



Upper Ordovician (Hirnantian) to Lower Silurian (Telychian, Llandovery) graptolite biostratigraphy of the Tielugou section, Shennongjia anticline, Hubei Province, China

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Abstract

The Tielugou section, Shennongjia Anticline, Hubei Province (China) includes a relatively complete succession of Hirnantian (latest Ordovician) to basal Telychian (Llandovery, early Silurian) graptolite faunas. The section shows the first record of a fauna of the late Aeronian *Stimulograptus halli* Biozone from South China, even though the index species was not reported. The *Stimulograptus sedgwickii* Biozone may not be represented, indicating a possible gap at the base of the *Stimulograptus halli* Biozone. The interval yields a number of taxa that are elsewhere reported to originate only in the *Stimulograptus halli* Biozone. The youngest graptolitic levels are included in the *Spirograptus guerichi* Biozone based on specimens of *Parapetalolithus dignus* and *Parapetalolithus palmeus* not known from earlier intervals. *Spirograptus guerichi* is not represented in the section. The Tielugou section provides the first detailed information on the faunas and thickness of the encountered biostratigraphic units for the Shennongjia region.

Keywords Graptolites · Biostratigraphy · Silurian · Llandovery · China · Yangtze platform

Introduction

Graptolitic successions of Late Ordovician to Early Silurian age are well known from the Yangtze platform of China and a number of faunal descriptions of the Late Ordovician to Early Silurian graptolites exist (Ni 1978; Chen and Lin 1978; Fang et al. 1990; Ge 1990; Li 1995, 1999). Interpretations by Chen et al. (2015, 2017) and Nie et al. (2017) indicated that the Ordovician/Silurian boundary interval is strongly condensed and the thickness of some biostratigraphic intervals shows values of sometimes less than 10 cm per graptolite

biozone (Chen et al. 2006). A number of successions on the eastern side of the Huangling massif (Fig. 1a) provide detailed information pertaining to this interval. Also, the GSSP section for the international Hirnantian Stage of the Ordovician System, the Wangjiawan section, is defined in this area. According to Maletz et al. (2019), the Rhuddanian interval is condensed and incomplete in the YD–1 drill core east of the Huangling massif of Hubei Province, China, whereas an extremely thick mid–Aeronian *Lituigraptus convolutus* Biozone was documented. Younger graptolites have not been registered in the drill core, unfortunately. Thus, the precise biostratigraphic correlation of some intervals is uncertain. Loydell (2012) indicated that the *Stimulograptus sedgwickii* and *Stimulograptus halli* biozones of the late Aeronian have not been documented unequivocally from South China. The *Spirograptus guerichi* Biozone is present as the oldest Telychian time interval, whereas the *Cyrtograptus sakmaricus* Biozone of late Telychian is the youngest interval recognized. Most of this information, however, originated from the northern Sichuan Basin successions (Chen 1984; Ge 1990; Fu et al. 2000; Chen et al. 2003; Wang et al. 2014) and the successions in the Huangling and Shennongjia regions are less well known.

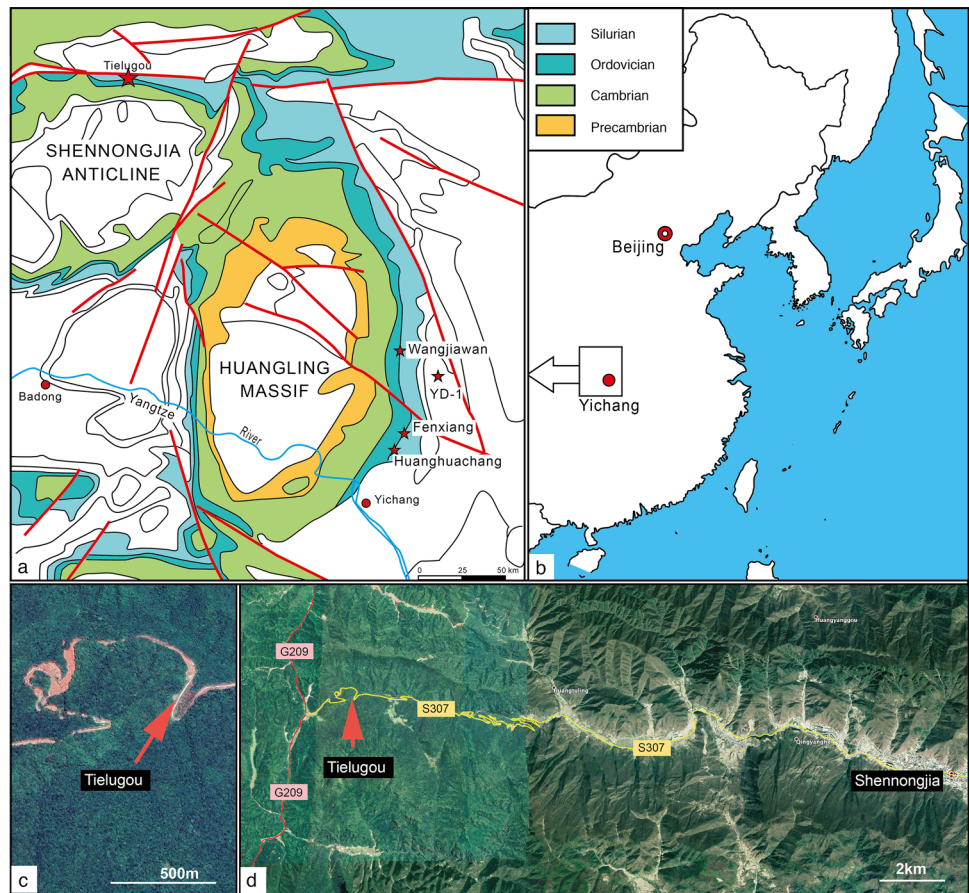
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Fig. 1 Geographical position of the Tielugou section. **a, b.** General map of eastern China (**b**) and of the Shennongjia and Huangling massifs (**a**) showing the location of the Tielugou section and other sections discussed in the paper and the main chronostratigraphic units (modified from Maletz et al. 2019, Fig. 1). **c–d.** Google Earth Maps (Sept. 2020) showing the precise location of the Tielugou section on the regional road S307 west of Shennongjia



Little information is available about the Lower Palaeozoic succession from the rim of the Shennongjia anticline (Fig. 1a). Bai et al. (2011) discussed the Huangling–Shennongjia area in the western Hubei province as part of the Yangtze continental nucleus with early Precambrian crystalline basement and a Proterozoic to Phanerozoic sedimentary cover. Ye et al. (2019) considered that the tectonic relationships between the Shennongjia terrane and the Huangling massif are unclear. Zhang and Dong (2016), however, interpreted the Shennongjia–Huangling massif as a single, rigid structure in the southern Dabashan unit.

Fan et al. (2011) discussed the Qingquan section, ca. 10 km east of Shennongjia and recognized the *Parakidograptus accuminatus* Biozone at the base of the Lungmaxi Shale. The Lungmaxi Shale is overlain by yellowish or gray–green shales and mudstones with a *Spirograptus guerichi* Biozone fauna. Information on the thickness of the lithostratigraphic and biostratigraphic units was not provided and the faunas have not been described. Thus, the here reported succession of the Tielugou section provides for the first time a detailed overview of the graptolite faunal succession of the lower Silurian of the region. It shows that the succession starts at least in the Upper Ordovician *Metabolograptus persculptus* Biozone and ranges upwards into the *Spirograptus guerichi*

Biozone (basal Telychian). The index species *Spirograptus guerichi* was not recognized, but appears to be present in the nearby Qingquan section (Fan et al. 2011).

Materials and methods

The Tielugou section

The Tielugou section (probably the Shennongjia section of Chen et al. 2014) is a roadside section on the Provincial Road S307 to the west of Shennongjia (Fig. 1c–d) in the Shennongjia Forestry district (listed in the UNESCO’s World Network of Biosphere Reserves). The section is about 15 km to the west of the city center of Shennongjia, north of the conspicuous U-turn in the road (Fig. 1c). The section measures ca. 57 m from the *Metabolograptus persculptus* Biozone to the top of the accessible outcrop. The higher part of the succession consists of silty, light colored siltstones and mudstones and does not bear any graptolite faunas. More than 70 samples with graptolites have been collected from the section (Figs. 2, 3), some of which include a considerable number of identifiable specimens.

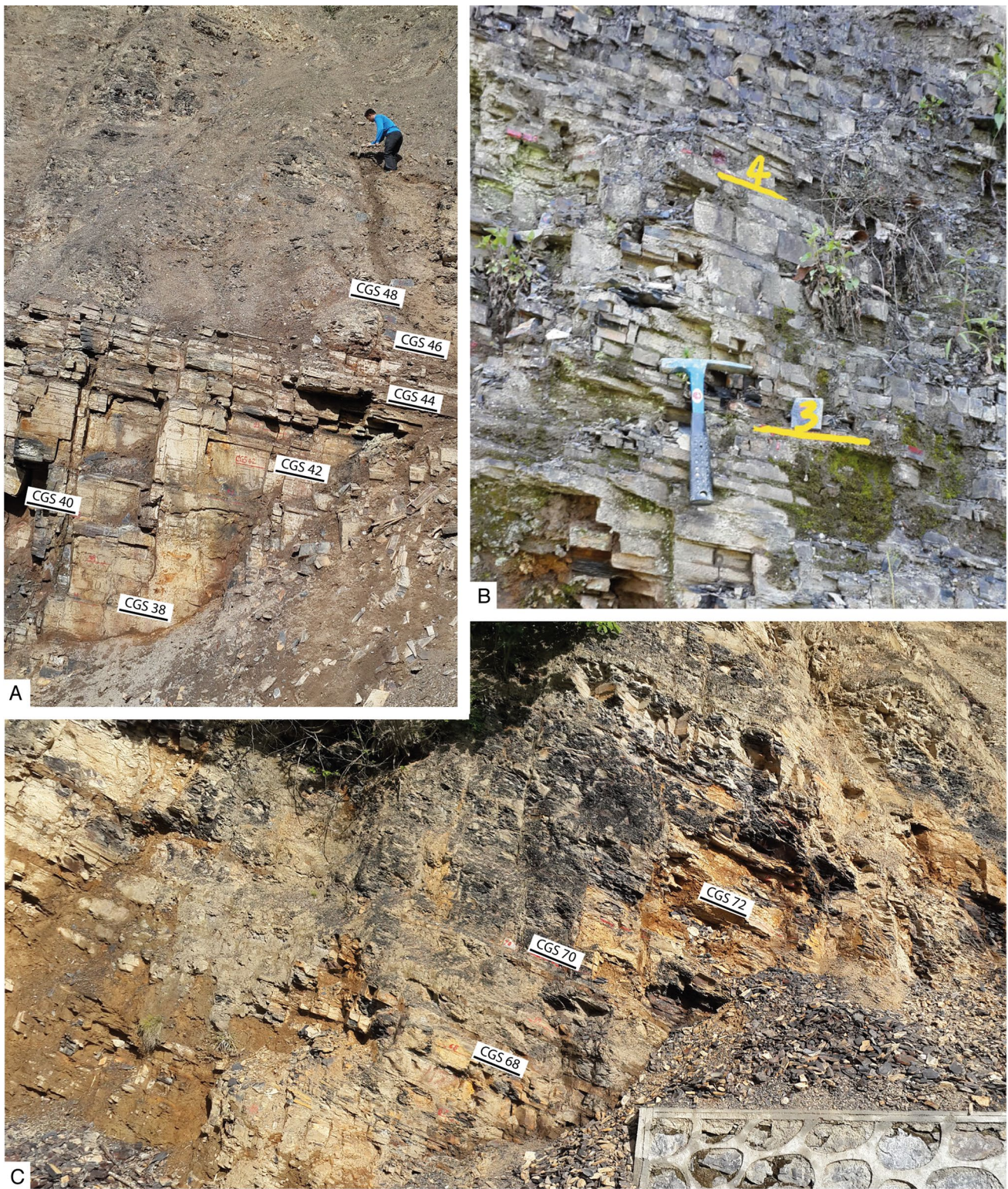


Fig. 2 The Tielugou section, exposure and lithology. **a** Middle part, samples CGS38–CGS48 (higher part during excavation) (*Coronograptus leei* to *Lituigraptus convolutus* Biozone). **b** Lower part,

samples 3 and 4 interval (*Metabolograptus persculptus* Biozone). **c** Higher part of succession (*Stimulograptus halli* Biozone), samples CGS68–CGS72 labeled. Photos by Wei Kai

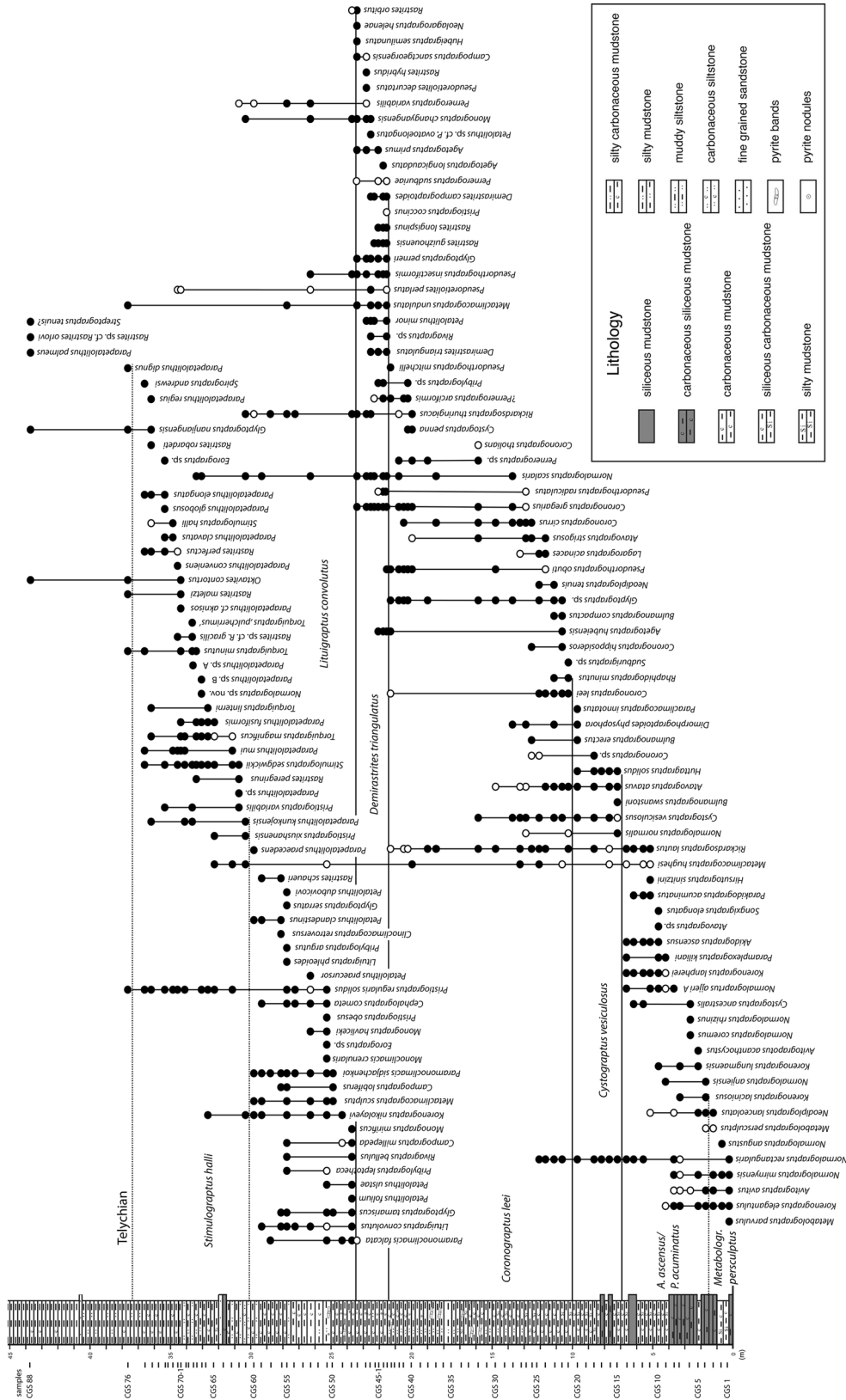


Fig. 3 The graptolite biostratigraphy of the Tielugou section. Open circles indicate uncertain identifications due to poor preservation

Lithology

The succession was documented recognizing 114 lithostratigraphic units that were carefully collected for fossils and described lithologically in the field. A shortened report is given here for the lithologies. The strata are in part strongly weathered, but parts closer the road are less weathered due to the fairly recent construction.

