular fossils is unimodal and moderately right-skewed (Fig. S4), suggesting that the population is monospecific. Annulations on well preserved ribbons are nearly parallel and closely spaced (Fig. 3E; Figs. S3A–S3C), with 2–6 annulations per mm of tube length.

DATA REPOSITORY FIGURES AND CAPTIONS

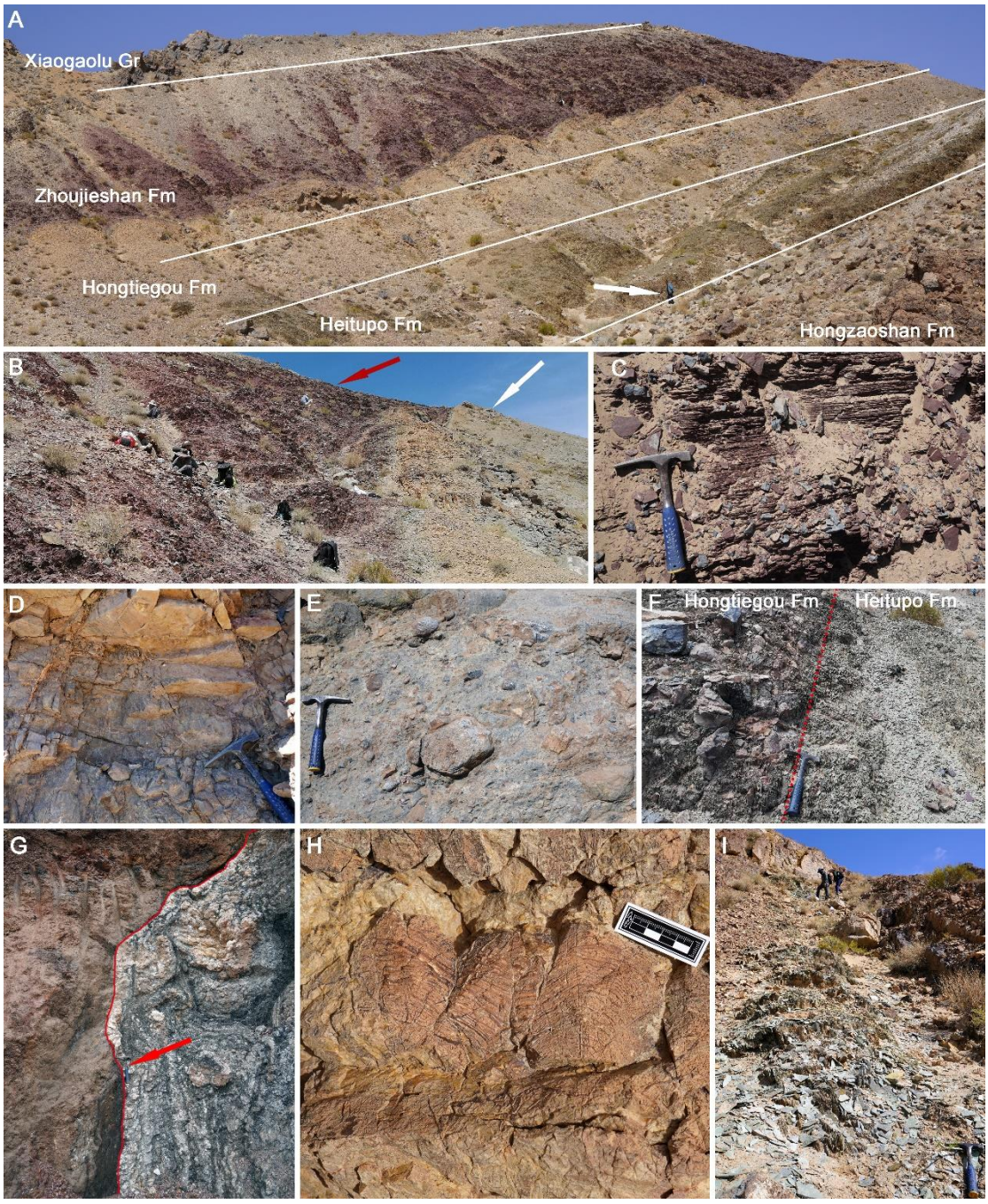

Figure S1. Field photographs of the Quanji Group at the Quanjishan section A (A, B, F, H, I) and section B (G) and the Shihuigou section (C–E) (China). A, Field photograph of the upper Quanji Group; arrow denotes a person of ~1.7 m tall for scale. B, Excavation site at the Zhoujieshan Formation; red and white arrows denote the fossiliferous sandstone and the basal cap dolostone unit atop diamictite of the