CGS1–8 (0–4 m). Black thin-bedded carbonaceous, siliceous mudstone inter-bedded with thin-bedded carbonaceous mudstone (Fig. 2b).

CGS9–12 (4–6 m). Black thin-bedded carbonaceous mudstone inter-bedded with a few thin-bedded siliceous mudstones.

CGS13–26 (6–13 m). Black thin-bedded carbonaceous siliceous mudstone, muddy siliceous mudstone inter-bedded with thin-bedded carbonaceous mudstone. Pyrite bands are more developed in the upper part.

CGS27–64 (13–32 m). Dark gray–black siltstone inter-bedded with carbonaceous mudstone and thin-bedded siltstone. Pyrite bands or nodules are present (Fig. 2a).

CGS65–69 (32–34.5 m). Black carbonaceous mudstone inter-bedded with thin-bedded siltstone or fine-grained sandstone lenses. A medium–thin-bedded (30 cm in total thickness) fine-grained sandstone at the base with plenty of scattered pyrite crystals.

CGS70–81 (34.5–40.5 m). Gray–dark gray silty mudstone or carbonaceous mudstone inter-bedded with thin-bedded siltstone (Fig. 2c).

CGS82–114 (40.5–57 m). Gray thin-bedded mudstone with a few very thin-bedded siltstones or small siltstone lenses (0.5–5 mm) in the lower part; dark gray to gray, thin-bedded muddy siltstones inter-bedded with a few black, thin-bedded carbonaceous mudstones at the middle; gray–dark gray thin-bedded mudstones in the upper part.

Graptolite faunas and preservation

The graptolite samples were taken from 20 to 50 cm thick intervals. A fairly precise graptolite biostratigraphy (Fig. 3) can be established through the samples. The biostratigraphic coverage of the samples shows that the graptolite record is very good in the lower 38 m of the section, whereas it is poor to extremely poor in the upper 20 m. Up to sample CGS76, nearly every collected sample bears graptolite specimens in various amounts, but above this level, only a single sample with graptolites has been secured (sample CGS88).

The invariably flattened graptolites are largely preserved in dark gray to black, often silty shales and siltstones and are generally easily spotted on the rock surface (Fig. 4) due to the contrast of the silvery shining fusellum to the dark background (Fig. 4g–i). In weathered material, the bedding

surfaces are lighter colored and the graptolite fusellum appears darker (Fig. 4c). In these specimens, the fusellum is often broken into small pieces and only small amounts of the fusellum are preserved. The preservation ranges from extremely poor in some of the siltstones and silty shales to fair in finer grained sedimentary rocks. The specimens are randomly oriented on the sediment surface and distinct current orientations are rare. Problems in the species identification are based either on the poor preservation of the material or in the amount of specimens on some slabs, but also on the fragmentation of many specimens (cf. Fig. 4a, b: *Lituigraptus convolutus* fragments). A few layers are so crowded with graptolites that it is not possible to identify individual specimens. The graptolite specimens range in size from single siculae to complete and undistorted biserial and uniserial graptolite specimens more than 10 cm in length, but fragmented material appears to be most common.

The preservation of the graptolites indicates some tectonic distortion and thermal heating of the sedimentary rocks (cf. Hartkopf–Fröder et al. 2015; Maletz and Steiner 2015; Maletz 2020) through the generally silvery color of the graptolite fusellum in less weathered material. Thus, the material (Fig. 4g–i) can be compared with the preservation of more strongly tectonized material from Thuringia, Germany, in which apart from the coalification, stronger tectonic distortion modifies the material (cf. Fig. 4d, e). Clearly, the Thuringian specimens of *Pseudorthograptus radiculatus* (Fig. 4d, e) are strongly elongated, while the specimens from the Tielugou section (Fig. 4g) show more densely spaced thecae. The color indicates graptolite reflectance reaching values of 3.0% or anchizone metamorphism (Hartkopf–Fröder et al. 2015; Maletz 2020). The fusellum is visible as a thin film of organic material, often surrounded by whitish pressure shadow minerals. In some cases, the tectonic strain is visible through parallel fractures in the fusellum of the specimens (e.g., Fig. 4h: *Parapetalolithus dignus*), but is difficult to observe in other specimens (Fig. 4i). This may in case provide considerable distortion of specimens and make taxonomic identification difficult. Slabs are also weathered on the surface to a variable degree, depending to the length of surface exposure of the material in the field. The strata are not horizontal, but are inclined towards the NE. Along the outcrop the inclination of the beds does not change considerably. However, no measurements are taken and further information on the tectonic situation is not available.

Repositories

All illustrated graptolites from the Tielugou section are preserved in the type collection at Nanjing Institute of Geology and Palaeontology, Academia Sinica (NIGPAS), Nanjing, China (NIGP). Additional illustrated material

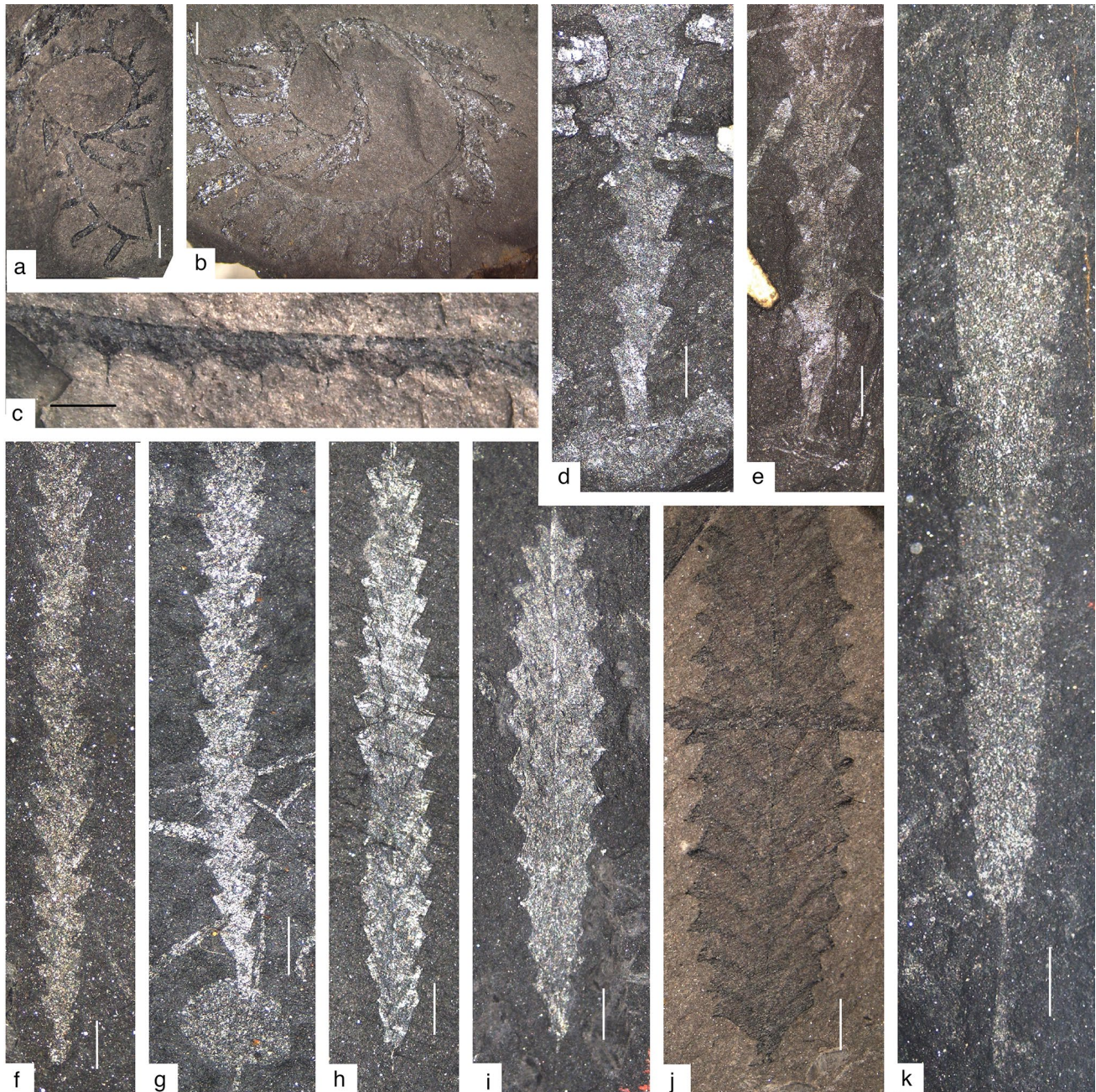


Fig. 4 Graptolite preservation and identification. **a** *Lituigraptus convolutus* (Hisinger, 1837), NIGP 174173, 23.7 m. **b** *Lituigraptus convolutus* (Hisinger, 1837), NIGP 174174, 23.7 m. **c** *Pribylograptus leptotheca* (Lapworth, 1876), NIGP 174175, 25.3 m, note ventral thecal spines. **d** *Pseudorthograptus radiculatus* (Manck, 1918), IRSNB a13462, Haselrain, Vogtland, Thuringia. **e** *Pseudorthograptus radiculatus* (Manck, 1918), BAF 8/28, lectotype (herein), Ölsnitz, Thuringia, Germany, *Demirastrites triangulatus* Biozone, see

ancora development and tectonic lineation. **f** *Glyptograptus perneri* (Štorch, 2018), NIGP 174176, 22.1 m. **g** *Pseudorthograptus radiculatus* (Manck, 1918), NIGP 174177, 21.6 m. **h** *Parapetalolithus dignus* (Koren' and Rickards, 1996), NIGP 174178, 37.7 m, see tectonic lineation. **i** *Parapetalolithus dignus* (Koren' and Rickards, 1996), NIGP 174179, 37.7 m. **j** *Petalolithus clandestinus* (Štorch, 2001), NIGP 1174180, 27.7 m. **k** *Normalograptus rhizinus* (Li and Yang in Yang et al., 1983), NIGP 174181, 2.7 m. Scale bars, 1 mm

belongs to the type collection at Technische Universität Bergakademie Freiberg (BAF) and the Royal Belgian Institute of Natural Sciences, Brussels, Belgium (IRSNB: Manck collection).

The graptolite biostratigraphy

The Hirnantian includes two graptolite biozones, the lower *Metabolograptus extraordinarius* Biozone and the overlying

Metabolograptus persculptus Biozone (Loydell 2012). A differentiation of these intervals is not possible in all regions worldwide, possibly due to incompleteness of the successions and the difficulty to identify the graptolite taxa in poorly preserved material. Graptolites from the Hirnantian have been reported frequently from the Yangtze region (Chen and Lin 1978; Wang et al. 1983; Lin and Chen 1984; Mu and Lin 1984; Fang et al. 1990; Chen et al. 2005, 2006). Numerous species have been described and the taxonomy of some important taxa is in need of revision. Many taxa appear to be based on fragments or special preservational aspects (cf. oblique and scalariform views of normalograptids with branched virgella in the *Normalograptus bifurcus/coremus/radicatus* group, but not only in these; see below).

The *Metabolograptus extraordinarius* Biozone of South China (cf. Chen et al. 2006) with its mixture of DDO and M graptolite faunas (see Melchin and Mitchell 1991; now Diplograptina and Neograptina; Štorch et al. 2011) has not been discovered in the Tielugou section. It appears that the characteristic Kuanyinchiao Limestone with the Hirnantian fauna separating the Upper Ordovician Wufeng Formation and the Llandovery Longmaxi (Lungmachi) Formation (see Wang 1978, 1987; Chen et al. 2005, 2006) in the region is not exposed in this section. Thus, it is unclear, whether the base of the *Metabolograptus persculptus* Biozone is represented in the local succession as older Ordovician graptolites have not been collected from the region (Fan et al. 2011: fig. 4). Unfortunately, the succession cannot be followed further downwards and additional sections in the region are not available. The oldest graptolites are from sample CGS1, yielding a small number of poorly preserved taxa that belong to the *Metabolograptus persculptus* Biozone, but most specimens are indeterminable at the species level.

Ordovician: Hirnantian

Metabolograptus persculptus Biozone (0–1.25 m).

The samples CGS1 – CGS3 are here included in the *Metabolograptus persculptus* Biozone (Fig. 5). The faunas are extremely poor in preservation and the specimens therefore are hard to identify. It is unclear, whether the base of the *Metabolograptus persculptus* Biozone is represented in the section, as older faunas have not been discovered. Possible specimens of *Metabolograptus persculptus* (Fig. 5p) have been recognized, but good proximal ends and specimens showing thecal details are not present. The identification of this species is surprisingly uncertain as can be seen by the comparison of material from various descriptions. Štorch and Loydell (1996) discussed this species in some detail including relief material. Loxton (2017) found the species only in the lower part of his *Metabolograptus persculptus* Biozone and illustrated a single specimen that

shows much more densely spaced proximal thecae and is not comparable with the Štorch and Loydell (1996) material. Thus, his *Metabolograptus persculptus* Biozone does not contain any true specimens of the index species. The material of Rickards and Riva (1981) also has to be questioned. It shows extreme tectonic deformation and is specifically indeterminable.