Hongtiegou Formation, respectively. C, Reddish sandstone of the Zhoujieshan Formation. D, The basal cap dolostone of the Zhoujieshan Formation. E, Diamictite of the Hongtiegou Formation with poorly sorted clasts. F, Field photograph showing diamictite with greenish matrix of the Hongtiegou Formation and greenish-gray shale of the underlying Heitupo Formation. G, Paleoweathering crust (red line) in the upper part of the Hongzaoshan Formation; arrow denotes a hammer for scale. H, Stromatolite in the dolostone of the middle part of the Hongzaoshan Formation. I, Volcanic tuff with lapilli in the lower part of the Hongzaoshan Formation. Gr = Group; Fm = Formation. Hammers in (C–G, H) are ca. 30 cm long. The Quanjishan section A and section B were described by Shen et al. (2010).

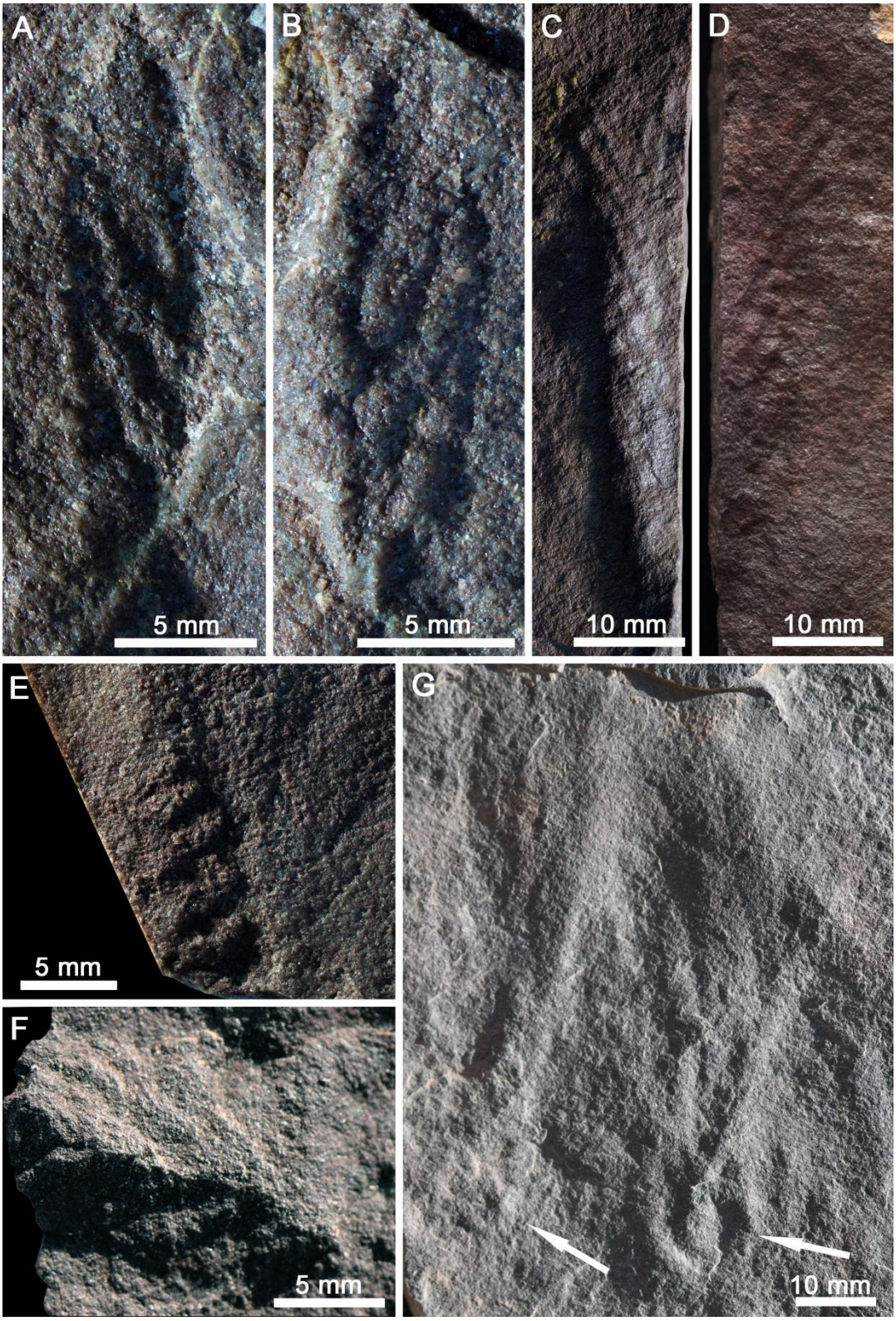

Figure S2. Frondose fossils from the Zhoujieshan Formation at the Quanjishan (A–D, F, G) and Shihuigou (E) sections (China). A, B, A *Charnia* specimen with only one petaloid excavated; (A) negative relief; (B) positive relief; part and counterpart,

stratigraphic orientation unknown; NIGP161616. C, D, An incomplete *Charnia* specimen; (C) positive relief on bed sole; (D) negative relief on bed top; part and counterpart; NIGP161617. E, An incomplete *Charnia* specimen; NIGP161618. F, An incomplete frondose fossil with a central stalk; NIGP161619. G, two frondose fossils with an *Aspidella*–type basal disc (arrows); NIGP161620.

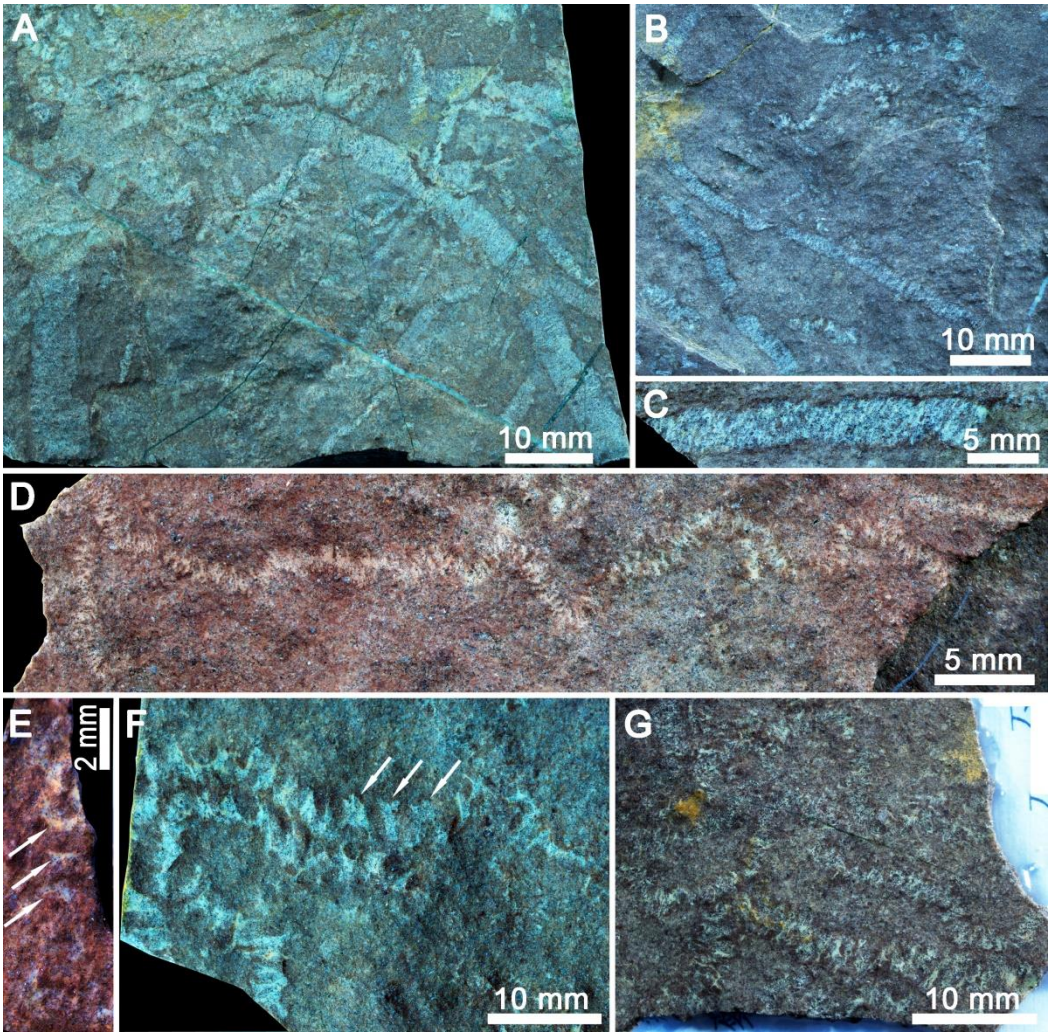

Figure S3. Tubular fossil *Shaanxilithes* from the Zhoujieshan Formation at the Quanjishan section (China). A, B, Slabs covered with abundant annulated ribbons in different width; (A) NIGP161621; (B) NIGP161622. C, A straight ribbon with densely packed annulations; NIGP161623. D, A bent and slightly disarticulated ribbon; NIGP161624. E, F, Ribbons with