Normalograptus mirnyensis (Fig. 5o) is common in the interval as is *Korenograptus elegantulus* (Mu and Ni, 1983) (Fig. 5a, c). A single well-preserved specimen identified as *Normalograptus* sp. (Fig. 5b), might be referable to *Avitograptus acanthocystus* (Fang et al., 1990) as described by Muir et al. (2020). A number of robust specimens are here identified as *Neodiplograptus* sp. (Fig. 5r), but as they do not provide any further information than the general shape of the colony, they cannot be identified to species level.

A number of slender normalograptids were identified as *Avitograptus avitus* (Fig. 5g, k) following the description in Melchin et al. (2011). Chen et al. (2006) identified comparable material from the Wangjianwan section as *Normalograptus rhizinus*. Chen et al. (2005) indicate a very short range of *Normalograptus rhizinus* in the top of the *Metabolograptus persculptus* Biozone at Wangjiawan. Better material of these taxa is necessary to support or reject the synonymy of both species and the identity of the genus *Avitograptus* and its various species.

Metabolograptus persculptus Biozone faunas have been described in some detail by Štorch et al. (2011) from north–central Nevada, where they show a considerable mixing of members of the Diplograptina and Neograptina. Chen et al. (2006: fig. 6) indicated the presence of *Anticostia uniformis* and *Paraorthograptus brevispinus* in the *Metabolograptus persculptus* Biozone, but these faunal elements were not illustrated. Previously, Chen et al. (2000) indicated the presence of the Diplograptina only reaching into the *Metabolograptus extraordinarius* Biozone. As no specimens of the Diplograptina were recorded in the *Metabolograptus persculptus* Biozone at Tielugou, a precise correlation of the interval may remain uncertain. However, diplograptine faunal elements were only discovered in some regions in the *Metabolograptus persculptus* Biozone, but not in others (e.g., Štorch et al. 2011).

Silurian: Llandovery (Rhuddanian)

Loydell (2012) differentiated four graptolite biozones in the Rhuddanian of South China, based on data in Chen (1984), Chen et al. (2003) and Fu et al. (2000). The *Akidograptus ascensus* and *Parakidograptus acuminatus* biozones are here combined, as they cannot be differentiated in the Tielugou section. Both species appear only in the higher part of the interval. The graptolite faunas around the base of the

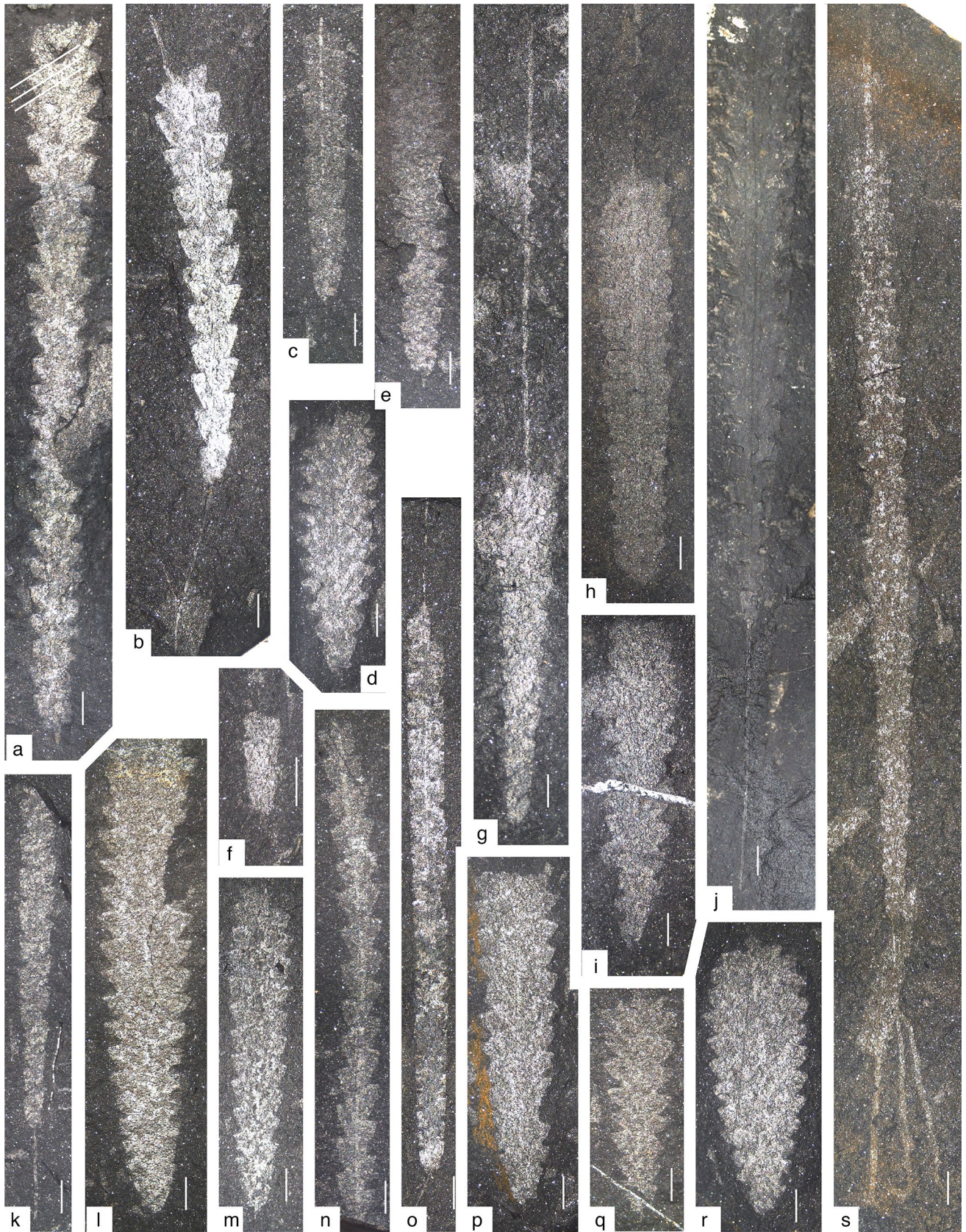


Fig. 5 Graptolites characteristic of the *Metabolograptus persculptus* and *Parakidograptus acuminatus*/*Akidograptus ascensus* biozones. **a** *Korenograptus elegantulus* (Mu and Ni, 1983), NIGP 173491, 0.75 m; white line indicates tectonic deformation. **b** *Normalograptus* sp., NIGP 173492, 2.25 m. **c** *Korenograptus elegantulus* (Mu and Ni, 1983), subscalariform view, NIGP 173,493, 0.35 m. **d** *Neodiplograptus lanceolatus* (Štorch and Serpagli, 1993), NIGP 173494, 1.25 m. **e** ?*Metabolograptus parvulus* (Lapworth, 1900), NIGP 173495, 0.35 m. **f** *Normalograptus anjiensis* (Yang, 1964), see proximal spines, NIGP 173496, 2.7 m. **g** *Avitograptus avitus* (Davies, 1929), NIGP 173497, 1.25 m. **h** *Cystograptus ancestralis* Štorch, 1985, NIGP 173498, 2.7 m. **i** *Neodiplograptus lanceolatus* (Štorch and Serpagli, 1993), NIGP 173499, 1.25 m. **j** *Normalograptus* sp., NIGP 173500, 0.35 m. **k** *Avitograptus avitus* (Davies, 1929), NIGP 173501, 0.35 m. **l** *Neodiplograptus lanceolatus* (Štorch and Serpagli, 1993), NIGP 173502, 1.75 m. **m** *Normalograptus/Metabolograptus* sp., NIGP 173503, 2.25 m. **n** *Normalograptus* sp.?, slender, parallel-sided fragment, NIGP 173504, 1.25 m. **o** *Normalograptus mirnyensis* (Obut and Sobolevskaya in Obut et al. 1967), NIGP 173,505, 3.7 m. **p** ?*Metabolograptus persculptus* (Elles and Wood 1907), NIGP 173506, 1.75 m. **q** *Neodiplograptus lanceolatus* (Štorch and Serpagli, 1993), NIGP 173507, 1.25 m. **r** *Neodiplograptus* sp., NIGP 173508, 1.25 m. **s** *Normalograptus minor* (Huang, 1982), NIGP 173509, 2.7 m. Scale bars, 1 mm

Rhuddanian have been thoroughly investigated in the last decades and a revision of the original GSSP definition was proposed differentiating an *Akidograptus ascensus* Biozone overlain by a *Parakidograptus acuminatus* Biozone in the Dobb's Linn section (Rong et al. 2008). The GSSP is defined with the FAD of *Akidograptus ascensus* in the stratotype section. While the *Cystograptus vesiculosus* Biozone is easily recognizable, it is preferred to identify the overlying interval as the *Coronograptus leei* Biozone and not the *Coronograptus cyphus* Biozone, as the latter species is not present.

Akidograptus ascensus/*Parakidograptus acuminatus* Biozone (1.75–6.7 m).

The base of the Silurian is difficult to determine due to the lack of important index taxa. It is here identified at the FAD of *Normalograptus anjiensis* (Fig. 5f), but *Akidograptus ascensus* and *Parakidograptus acuminatus* first appear much higher in the succession. The local FAD of *Parakidograptus acuminatus* is in CGS 11, while *Akidograptus ascensus* appears slightly lower, in CGS 09. These first appearances of the index species may be based on the poor preservation and difficulty to identify most biserial graptolites of the interval. It may also be based on insufficient material available for the investigation and the possibility remains that there is a gap at the base of the biozone.

Loxton (2017) noted that *Normalograptus anjiensis* first appears in the *Akidograptus ascensus* Biozone in China and in Yukon, Canada. The species was initially described from the *Akidograptus ascensus*/*Glyptograptus bifurcus* Biozone of South China, but later found also in the Kurama range of Uzbekistan (Koren' and Melchin 2000). It is similar to

Normalograptus trifilis (Manck, 1923) as described by Štorch and Serpagli (1993) and Štorch and Feist (2008) and was identified as *Normalograptus lubricus* in the past (Loxton 2017). The *Akidograptus ascensus*/*Parakidograptus acuminatus* Biozone interval contains a number of biserial taxa, but includes also the earliest monograptids, here referred to *Atavograptus* sp. (Fig. 6h). The material is extremely poor and thecal details are not available. The index taxa of the interval, *Akidograptus ascensus* (Fig. 6i, l) and *Parakidograptus acuminatus* (Fig. 6j) are uncommon in the interval, but a number of easily recognizable species also appear. Poor specimens of *Normalograptus trifilis* (Fig. 6k) are present in sample CGS9 (4.25 m). *Paramplexograptus kilianii* (Fig. 6b, d) is a frequent member of the fauna, ranging through the higher part of the interval. Loxton (2017) reported the species only from the *Akidograptus ascensus* Biozone in Canada. *Songxigraptus elongatus* (Fig. 6f) is restricted to a single level, in which it is a common member of the fauna. The known material of *Songxigraptus elongatus* is very poor and details of the development are unknown. Maletz (2019) synonymized the genus with *Talacastograptus* Cuerda et al., 1988, but the latter may be considerably younger as the associated fauna indicates (cf. Melchin 2007). Loxton (2017) referred the species to the *Akidograptus ascensus* Biozone and did not report it from higher intervals. *Neodiplograptus lanceolatus* (Štorch and Serpagli, 1993) (Fig. 5d, i, l, q) is common in the *Akidograptus ascensus*/*Parakidograptus acuminatus* Biozone. The species may be identical to *Neodiplograptus shangchongensis* (Li, 1984).

Slightly higher is the first appearance of the spinose *Hirutograptus sinitzini* (Fig. 6g), associated with the robust *Cystograptus ancestralis*. Several species of *Normalograptus* are present in the interval, but often show only the scalariform view, making a specific identification difficult. Poor specimens of *Neodiplograptus* sp. and *Rickardsograptus lautus* (Fig. 6c) are also present in the upper part of the interval. A number of specimens have been identified as *Korenograptus lungmaensis* (Sun, 1933) (Fig. 6a), but may be more closely related to *Korenograptus lacinosus*, based on their characteristic thecal style.

The presence of *Cystograptus ancestralis* (Fig. 5h) in sample CGS6 could indicate the *Akidograptus ascensus* Biozone as the species is considered to have its FAD in this interval (Štorch 1986). Another taxon is *Normalograptus minor* (Fig. 5s) with its characteristic development of the distally branching virgella. The species belongs to the *Normalograptus bifurcus/coremus/radicatus* group of normalograptids characterized by the distal branching of the virgella into a variable number of 'spines'. *Normalograptus minor* is common in the *Metabolograptus persculptus* Biozone in other sections, but ranges into the *Akidograptus ascensus*/*Parakidograptus acuminatus* Biozone in Sardinia (Štorch and Serpagli 1993). Štorch and Schönlaub (2012)

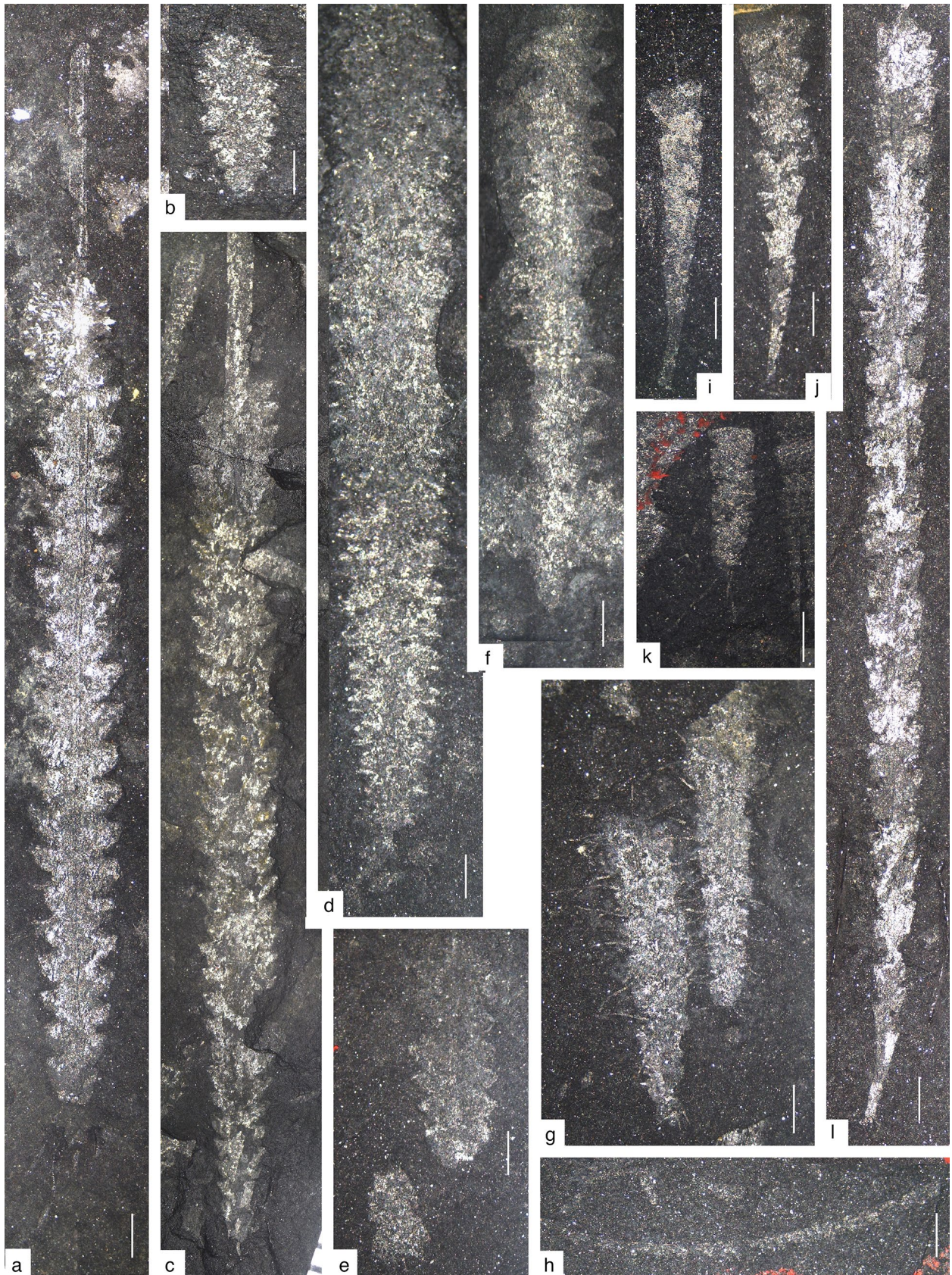


Fig. 6 Graptolites characteristic of the *Parakidograptus acuminatus*/*Akidograptus ascensus* Biozone. **a** *Korenograptus lungmaensis* (Sun, 1933), NIGP 173510, 5.7 m. **b** *Paramplexograptus kiliani* (Legrand, 1976), NIGP 173511, 6.7 m. **c** *Rickardsograptus lautus* (Štorch and Feist, 2008), NIGP 173512, 6.3 m. **d** *Paramplexograptus kiliani* (Legrand, 1976), NIGP 173513, 4.25 m. **e** *Neodiplograptus* sp., NIGP 173514, 5.7 m. **f** *Songxigraptus elongatus* Fang et al., 1990, NIGP 173515, 4.75 m. **g** *Hirsutograptus sinitzini* Koren' and Melchin, 2000, NIGP 173516, 5.7 m. **h** *Atavograptus* sp. NIGP 173517, 4.75 m. **i** *Akidograptus ascensus* (Davies, 1929), NIGP 173518, 4.75 m. **j** *Parakidograptus acuminatus* (Nicholson, 1867), NIGP 173519, 5.7 m. **k** *Normalograptus trifilis* (Manck, 1923), NIGP 173520, poor specimen showing three long spines, 4.25 m. **l** *Akidograptus ascensus* (Davies, 1929), NIGP 173521, long specimen, 5.7 m. Scale bar is 1 mm

discussed basal Silurian species with branching virgella and included *Glyptograptus bifurcus* Ye, 1978 with reservation in *Rickardsograptus*. The thecal style is, unfortunately, unknown for most taxa of the *Normalograptus bifurcus/coremus/radicatus* group. These species appear to be common in the *Akidograptus ascensus*/*Parakidograptus acuminatus* Biozone in China. Chen et al. (2005) considered *Climacograptus radicans* Chen and Lin, 1978 and *Diplograptus coremus* Chen and Lin, 1978 as preservational aspects of a single species, identified as *Normalograptus coremus*, but considered *Normalograptus minor* (Huang, 1982) to be a separate species. Štorch et al. (2019) referred *Normalograptus bifurcus* and related taxa to the genus *Korenograptus*, based on the non-geniculate thecae of the illustrated specimens in lateral view and synonymized several taxa with *Korenograptus bifurcus*.

Chen et al. (2005) discussed and revised a number of Hirnantian taxa from the Upper Yangtze region of South China based on their new collections from the Wangjiawan section. The authors synonymized a number of species that had previously been considered endemic of China with other taxa. Their material of *Korenograptus lacinosus* (Churkin and Carter, 1970) appears to be identical to material described as *Normalograptus elegantulus* (Mu and Ni, 1983) by Storch et al. (2011), who separated *Korenograptus lacinosus* from the very similar *Normalograptus elegantulus* through a shorter sicula and a more narrow proximal end. Loxton (2017) discussed the identity of *Korenograptus lacinosus* and the differentiation from other, closely related taxa.

The base of the *Akidograptus ascensus* Biozone at the base of the Silurian System has been described in great detail from South China. The faunas are especially well documented from the GSSP of the Hirnantian at Wangjiawan, where the *Akidograptus ascensus* Biozone is just about 10 cm thick, while the following *Parakidograptus acuminatus* Biozone measures more than 1 m in thickness (e.g., Chen et al. 2005, 2006). Based on Wang et al. (1983) and Wang (1987), the *Parakidograptus acuminatus* Zone is 40 cm thick in the Wangjiawan section. *Akidograptus*

ascensus only appears in the lower 17 cm of the zone, and *Parakidograptus acuminatus* in the upper 23 cm. In the Tielugou section, the combined *Akidograptus ascensus* and *Parakidograptus acuminatus* biozone interval measures about 5 m in thickness.

The *Akidograptus ascensus*/*Parakidograptus acuminatus* Biozone interval is well known from numerous sections around the world and will not be discussed here in detail. Štorch (1996) discussed the distribution in peri-Gondwanan Europe and Masiak et al. (2003) added details of the interval from the Holy Cross Mountains of Poland. Štorch and Feist (2008) added new taxa in their descriptions of material from the Montagne Noire of France. Štorch et al. (2019) recorded a number of species from Spain that were earlier known only from China. Loxton (2017) revised and provided detailed taxonomic descriptions of many taxa from the Blackstone River, Yukon, Canada.

Cystograptus vesiculosus Biozone (7.3–9.8 m).

The first appearance of *Cystograptus vesiculosus* (Fig. 7j) defines the base of the interval. The top can be seen in sample CGS20. The *Cystograptus vesiculosus* Biozone is a widely distributed and easily recognizable interval due to the characteristic index species with its robust tubarium and the extensive nematularium often found in this species (Fig. 7j). The interval is about 2.5 m thick in the section and includes silty black shales with randomly distributed, often large graptolite specimens. Numerous slender monograptid fragments are typical of the interval in the Tielugou section, but proximal ends have not been collected.

Cystograptus vesiculosus appears to have a fairly long biostratigraphic range, originating at the base of the *Cystograptus vesiculosus* Biozone and ranging into the *Monograptus revolutus* Biozone (Zalasiewicz et al. 2009). In the Tielugou section, slender specimens from the higher part of the *Coronograptus leei* Biozone have been identified as *Cystograptus penna* (Fig. 7c). The differentiation of both species is difficult, as it is mainly based on the dorso-ventral width of the colonies and the everted thecal apertures in *Cystograptus penna* (Hopkinson, 1869), which may be the result of the preservation as internal casts in relief (see Jones and Rickards 1967). Hutt (1974b: 46) considered both taxa to be extreme variants of a single species.

At the base of the interval, the monograptids *Atavograptus atavus* and *Huttagraptus solidus* have been found, but other slender, unidentifiable monograptids are also present. A specimen of *Coronograptus* cf. *cyphus* with its characteristic curvature and simple distal thecae was found at 8.8 m (Fig. 7k). Specimens of *Normalograptus* are not uncommon and may belong to *Normalograptus rectangularis*. More slender taxa are also present, but are impossible to identify due to the poor preservation. *Bulmanograptus swanstoni* (Fig. 7a) is the first truly uni-biserial dimorphograptid

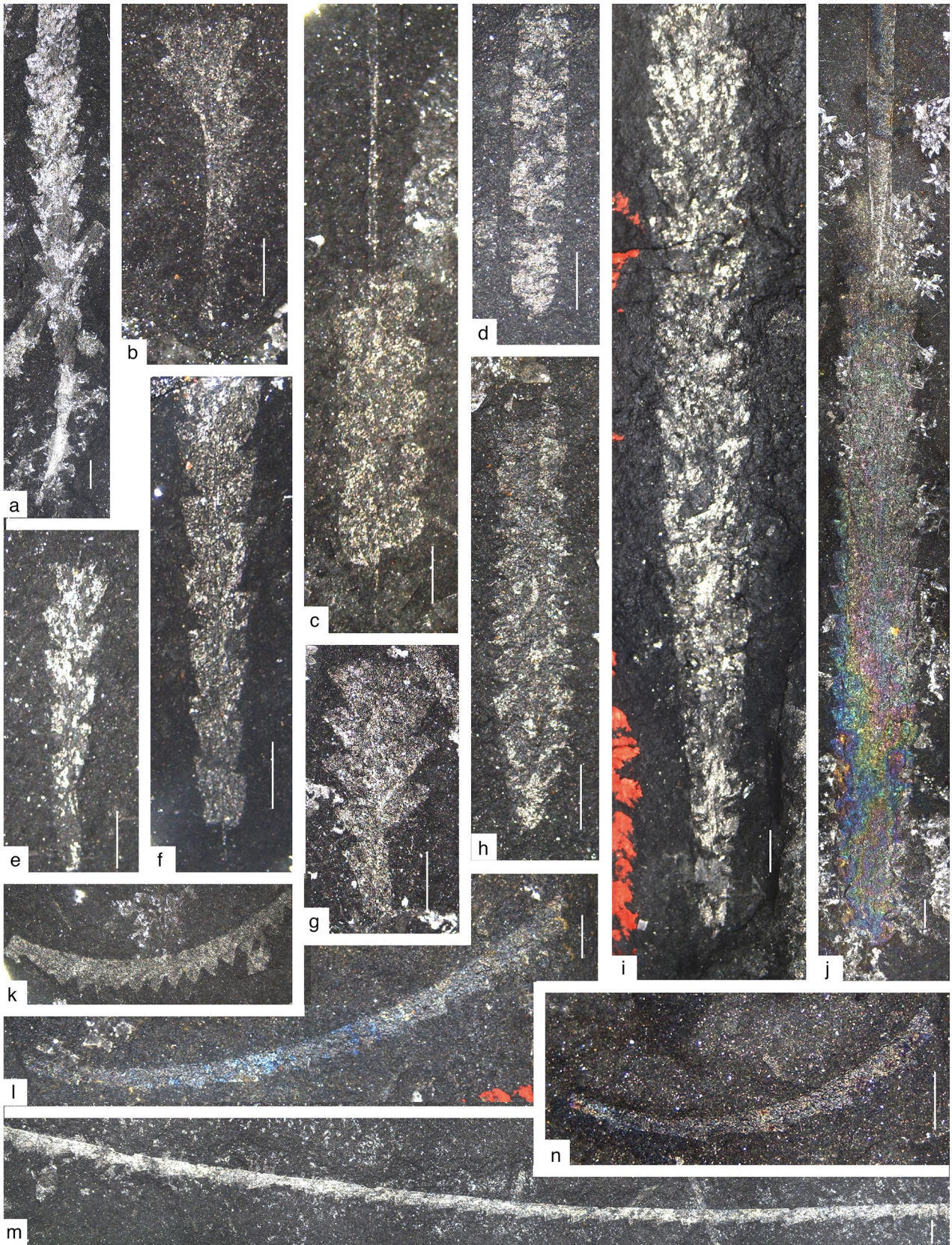


Fig. 7 Graptolites characteristic of the *Cystograptus vesiculosus* Biozone. **a** *Bulmanograptus swanstoni* (Lapworth, 1876), NIGP 173522, 7.3 m. **b** ?*Bulmanograptus erectus* (Elles and Wood, 1908), NIGP 173523, 9.8 m. **c** *Cystograptus penna* (Hopkinson, 1869), NIGP 173524, 8.8 m. **d** *Metaclimacograptus* sp., NIGP 173525, 7.8 m. **e** *Rhaphidograptus minutus* (Chen and Lin 1978), NIGP 173526, 10.4 m. **f** *Sudburigraptus* sp. or *Korenograptus* sp., NIGP 173527, 10.4 m. **g** *Dimorphograptoides physophora* (Nicholson, 1868), NIGP 173528, 9.8 m. **h** *Paraclimacograptus innotatus* (Nicholson, 1869), NIGP 173529, 9.8 m. **i** *Rickardsograptus lautus* (Štorch and Feist, 2008), NIGP 173530, 10.4 m. **j** *Cystograptus vesiculosus* (Nicholson, 1868), NIGP 173531, 9.8 m. **k** *Coronograptus* cf. *cyphus* (Lapworth, 1876), NIGP 173532, 8.8 m. **l** *Huttagraptus solidus* (Štorch and Feist, 2008), NIGP 173533, 8.8 m. **m** *Atavograptus atavus* (Jones, 1909), NIGP 173534, 7.8 m. **n** *Huttagraptus solidus* (Štorch and Feist, 2008), NIGP 173535, 9.8 m. Scale bar is 1 mm

in the succession, showing a long uniserial proximal end. Younger species of *Bulmanograptus* show a shorter uniserial part of the colony as is exemplified by *Bulmanograptus erectus* (Fig. 7b) and *Dimorphograptoides physophora* (Fig. 7g). *Bulmanograptus erectus* only appears in the uppermost sample of the interval, associated with *Paraclimacograptus innotatus* (Fig. 7h) and early specimens of *Dimorphograptoides physophora* (Fig. 7g). While *Paraclimacograptus innotatus* has been discovered only at a single level, the other two taxa range into the overlying *Coronograptus leei* Biozone.

A number of robust specimens of *Rickardsograptus lautus* (Fig. 7i) have been identified in the interval. The species has been described from the *Cystograptus vesiculosus* Biozone of the Montagne Noire, but Štorch and Feist (2008: 948) indicated that the species is also present in the *ascensus-acuminatus* Biozone, as it is in the Tielugou section.

The *Cystograptus vesiculosus* Biozone can be correlated with the *Atavograptus atavus* and *Huttagraptus acinaces* biozones of Britain (Zalasiewicz et al. 2009; Loydell 2012). Štorch and Feist (2008) described the fauna of the *Cystograptus vesiculosus* Biozone from the Montagne Noire in some detail and provided information on the biostratigraphic ranges of a number of faunal elements. Štorch et al. (2018) discussed the upper part of the *Cystograptus vesiculosus* Biozone from the Czech Republic, underlain by an unconformity in the proposed GSSP section at Hlásná Třebaň. Even though enough faunas of the *Cystograptus vesiculosus* Biozone interval have been described worldwide (Schauer 1971; Chen and Lin 1978; Ni 1978; Wang 1987; Loydell 2007; Loydell et al. 2017), precise biostratigraphic ranges are rarely given. Koren' and Bjerreskov (1997, 1999) provided information on the monograptid radiation in the *Cystograptus vesiculosus* Biozone using Bornholm, Denmark and the southern Urals, Russia as example. Melchin (1989) and Lukasik and Melchin (1997) provided additional information. They recognized both the *Atavograptus atavus* and *Lagarograptus acinaces* biozones. Thus, the *Lagarograptus acinaces* Biozone of Lukasik and Melchin (1997) is the

equivalent of the upper part of the *Cystograptus vesiculosus* Biozone. Legrand (2003) referred the interval of the North African part of Gondwana to the *Neodiplograptus africanus* Biozone, but *Neodiplograptus africanus* appears much earlier in Jordan (Loydell 2007), indicating that there is a considerable biogeographic differentiation.