disarticulated segments (arrows) resembling *Palaeopascichnus*; (E) NIGP161625; (F) NIGP161626. G, Dense accumulation of slightly disarticulated ribbons; NIGP161627.

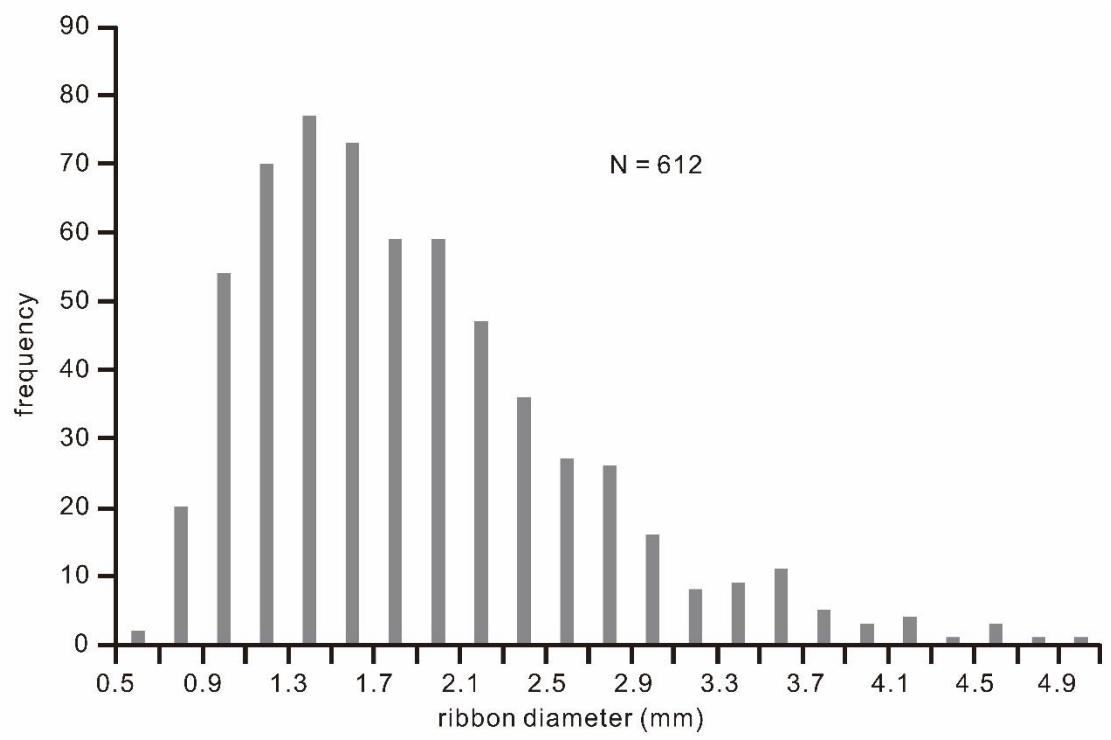

Figure S4. Frequency distribution of ribbon diameter of *Shaanxilithes* from the Zhoujieshan Formation at the Quanjishan section (China).

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