Coronograptus leei Biozone (10.4–21.4 m).

The base of the *Coronograptus leei* Biozone is found in sample CGS21 with the first occurrence of *Coronograptus leei*. As *Demirastrites triangulatus* appears in sample CGS44 (21.6 m), the top of the *Coronograptus leei* Biozone can be seen in CGS43 (21.4 m). The interval is identified as the *Coronograptus leei* Biozone following Hsü (1934) and Ni (1978). *Coronograptus leei* is characterized by its thecal style and differs considerably from the better-known *Coronograptus cyphus*. *Coronograptus leei* (Hsü, 1934) is widely distributed in China (see Hsü 1934; Ni 1978; Fu 1986; Fu and Song 1986; Mu et al. 2002), but has not been identified in other regions. Wang (1987) identified the interval as the *Huttagraptus acinaces* Biozone in the Yangtze region. Chen and Lin (1978) and Chen (1984) used the *Pristiograptus cyphus*–*Monoclimacis lunata* Biozone for the interval, as defined in Guizhou, overlain by the *Pristiograptus gregarius* Biozone. Maletz et al. (2019) indicated a gap in this interval in the YD–1 drill core on the eastern side of the Huangling massif.

Coronograptus leei (Fig. 8l) is especially common in the lower part of the interval, but a number of further species of *Coronograptus* occur in the zone. *Coronograptus hipposideros* (Fig. 8n), *Coronograptus cirrus* (Fig. 8m) and *Coronograptus gregarius* have been identified. Species of *Perneroagraptus* and *Pribylograptus* are present, but the material is largely not identifiable to species level. A few poor specimens are referred to *Huttagraptus acinaces*. Apart from a number of taxa surviving from the *Cystograptus vesiculosus* Biozone (Fig. 3), a number of additional taxa appear. *Rhaphidograptus minutus* (Fig. 8k) is present at the base of the zone, as is *Sudburigraptus* sp., *Agetograptus hubeiensis* (Fig. 8f) and *Bulmanograptus compactus* (Fig. 8d) appear slightly higher in the succession. *Rickardsograptus lautus* (Fig. 8b) can be found through the whole interval. The robust *Pseudorthograptus obuti* (Fig. 8o) is found in a number of fairly well-preserved specimens. The specimens show the distinct ancora hub of the retiolitids, but the typical more complex ancora development described by Štorch (2015) is not present in any of the specimens. A single long specimen also bears a long and slender nematularium and a distally narrowing tubarium. Štorch (2015: 862) indicated a possible origin of the petalolithids from *Pseudorthograptus obuti*, as the very similar *Petalolithus minor* (Fig. 9e) from the *Demirastrites triangulatus* Biozone appears to be one of the earliest species of this genus and is quite similar in

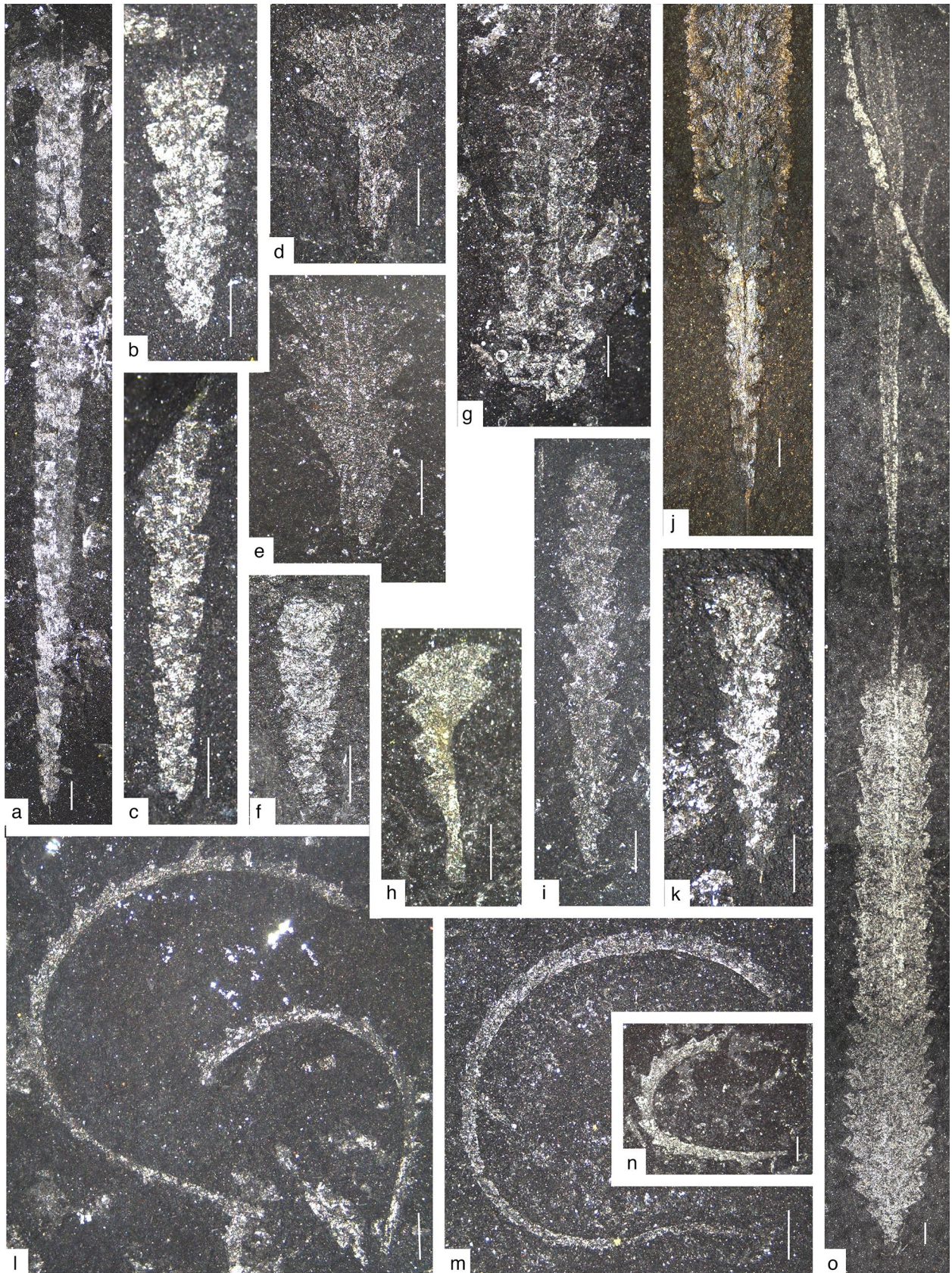


Fig. 8 Graptolites characteristic of the *Coronograptus leei* Biozone. **a** *Rickardsograptus elongatus* (Churkin and Carter, 1970), NIGP 173536, long specimen, 10.8 m. **b** *Rickardsograptus lautus* (Štorch and Feist, 2008), NIGP 173537, proximal end, 10.8 m. **c** *Rickardsograptus elongatus* (Churkin and Carter, 1970), NIGP 173538, proximal end, 10.8 m. **d** *Bulmanograptus compactus* (Štorch and Feist, 2008), NIGP 173539, short uniserial part, 10.8 m. **e** *Dimorphograptoides physophora* (Nicholson, 1868), NIGP 173540, 13.7 m. **f** *Agetograptus hubeiensis* (Ni, 1978) (see Russel–Houston 2001, pl. 1), NIGP 173541, small specimen, 10.8 m. **g** *Cystograptus vesiculosus* (Nicholson, 1868), NIGP 173542, 10.8 m. **h** *Bulmanograptus swanstoni* (Lapworth, 1876), NIGP 173543, note short uniserial part, 12.8 m. **i** *Pseudorthograptus radiculatus* (Manck, 1918), NIGP 173544, 13.1 m. **j** *Rickardsograptus thuringiacus* (Kirste, 1919)?, NIGP 173545, 19.7 m, distally covered by secondary mineral growth. **k** *Rhaphidograptus minutus* Chen and Lin, 1978, NIGP 173546, 11.3 m. **l** *Coronograptus leei* (Hsü, 1934), NIGP 173547, two specimens, 11.3 m. **m** *Coronograptus cirrus* Hutt, 1975, NIGP 173548, 13.7 m. **n** *Coronograptus hipposideros* (Toghill, 1968), NIGP 173549, 12.8 m. **o** *Pseudorthograptus obuti* (Rickards and Koren, 1974), NIGP 173550, long specimen with nematularium, 20.8 m. Scale bar is 1 mm

shape. *Petalolithus ovatoelongatus* (Kurck, 1882) has a less protracted proximal end and more horizontal thecal apertures proximally, but was not found during this investigation. *Dimorphograptoides physophora* (Fig. 8e) extends from the *Cystograptus vesiculosus* Biozone into the lower part of the *Coronograptus leei* Biozone. It can be recognized through the short uniserial proximal end including a single theca. Elles and Wood (1908); Schauer (1971) and Koren' and Rickards (1996) described material of this species with a distinct ancora development from the *Cystograptus vesiculosus* to the *Coronograptus gregarius* Biozone of western Europe and the southern Urals. Štorch and Feist (2008) described the lowermost Silurian graptolite faunas from the Montagne Noire, France and referred *Dimorphograptus swanstoni* and *Dimorphograptoides physophora* to the higher part of the *Cystograptus vesiculosus* Biozone.

The genus *Coronograptus* ranges from the *Coronograptus cyphus* Biozone to the *Lituigraptus convolutus* Biozone and a number of species have been differentiated (see Lukasik and Melchin 1997; Sennikov 1998; Štorch 2015). Lukasik and Melchin (1997) showed *Coronograptus cyphus* to be restricted to the zone bearing its name, but did not report any specimens from their samples. Štorch (1988, Table 1) listed it from the *Coronograptus cyphus* Biozone. Lenz (1982) did not find *Coronograptus cyphus* in the Northern Canadian Cordillera. Thus, it seems that *Coronograptus cyphus* is rare in North America and may not be very useful as an index species in most regions. However, Melchin (1989) illustrated two fragments under this name from the Cape Phillips Formation of the Canadian Arctic Islands.

Zalasiewicz and Tunnicliff (1994: 697) revised the *Coronograptus cyphus* Biozone of Britain and indicated that the index species ranges downwards into the *Huttagraptus acinaces* Biozone. The authors regarded the incoming of monograptids of the *revolutus/austerus* group as indicative of the base of the *Coronograptus cyphus* Biozone (see also Zalasiewicz et al. 2009).

Silurian: Llandovery (Aeronian)

The base of the Aeronian is defined at the base of the *Demirastrites triangulatus* Biozone (e.g., Štorch 1994; Melchin et al. 2012; Štorch et al. 2018), while the top is defined by the base of the Telychian at the FAD of *Spirograptus guerichi*. However, the Rhuddanian/Aeronian boundary is under discussion due to problems with the original GSSP section (Cocks et al. 1984; Melchin et al. 2012; Štorch et al. 2018). Melchin et al. (2018) provided a report to assess the Rheidol Gorge section as a replacement for this GSSP section, as it includes a good succession of graptolite faunas from the middle *Pernerograptus revolutus* or *Coronograptus cyphus* Biozone to the middle *Demirastrites triangulatus* Biozone. Štorch et al. (2018) proposed a section in the Czech Republic as a replacement of the original GSSP section. Štorch and Melchin (2019) supported the data with a documentation of the precise succession of the *Demirastrites* species in this section and provided an understanding of the evolution of the group.

A number of local biostratigraphic schemes have been established to subdivide the Aeronian time interval into graptolite biozones (Loydell 2012). While the Avalonia/Baltica succession is subdivided into six biozones, the South China succession appears to be fairly incomplete. Loydell (2012: fig. 4) identified the lower part as an extensive *Coronograptus gregarius* Biozone interval, followed by the *Lituigraptus convolutus* Biozone, but he indicated that the upper part of the Aeronian has not been verified by described faunas.

Demirastrites triangulatus Biozone (21.6–23.2 m).

The *Demirastrites triangulatus* Biozone was recognized from ca. 21.60–23.20 m in the succession (samples CGS44 to CGS47). The fauna is moderately diverse, but poorly preserved graptolite specimens dominate bedding–plane assemblages and many specimens, especially the slender monograptids (cf. *Pribylograptus*, *Pernerograptus*) are impossible to determine to species level. A gap at the base of the *Demirastrites triangulatus* Biozone may be

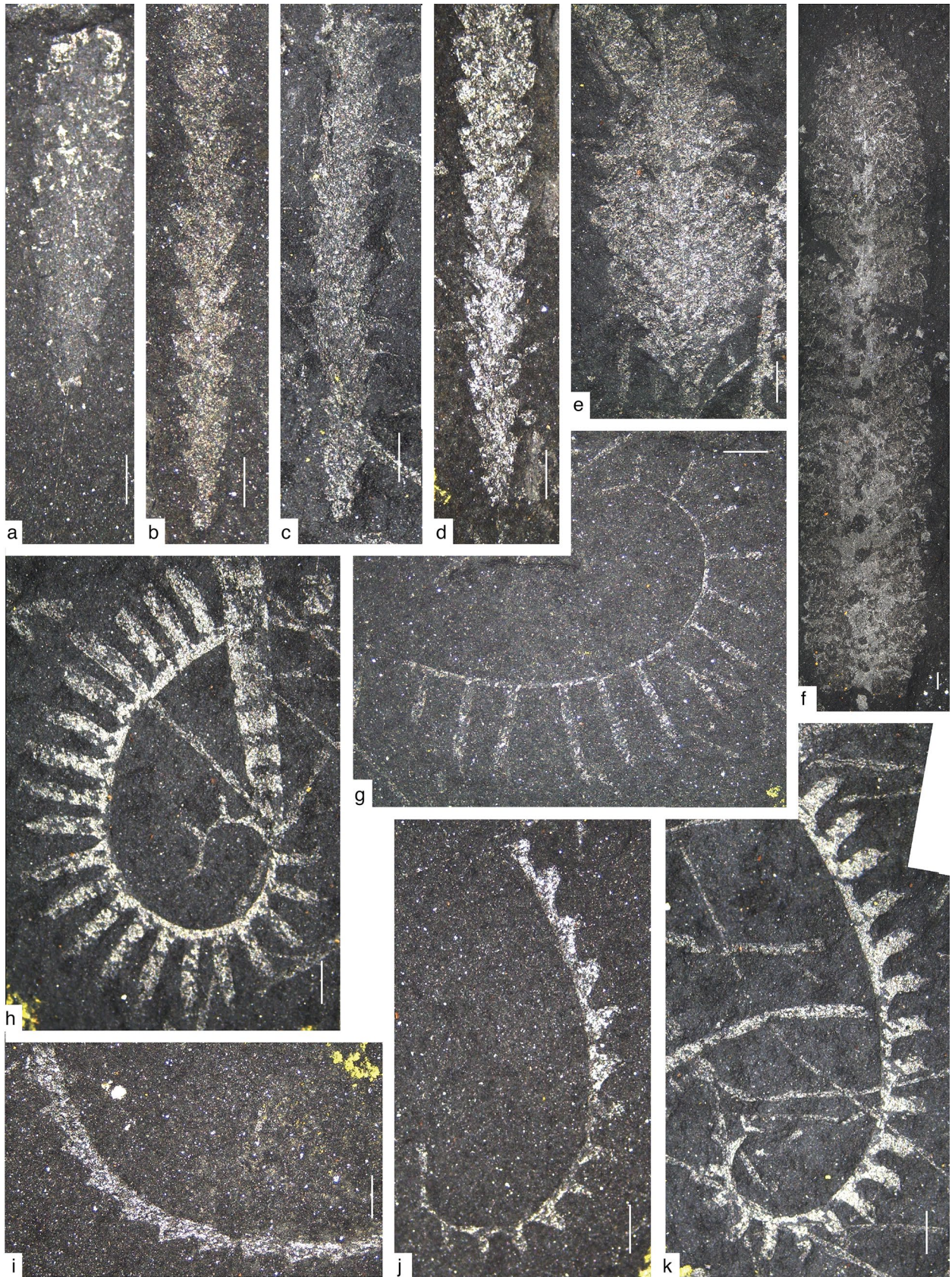


Fig. 9 Graptolites characteristic of the *Demirastrites triangulatus* Biozone. **a** *Rivagraptus* sp., NIGP 173551, note long virgella, 44.8 m. **b** *Glyptograptus perneri* (Štorch, 2015), NIGP 173552, 21.6 m. **c** *Pseudorthograptus insectiformis* (Nicholson, 1868), NIGP 173553, poor specimen, 21.6 m. **d** *Agetograptus longicaudatus* (Chen and Lin, 1978), NIGP 173554, 21.8 m. **e** *Petalolithus minor* (Elles, 1897), NIGP 173555, 21.6 m. **f** *Pseudoretiolites* sp., NIGP 173556, robust, but incomplete specimen showing thecal floor preservation, 21.6 m. **g** *Rastrites longispinus* (Perner, 1897), NIGP 173557, 21.6 m. **h** *Rastrites guizhouensis* (Mu et al., 1974), NIGP 173558, 21.6 m. **i** *Coronograptus gregarius* (Lapworth, 1876), NIGP 173559, fragment, 21.8 m. **j** *Demirastrites campograptoides* Štorch and Melchin, 2019, NIGP 173560, note thecal style, 21.8 m. **k** *Demirastrites triangulatus* (Harkness, 1851), early form of Štorch and Melchin (2019), NIGP 173561, 21.6 m. Scale bar is 1 mm

indicated by the sudden appearance of quite a number of new taxa. The upper part of the biozone does not bear the typical members of the interval, but cannot be included in any other biozone due to the lack of biostratigraphic index species.

The specimens here assigned to *Demirastrites triangulatus* (Fig. 9k) most closely match the material identified as *Demirastrites triangulatus* early form by Štorch and Melchin (2019). They are associated with common *Rastrites guizhouensis* (Fig. 9h). Other monograptids in the interval include *Rastrites longispinus* with its very slender metathecae (Fig. 9g), as well as fragments of *Pernerograptus* and slender specimens, probably belonging to *Pristiograptus*. *Demirastrites campograptoides* (Fig. 9j) has recently been described from the *Demirastrites triangulatus* Biozone of the Czech Republic (Štorch and Melchin 2019) and nothing is known on its further biostratigraphic and palaeobiogeographic distribution. Thus, the record in the Tielugou section adds important new information.

Specimens of *Coronograptus gregarius* (Fig. 9i) are not uncommon through the interval. A number of biserial species are present, including *Petalolithus minor* (Fig. 9e), *Pseudorthograptus insectiformis* (Fig. 9c), *Rivagraptus* sp. (Fig. 9a) and, in the higher part of the interval, *Agetograptus longicaudatus* (Fig. 9d) and *Agetograptus primus* (Fig. 10d). *Pseudorthograptus radiculatus* (Manck, 1918) (= *Pseudorthograptus finneyi* Štorch and Kraft, 2009) is common in the lower part of the interval (Fig. 4g). The earliest specimen of this species is present in the underlying *Coronograptus leei* Biozone at 23.1 m (CGS27) (Fig. 8i). Manck (1918) described the species from a number of well-preserved, flattened specimens found in the *Demirastrites triangulatus* Biozone of Thuringia, but the name has not been used since its original description.

Štorch and Melchin (2019) recently discussed the biostratigraphic importance of *Demirastrites triangulatus* as index of the zone of its name. The authors documented in great detail the faunas from a single section in the Czech Republic and suggested evolutionary relationships or lineages of the various species recognized. It is uncertain, however, how precisely the succession can be matched in other areas. Little is known on the intraspecific variation of the species and their biostratigraphical changes, even though early and late forms of certain species have been illustrated from the Hlásná Třebaň section in the Prague Synform of the Czech Republic.

The *Demirastrites triangulatus* Biozone has been previously discussed for South China (Wang 1978, 1987; Chen and Lin 1978; Li 1995), but illustrated specimens of *Demirastrites triangulatus* appear to be misidentified according to Štorch and Melchin (2019), who considered the presence of this taxon in China as unproven. The here illustrated specimens can be compared with the early form of *Demirastrites triangulatus*. As the species of the genera *Demirastrites*, *Rastrites* and *Petalolithus* appear all at the same level, there might be the chance of a condensation or a gap at the base of the *Demirastrites triangulatus* Biozone. In other regions like the Czech Republic and in Wales, species of *Rastrites* and *Petalolithus* appear after the FAD of *Demirastrites triangulatus* (Zalasiewicz et al. 2009; Štorch et al. 2018). Thus, the presence of *Demirastrites triangulatus* in the Tielugou section may be regarded as a late appearance.

A number of new taxa also appear within the uppermost part of the *Demirastrites triangulatus* Biozone, in which the index species is lacking. A single specimen of *Petalolithus ovatoelongatus* (Fig. 10b) is present, as are poor specimens of *Pseudoretiolites* sp. (Fig. 10a) showing the typical floored thecae. *Rickardsograptus tcherskyi* shows the characteristic change of its thecal style (Fig. 10e) and slender, spined specimens of *Pseudorthograptus insectiformis* (Fig. 10c) were identified. *Rastrites orbitus* (Fig. 10l) has been discovered in a few fragmentary specimens and the slender, coiled *Monograptus changyangensis* (Fig. 10g) is common. As an interesting faunal element, *Hubeigraptus semilunatus* (Fig. 10j) appears in the top of the interval. Maletz et al. (2019) found the species to be common in the *Lituigraptus convolutus* Biozone of the YD-1 drill core.

Wang (1978, 1987) described the *magnus-thuringiacus* and *argenteus* biozones above the *Demirastrites triangulatus* Biozone for the E. Yangtze Gorges region of China, but Maletz et al. (2019) indicated that most of the interval is not recognized in the region. Maletz et al. (2019) discussed

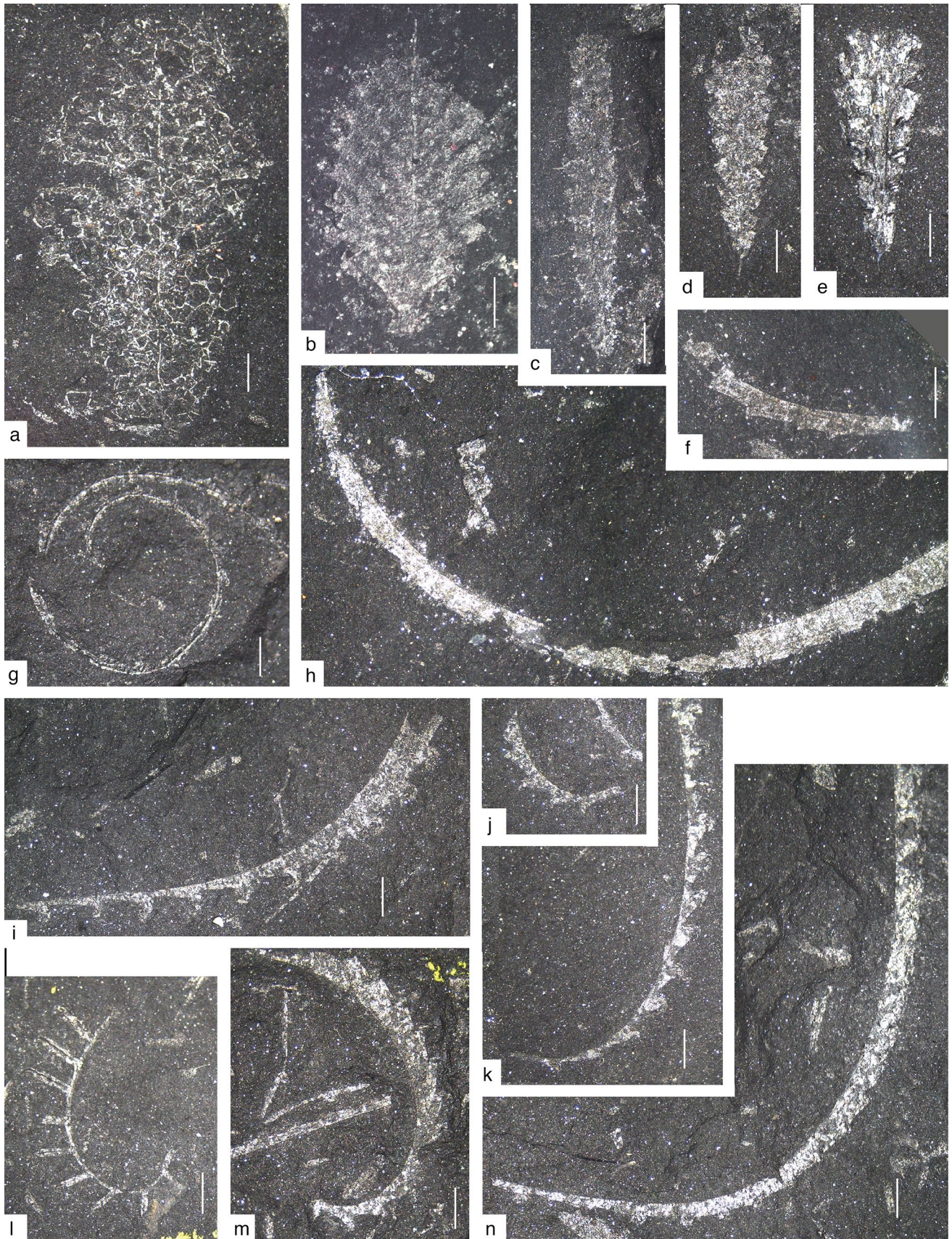


Fig. 10 Graptolites characteristic of the *Demirastrites triangulatus* Biozone. **a** *Pseudoretiolites* sp., NIGP 173562, 22.9 m. **b** *Petalolithus ovatoelongatus* (Kurck, 1882), NIGP 173563, 22.9 m. **c** *Pseudorthograptus insectiformis* (Nicholson, 1868), NIGP 173564, 22.9 m. **d** *Agetograptus primus* Obut and Sobolevskaya in Obut et al., 1968, NIGP 173565, 23.2 m. **e** *?Rickardsograptus tcherskyi* (Obut and Sobolevskaya in Obut et al., 1967), NIGP 173566, 23.2 m. **f** *Coronograptus gregarius* (Lapworth, 1876), NIGP 173567, 22.9 m. **g** *Monograptus changyangensis* Sun, 1933, NIGP 173568, 23.2 m. **h** *?Pribylograptus* sp. NIGP 173569, 22.9 m. **i** *Pernerograptus arciformis* (Chen and Lin, 1978), NIGP 173570, 23.2 m. **j** *Hubeigraptus semilunatus* Li, 1995, NIGP 173571, 23.2 m. **k** *Campograptus* sp., NIGP 173572, 23.2 m. **l** *Rastrites orbitus* Churkin and Carter, 1970, NIGP 173573, 23.2 m. **m** *Hubeigraptus semilunatus* Li, 1995, NIGP 173574, 23.2 m. **n** *Pernerograptus sudburiae* (Hutt, 1974a), NIGP 173575, 23.2 m. Scale bar is 1 mm

the presence of a *Pribylograptus leptotheca* Biozone in the YD-1 drillcore, but this species is present at Tielugou only in the *Lituigraptus convolutus* Biozone. Therefore, a strong condensation or a biostratigraphical gap at the top of the *Demirastrites triangulatus* Biozone may have to be postulated for the section. Loydell (2012) referred the early Aeronian of South China to an extensive *Coronograptus gregarius* Biozone followed by the *Lituigraptus convolutus* Biozone. He correlated the *Coronograptus gregarius* Biozone of the region with the *Demirastrites triangulatus* to *Pribylograptus leptotheca* biozones of Avalonia and Baltica. A similar situation appears to be present in Arctic Canada. Loydell (2012) used the *Campograptus curtus* Biozone for the interval of the *Coronograptus gregarius* Biozone of South China, based on Melchin (1989). Melchin (1989) and Melchin et al. (2017) subdivided the *Campograptus curtus* Zone into lower and upper subzones, the upper one being the *Rastrites orbitus* Subzone. Recently, Melchin (in Strauss et al. 2020) recognized the *Rastrites orbitus* Zone as a distinct zone between the *Demirastrites triangulatus* and *Lituigraptus convolutus* biozones in Yukon, Canada.

Lituigraptus convolutus Biozone (23.7–29.8 m).

The base of the *Lituigraptus convolutus* Biozone is defined in sample CGS48. The eponymous species is not uncommon in the interval, but complete specimens have not been recognized (Fig. 4a, b). The interval is about 7 m thick and bears a quite diverse fauna that has been documented recently by Maletz et al. (2019) from the YD-1 drill core on the eastern limb of the Huangling anticline, where the thickness of the *Lituigraptus convolutus* Biozone is considerably higher, measuring about 385 m.

A number of new faunal elements appear at the base of the *Lituigraptus convolutus* Biozone, but also quite a number of long-ranging taxa (e.g., *Normalograptus scalaris*, *Metaclimacograptus hughesi*, *Pseudoretiolites* sp., *Korenograptus nikolayevi* (Fig. 12d) extend their ranges into this interval.

Petalolithus intermedius (Fig. 11c) and *Petalolithus ulstae* (Fig. 11i) appear at the base of the zone as do *Glyptograptus serratus* (Fig. 11j), *Monograptus mirificus* and *Pribylograptus argenteus*. *Petalolithus ulstae* can be differentiated from other species of *Petalolithus* through its long sicula. It has been described from the *Pribylograptus leptotheca* Biozone of the Kaliningrad region, Russia (Suyarkova, 2017). *Paramonoclimacis sidjachenkoi* (Fig. 11n) and *Metaclimacograptus sculptus* (Fig. 11k) appear at the same level. Thus, a subdivision of the *Lituigraptus convolutus* Biozone based on these taxa (cf. Maletz et al. 2019) cannot be provided and the presence of a gap at the base of the interval cannot be excluded. *Cephalograptus cometa* (Fig. 11d) appears in the middle part of the zone. *Petalolithus dubovikovi* (Fig. 11a) and *Petalolithus clandestinus* (Fig. 11g) are also present in the interval. *Petalolithus clandestinus* was first described by Štorch (2001) from the lowermost *Stimulograptus sedgwickii* Biozone of the Czech Republic. It can be recognized by a robust tubarium with a very small ancora and everted, ventrally facing apertures. The similar *Parapetalolithus globosus* (Fig. 13b) can be distinguished by its simple virgella. *Petalolithus clandestinus* is not uncommon in the higher part of the *Lituigraptus convolutus* biozone in the Tielugou section.

Parapetalolithus kunkojensis (Figs. 11b, 12c) appears as the earliest species of the genus *Parapetalolithus*, lacking any indications of an ancora. Retiolitids are rare, but include a single specimen of *Aeroretiolites* sp. Fragments of a species of *Pristiograptus* are common, but few proximal ends are present. A few specimens clearly show a strongly curved proximal end and are assigned to *Pristiograptus xiushanensis* (Fig. 12k). They are similar to the younger *Pristiograptus renaudi* (Philippot, 1950) from the *Spirograptus guerichi* Biozone (see Loydell 1993). *Lituigraptus phleoides* was discovered only at a single level in the succession (Fig. 11m).

Štorch (1995) discussed a considerable extinction event in the late *Lituigraptus convolutus* Biozone in the Czech Republic and a restructuring of the faunal composition subsequently. He identified this extinction as the *Convolutus* Event and recognized a drop from 51 taxa in the *Lituigraptus convolutus* Biozone to 15 at the base of the *Stimulograptus sedgwickii* Biozone in the Czech Republic. Melchin et al. (1998) concluded that the extinction reached its peak only in the *Stimulograptus sedgwickii* Biozone and renamed it accordingly. This extinction led to the origin and early evolution of the genus *Parapetalolithus* from a *Petalolithus*-type ancestor. Štorch and Frýda (2012) discussed the *Sedgwickii* Event and its faunal differentiation in the Barrandian area, Czech Republic. Loydell (1994) documented the diversity of *Parapetalolithus* (as *Petalolithus*) in the *Spirograptus guerichi* Biozone and Loydell et al. (2015) described the species of *Parapetalolithus* of the *Stimulograptus halli* to

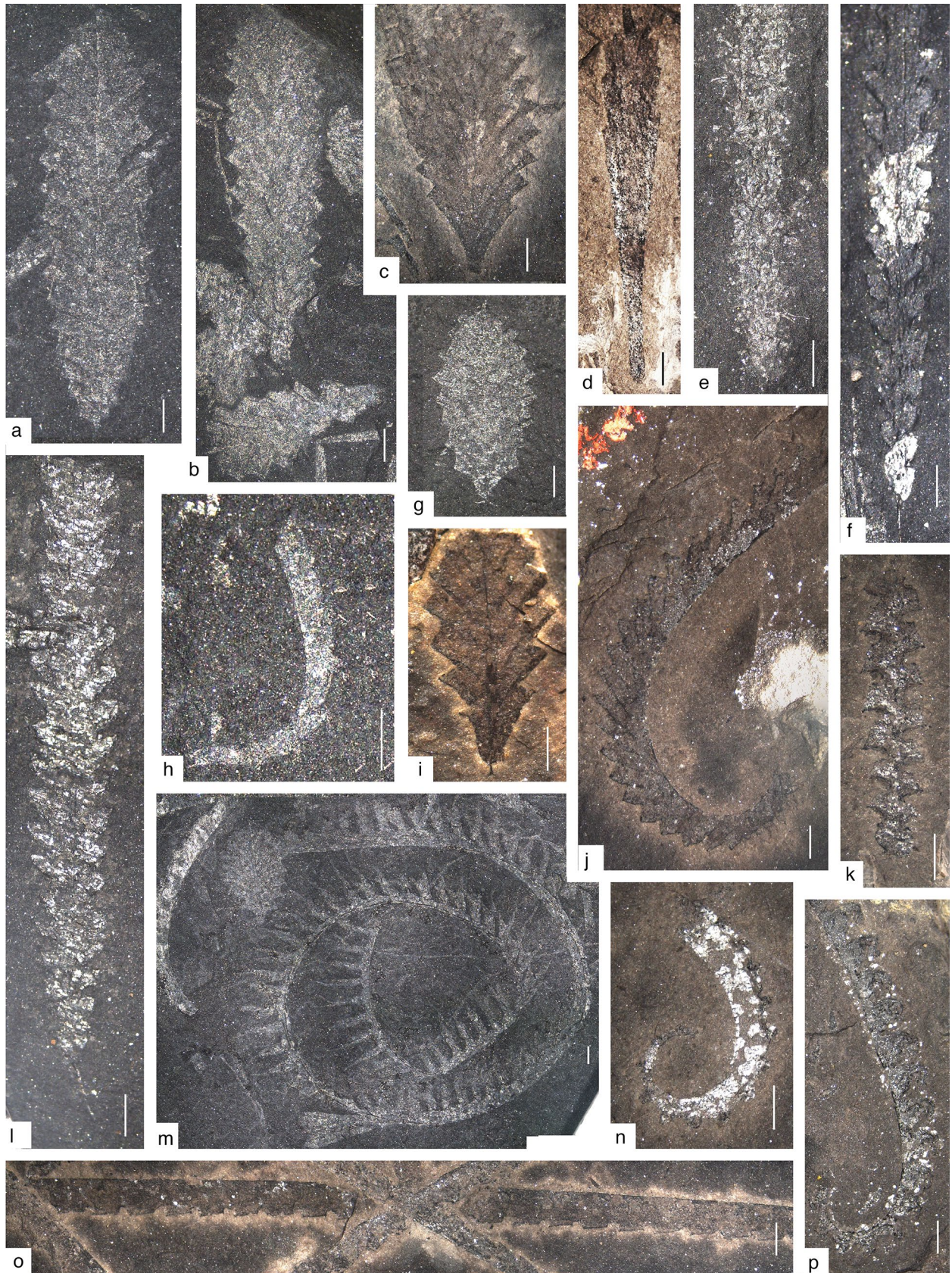


Fig. 11 Graptolites characteristic of the *Lituigraptus convolutus* Biozone. **a** *Petalolithus dubovikovi* Obut and Sobolevskaya in Obut et al., 1967, NIGP 173576, 27.2 m. **b** *Parapetalolithus kunkojensis* Paškevičius, 1979, NIGP 173577, 30.3 m, two specimens. **c** *Petalolithus intermedius* (Bouček and Přibyl, 1942), NIGP 173578, 23.7 m. **d** *Cephalograptus cometa* (Geinitz, 1852), NIGP 173579, 25.3 m. **e** *Pseudorthograptus insectiformis* (Nicholson, 1868), NIGP 173580, 23.7 m. **f** *Rickardsograptus thuringiacus* (Kirste, 1919), NIGP 173581, 25.3 m. **g** *Petalolithus clandestinus* Štorch, 2001, NIGP 173582, small specimen, 29.2 m. **h** *Pernerograptus variabilis* (Ni, 1978), NIGP 173583, 25.7 m. **i** *Petalolithus ulstae* Suyarkova, 2017, NIGP 173584, 25.3 m. **j** *Monograptus* sp., NIGP 173585, 25.3 m. **k** *Metaclimacograptus sculptus* (Chen and Lin, 1978), NIGP 173586, 25.3 m. **l** *Glyptograptus serratus* (Elles and Wood, 1907), NIGP 173587, 27.2 m. **m** *Lituigraptus phleoides* (Törnquist, 1887) and *Petalolithus praecursor* (Bouček and Přibyl, 1942), NIGP 173588, 27.2 m. **n** *Paramonoclimacis sidjachenkoi* (Obut and Sobolevskaya in Obut et al., 1965), NIGP 168419, 25.3 m. **o** *Monoclimacis crenularis* (Lapworth, 1880), NIGP 173589, 25.3 m. **p** *Campograptus millepeda* (M'Coy, 1850), NIGP 173590, 23.7 m. Scale bar is 1 mm

Spirograptus guerichi Biozone interval of the El Pintado Reservoir, Spain, showing the explosive diversification of the genus. It is unclear, however, when exactly this diversification happened as the petalolithids from the *Stimulograptus sedgwickii* Biozone are not well described from most regions. According to the record at the Tielugou section, the diversification may have happened in the upper part of the *Stimulograptus sedgwickii* Biozone. However, the *Stimulograptus halli* Biozone has not been differentiated in many regions. Loydell (2012) indicated a differentiation of a *Stimulograptus halli* Biozone only in Avalonia and Baltica. Walasek et al. (2018) discussed the succession of Dalarna and recognized a *Stimulograptus halli* Biozone, but indicated the presence of a gap at the base of the interval, where the *Stimulograptus sedgwickii* Biozone is lacking.

Stimulograptus sedgwickii Biozone (missing?).

The *Stimulograptus sedgwickii* Biozone appears to be lacking in the Tielugou section, as a number of species are found at the base of this interval that are known only from the *Stimulograptus halli* Biozone upwards (cf. *Parapetalolithus mui*, *Parapetalolithus kunkojensis*, *Torquigraptus linterni*, *Pristiograptus xiushanensis*). However, *Stimulograptus halli* has not been recognized during this investigation, but the closely related *Stimulograptus sedgwickii* is common in many layers. The interval could easily be referred to the *Stimulograptus sedgwickii* Biozone instead unless other faunal elements are considered (cf. Loydell et al. 2015). The biostratigraphic range of *Stimulograptus sedgwickii* and *Stimulograptus halli* strongly overlaps (Loydell et al. 2015: fig. 12) and *Stimulograptus sedgwickii* even ranges through the *Spirograptus guerichi* Biozone.

A gap in the Llandovery graptolite succession is known in southern Scandinavia (Bjerreskov 1975; Loydell et al. 2017; Walasek et al. 2018) and possibly in China (see Loydell 2012), but more complete successions across the *Stimulograptus sedgwickii* and *Stimulograptus halli* biozones can be found in the Southern Uplands of Scotland and in further regions worldwide as discussed by Loydell et al. (2015).

Stimulograptus halli Biozone (30.3–36.7 m).

Loydell (2012: fig. 4) questioned the presence of the late Aeronian *Stimulograptus sedgwickii* and *Stimulograptus halli* biozones in South China, but did not provide details for this interpretation. Wang (1987) reported a *Stimulograptus sedgwickii* Biozone that was 138.9 m thick in the Wangjiawan section. The fauna was not described and the single fragment illustrated as *Stimulograptus sedgwickii* is unidentifiable. *Stimulograptus sedgwickii* (Fig. 12s–u) is common at Tielugou, often preserved as long straight fragments. The interval, however, might be referred to the *Stimulograptus halli* Biozone based on the record of *Pristiograptus xiushanensis* (see Loydell et al. 2015: 780) and especially of the genus *Parapetalolithus* first appearing in the *Stimulograptus halli* Biozone (Lenz et al. 2018).

Stimulograptus sedgwickii is commonly associated with *Pristiograptus regularis* (Fig. 12q–r) and a number of biserial graptolites in the interval, but *Stimulograptus halli* has not been recognized so far. Several species of *Parapetalolithus* can be found in the interval, of which *Parapetalolithus mui* (Fig. 13a, h) and *Parapetalolithus fusiformis* (Figs. 12b, 13g) may be the most common species. A few specimens of *Parapetalolithus* sp. A (Fig. 12f) and *Parapetalolithus* sp. B (Fig. 12g) were found in the middle of the interval. The specimens strongly remind of the genus *Cephalograptus*, but their proximal ends are less strongly elongated. They do not possess an ancora and a closer relationship to the genus *Cephalograptus* may not be reasonable to suggest. Similarities can be seen to *Parapetalolithus aknisos* Loydell et al., 2015 with its elongated, slender and low inclined thecae, but the specimens show a distinct distal widening of the tubarium and certainly not represent this species.

Sample CGS67 also bears specimens here identified as *Normalograptus* sp. nov. (Fig. 12h). The specimens are poorly preserved, but appear to show extreme genicular expansions on one or two proximal thecal pairs. The material may show a similar development of the genicula to *Normalograptus* sp. nov. from the *Spirograptus guerichi* Biozone in Russel–Houston (2001: pl. 13f). *Torquigraptus linterni* (Fig. 12j) was found in a specimen possibly showing cladial branching. A number of specimens of *Torquigraptus* may belong to *Torquigraptus minutus* and *Torquigraptus*

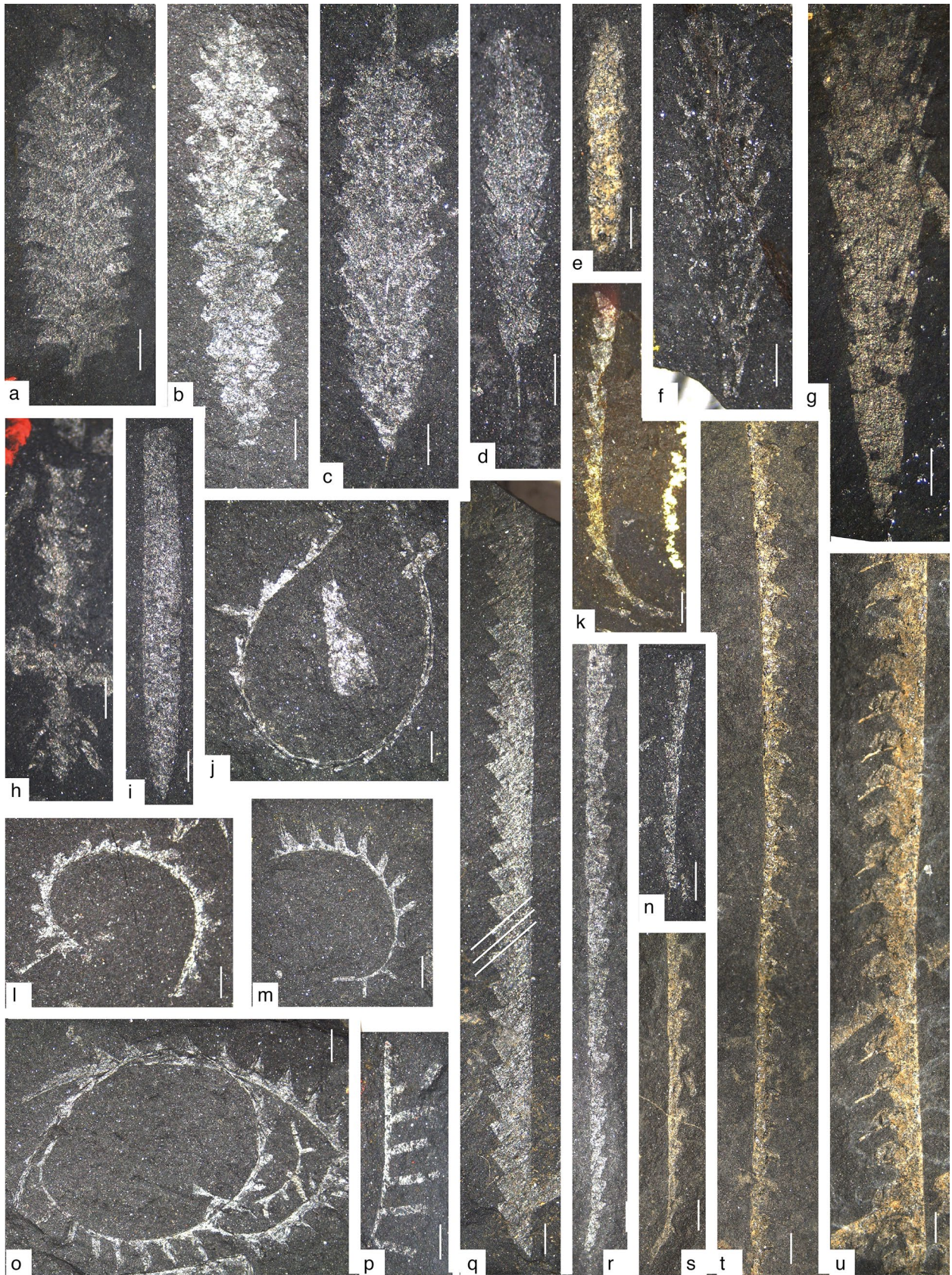


Fig. 12 Graptolites characteristic of the *Stimulograptus halli* Biozone. **a** *Parapetalolithus* sp., NIGP 173591, 30.8 m. **b** *Parapetalolithus fusiformis* (Chen, 1984), NIGP 173592, 32.8 m. **c** *Parapetalolithus kunkojensis* (Paškevičius, 1979), NIGP 173593, 34.1 m. **d** *Korenograptus nikolayevi* (Obut, 1965), NIGP 173594, 29.8 m. **e** *Metaclimacograptus undulatus* (Kurck, 1882), NIGP 173595, 31.2 m. **f** *Parapetalolithus* sp. A, NIGP 173596, 33.6 m. **g** *Parapetalolithus* sp. B, NIGP 173597, 33.2 m. **h** *Normalograptus* sp. nov., NIGP 173598, showing genicular additions, 33.2 m. **i** *Normalograptus scalaris* (Hisinger, 1837), NIGP 173599, 33.6 m. **j** *Torquigraptus linterni* (Williams et al., 2003), NIGP 173600, see cladal branching, 32.8 m. **k** *Pristiograptus xiushanensis* Mu et al., 1974, NIGP 173601, 32.2 m. **l** *Torquigraptus* sp.?, fragment, NIGP 173602, 33.6 m. **m** *Torquigraptus magnificus* (Příbyl and Münch, 1942), NIGP 173603, 32.8 m. **n** *Pristiograptus* sp., NIGP 173604, 33.6 m. **o** *Torquigraptus magnificus* (Příbyl and Münch, 1942), NIGP 173,605, 32.8 m. **p** ?*Rastrites peregrinus* Barrande, 1850, NIGP 173606, 30.8 m. **q** *Pristiograptus regularis* (Törnquist, 1899), NIGP 173607, 34.4 m, white lines indicate deformation. **r** *Pristiograptus regularis* (Törnquist, 1899), NIGP 173608, 32.8 m. **s** *Stimulograptus sedgwickii* (Portlock, 1843), NIGP 173609, proximal end, 31.2 m. **t** *Stimulograptus sedgwickii* (Portlock, 1843), NIGP 173610, 31.2 m. **u** *Stimulograptus sedgwickii* (Portlock, 1843), NIGP 173611, 31.2 m. Scale bar is 1 mm

magnificus (Fig. 12m, o). A single fragment has been identified as a possible specimen of *Rastrites peregrinus* (Fig. 12p).

Zalasiewicz et al. (2009) referred *Rastrites perfectus* (Fig. 13l) to the *Stimulograptus halli* Biozone, but the species is present only in the higher part the interval at Tielugou. A number of species appear at CGS 73 (36.2 m) including *Rastrites robardeti*, *Torquigraptus linterni* (Fig. 13r) and *Parapetalolithus regius* (Fig. 13c) that appear to be typical of the interval. *Spirograptus andrewsi* (Fig. 13t) was found in CGS74 (36.7 m). Loydell et al. (1993) found the species in the *Stimulograptus halli* Biozone, but it appears to be lacking in Spain (see Loydell et al. 2015).

Loydell (1991: fig. 5) discussed the *St. halli* Biozone and listed 31 graptolite species, but he did not illustrate most taxa, but these were treated in detail in Loydell (1992, 1993). Loydell (1993) listed all until then known records of *Stimulograptus halli* including those from China. Mu et al. (2002) discussed *Stimulograptus halli* in China, but most of the known specimens are poorly preserved and could also represent *Stimulograptus sedgwickii*. Thus, the presence of *Stimulograptus halli* in China needs to be revised. Shao et al. (2018) erected a *Spirograptus andrewsi* Biozone for the Llandovery succession in Shaanxi Province and differentiated a lower *Monograptus enshiensis* and an upper *Hubeigraptus* sp. nov. subzone in the late Aeronian. Loydell (1993) synonymized *Monograptus enshiensis* with *Stimulograptus halli*, but it may be better regarded as a synonym of *Stimulograptus sedgwickii*.

Štorch and Frýda (2012) erected the *Lituigraptus rastrum* Biozone above the *Stimulograptus sedgwickii* Biozone in the Czech Republic. The interval is characterized by the common occurrence of *Lituigraptus rastrum*, which

is associated with *Spirograptus andrewsi* throughout the interval. Štorch and Frýda (2012) indicated that *Spirograptus andrewsi* vanished from the record below the base of the Telychian and referred the earliest Telychian fauna to their *Rastrites linnaei* Biozone. *Stimulograptus halli* originates in the lower part of the interval. This biozone may be correlatable with the *Stimulograptus halli* Biozone of Britain (Loydell 1991; Zalasiewicz et al. 2009). Loydell et al. (2015) defined a *Lituigraptus rastrum* subzone in the middle part of the *Stimulograptus halli* Biozone in the El Pintado reservoir of Spain and discussed the correlation of this interval in some detail. The authors indicate that the upper half of the *Stimulograptus sedgwickii* Biozone in the Prague syncline may correlative with the lower *Stimulograptus halli* Biozone.

Silurian: Llandovery (Telychian) (37.7–43.7 m)

Loydell et al. (2015) discussed the base of the Telychian based on the data from the El Pintado section and provided biostratigraphical data from the rich graptolite fauna encountered in the succession. This information may be used to understand and define the base of the Telychian even if important index species are not found. Loydell et al. (1993) described the late Aeronian to early Telychian species of *Spirograptus* in some detail and provided a key to their differentiation, defining the *Spirograptus guerichi* Biozone as the basal Telychian graptolite biozone. As specimens of *Spirograptus guerichi* do not appear in the Tielugou section, a record of early Telychian strata may be questioned. However, the presence of the Telychian *Parapetalolithus dignus* (Fig. 4h, i) associated with a number of taxa already present in the top of the Aeronian, but ranging into the Telychian (Fig. 3), may indicate that the basal Telychian is in fact represented. The presence of *Parapetalolithus palmeus* at 43.7 m (Fig. 13d) definitely indicates the *Spirograptus guerichi* Biozone, as all previously described material of this species originated from the middle part of the *Spirograptus guerichi* Biozone (cf. Loydell 1992; Gutiérrez-Marco and Štorch 1998; Loydell et al. 2015). The higher part of the section did not provide any graptolite faunas. *Spirograptus guerichi* has been described from the Yangtze region (e.g. Mu et al. 2002; Shao et al. 2018) and appears to be common in certain sections. It is not unlikely that this species may be found in the Tielugou section in the future.

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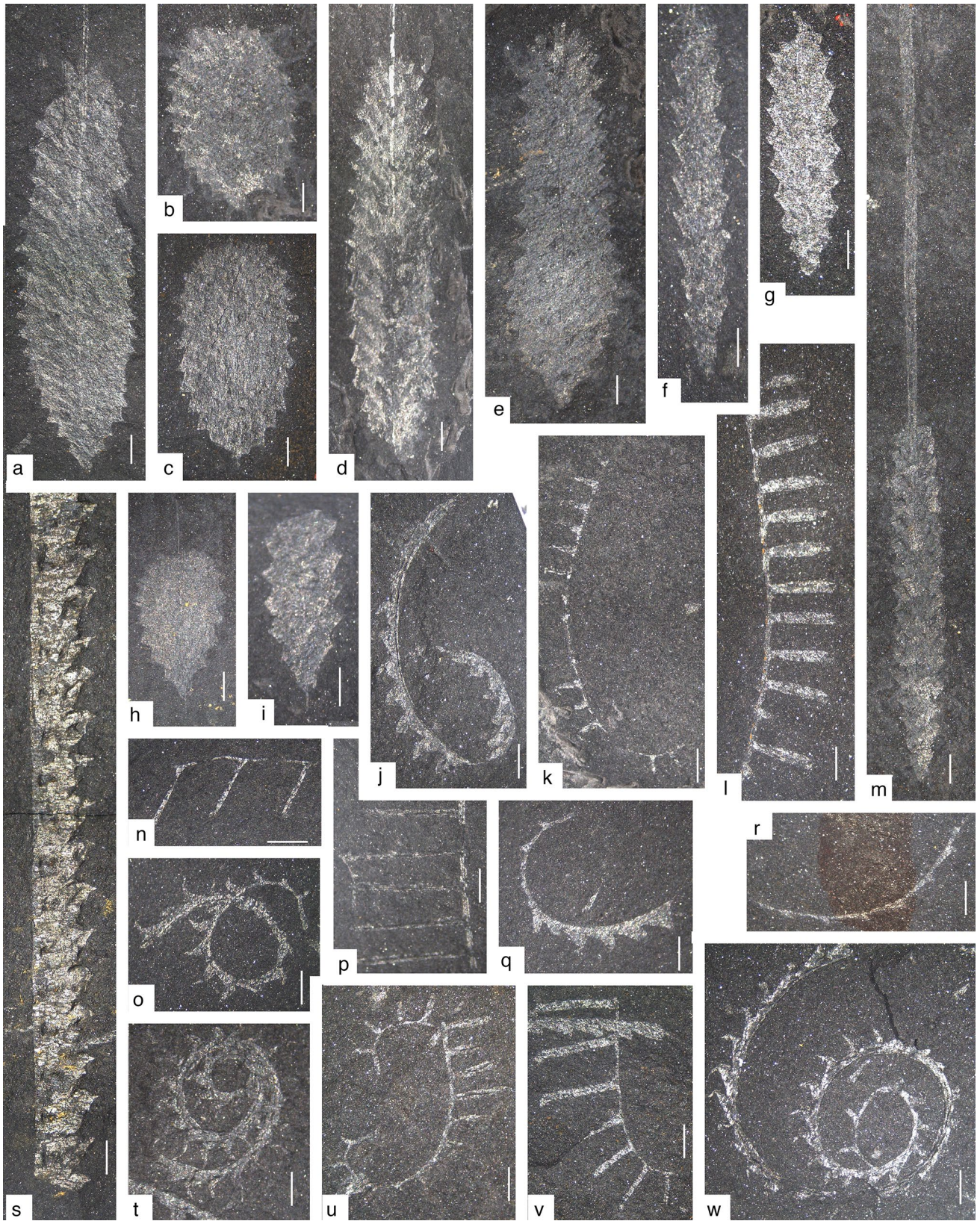


Fig. 13 Graptolites characteristic of the *Stimulograptus halli* and *Spirograptus guerichi* biozones. **a** *Parapetalolithus mui* Loydell et al., 2015, NIGP 173612, 34.6 m. **b** *Parapetalolithus globosus* (Chen, 1984), NIGP 173613, 35.7 m. **c** *Parapetalolithus regius* (Hundt, 1957), NIGP 173614, 36.2 m. **d** *Petalolithus palmeus* (Barrande, 1850), NIGP 173615, 43.7 m. **e** *Parapetalolithus clavatus* (Bouček and Přibyl), NIGP 173616, 35.1 m. **f** *Parapetalolithus cf. aknisis* Loydell et al., 2015, NIGP 173617, 34.85 m. **g** *Parapetalolithus fusiformis* (Chen, 1984), NIGP 173618, 34.6 m. **h** *Parapetalolithus mui* Loydell et al., 2015, NIGP 173619, 35.1 m. **i** *Parapetalolithus fusiformis* (Chen, 1984), NIGP 173620, 34.85 m. **j** *Torquigraptus linterni* Williams et al., 2003, distal fragment, NIGP 173621, 36.2 m. **k** *Rastrites cf. hacari* Loydell et al., 2015, NIGP 173622, 43.7 m. **l** *Rastrites perfectus* Přibyl, 1942, NIGP 173623, 34.85 m. **m** *Parapetalolithus elongatus* (Bouček and Přibyl, 1941), NIGP 173624, 35.7 m. **n** *Rastrites* sp. ex gr. *Rastrites linnaei*, NIGP 173625, 37.7 m. **o** *Oktavites contortus* (Perner, 1897), NIGP 173626, 43.6 m. **p** *Rastrites cf. orlovi* Obut and Sobolevskaya in Obut et al., 1965, NIGP 173627, 43.7 m. **q** *Torquigraptus minutus* (Chen, 1984), NIGP 173628, 37.7 m. **r** *Torquigraptus linterni* Williams et al., 2003, NIGP 173629, 36.2 m. **s** *Stimulograptus sedgwickii* (Portlock, 1843) or *Stimulograptus halli* (Barrande, 1850), oblique view, NIGP 173630, 34.6 m. **t** *Spirograptus andrewsi* (Sherwin, 1974), NIGP 173631, 36.7 m. **u** *Rastrites cf. gracilis* Přibyl, 1942, NIGP 173632, 34.85 m. **v** *Rastrites maletzi* Loydell et al., 2015, NIGP 173633, 34.6 m. **w** *Oktavites contortus* (Perner, 1897), NIGP 173634, 34.6 m. Scale bar is 1 mm

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