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Two new eurypterids (Arthropoda, Chelicerata) from the upper Silurian Yulongsi Formation of south-west China

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Abstract.—Two new eurypterids, a pterygotid *Erettopterus qujingensis* n. sp., and a slimoniid, *Slimonia* sp., are described from the upper Silurian (Pridolian) Yulongsi Formation of Yunnan Province, China. *Erettopterus qujingensis* n. sp. is characterized by several inversely curved ramus denticles and a metastoma with a deep notch in the center. The discovery not only extends the geographic extent of the genus *Erettopterus* and *Slimonia* from Euramerica to southwest China, but also gives insight into the similarity of ecosystem structures across the Silurian world.

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Introduction

Eurypterids, informally known as sea scorpions, are aquatic carnivorous or sweep-feeding chelicerates that originated in the early Middle Ordovician and went extinct in the late Permian (Tetlie, 2007; Lamsdell et al., 2015; Lamsdell and Selden, 2017; Hughes and Lamsdell, 2020). They include some of the largest arthropods known to exist, growing to two meters or more in length (Kjellesvig-Waering, 1964; Chlupáč, 1994; Braddy et al., 2008; Lamsdell and Braddy, 2010). The family Pterygotidae is the most diverse clade of the order Eurypterida, with ~46 species in five genera (Lamsdell and Selden, 2017). Slimoniidae, comprising four species in the genera *Slimonia* and *Salteropterus*, resolving as a sister group to the pterygotids (Lamsdell et al., 2015; McCoy et al., 2015; Lamsdell and Selden, 2017). Pterygotidae originated in the Llandovery (early Silurian), went extinct in the Middle Devonian (Tetlie, 2007; McCoy et al., 2015), and were characterized by the possession of a laterally expanded pretelson, with most species having enlarged chelicerae with elongated peduncular podomeres (Tetlie and Briggs, 2009). Pterygotids attained a nearly global distribution (Poschmann and Tetlie, 2006; Miller, 2007; Tetlie and Briggs, 2009; Lamsdell and Legg, 2010; Wang and Gai, 2014) and were ecologically diverse predators with a range of visual acuity and a variety of cheliceral morphologies indicating adaptations for capturing a variety of benthic and actively swimming prey (Anderson et al., 2014; McCoy et al., 2015).

Despite their longevity and wide geographic dispersal, eurypterids are generally rare in the fossil record, especially in China (Tetlie, 2007). This state has changed in recent years as research intensity increases, with the Chinese record of eurypterids expanding beyond the lower Permian *Adelophthalmus chinensis* from Hebei Province (Grabau, 1920) to include *Hughmilleria wangi* Tetlie, Selden, and Ren, 2007, described based on an almost complete specimen from the Silurian (late Llandovery) Xiaoxiyu Formation (Tetlie et al., 2007; Zong et al., 2017), and an isolated pterygotid chelicera with its two rami preserved from the Xitun Formation of the Lower Devonian in Yunnan Province (Wang and Gai, 2014). Several putative eurypterid specimens were also described by Chang (1957) from the Silurian of Hubei; however, the eurypterid affinity of this material is dubious, and the three described species are considered invalid (Tetlie et al., 2007). Recently a new eurypterid, *Terropterus xiushanensis* Wang et al., 2021, has been reported in the Chongqing area and is the first Mixopteridae to be found in China (Wang et al., 2021; Table 1). Here, we report eurypterid specimens representing a new species of the pterygotid *Erettopterus* (Salter in Huxley and Salter, 1859) and an occurrence of *Slimonia* (Page, 1856) from the upper Silurian (Pridolian) Yulongsi Formation of Yunnan, China.

Geological setting and stratigraphy

Pridoli–Lower Devonian deposits are well developed in the Qujing area. The Silurian layers are assigned to the Miaogao and Yulongsi formations while the Xiaxishancun, Xitun, Guijiatun, and Xujiachong formations belong to the Devonian. Our study outcrop of the Yulongsi Formation is ~11 km west of Qujing

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Table 1. Eurypterids recorded from China. Asterisks indicate taxa that might be based on dubious material.

Permian		
Adelophthalmus chinensis	Grabau, 1920	Hebei Province
Devonian		
Pterygotidae gen. et sp. indet.	Wang and Gai, 2014	Yunnan Province
Silurian		
Erettopterus qujingensis n. sp.	This paper	Yunnan Province
Slimonia sp.	This paper	Yunnan Province
Hughmilleria wangi	Tetlie et al., 2007	Hunan Province
Terropterus xiushanensis	Wang et al., 2021	Chongqing City
*Eurypterus loi**	Chang, 1957	Hubei Province
*Eurypterus styliformis**	Chang, 1957	Hubei Province
*Eurypterus yangi**	Chang, 1957	Hubei Province
Mixopterus sp.*	Chang, 1957	Hubei Province

City (coordinates 25.474544°N, 103.696914°E; Fig. 1). The Yulongsi Formation is ~250 m thick and conformable with the underlying Miaogao Formation; its top is also conformable with a yellow-green sandstone of the Xiaxishancun Formation. The Yulongsi Formation can be divided into three parts: the lower part begins with a large amount of black shale known as the "lower weathering shale," with few fossils, but contains brachiopods, corals, bivalves, ostracodes, and gastropods. The middle part is gray and light gray calcareous shale with a thin gray layer of nodular limestone and limestone lenses containing brachiopods, bivalves, trilobites, and ostracodes. The upper part is black, gray-green and gray-blue shale, also known as the "upper weathering shale," that contains brachiopods, bivalves, and jawless fishes (Wang, 2000, Fig. 2).

There were many debates about the age of the Yulongsi Formation. In the twentieth century, some scholars insisted that the whole formation was Devonian in age (Wu, 1977; Lin et al., 1982) or the boundary between Devonian and Silurian should be below the upper black shale of the formation (P'an et al., 1978; Yang and Li, 1978). However, with further research in the Qujing area—especially recent research in palynology and other microfossils such as conodonts and chitinozoas (Wang, 1980; Fang et al., 1994; Tian et al., 2011; Peng et al., 2016)—all evidence indicates that the age of the Yulongsi Formation is Pridolian (Tian et al., 2011; Rong et al., 2019). All the specimens described in this paper were collected in the upper part of the Yulongsi Formation.

Materials

The specimens (YN-415001–11) described in this paper were collected from the upper part of the Yulongsi Formation. Being preserved in fine shales, the material is flattened and shows some tectonic distortion. The holotype (YN-415005) preserves the free ramus of the chelicera while the prosomal carapace, prosomal appendage VI, metastoma, and several tergites are represented among paratype material.

All photographs were taken with a Sony ILCE-7M3 digital camera with a FE 24-105 mm f/4 G OSS lens. Photographs were processed and arranged into figures using image editing software (Adobe Illustrator CS5 and Adobe Photoshop CS). Morphological terminology follows Tollerton (1989) with denticle terminology following Miller (2007).

Repository and institutional abbreviation.—All specimens and pictures examined in this study are deposited in the fossil specimen room of Southwest Petroleum University (SWPU), Chengdu, Sichuang Province, China.

Systematic paleontology

Order Eurypterida Burmeister, 1843
Suborder Eurypterina Burmeister, 1843
Superfamily Pterygotoidea Clarke and Ruedemann, 1912
Family Pterygotidae Clarke and Ruedemann, 1912

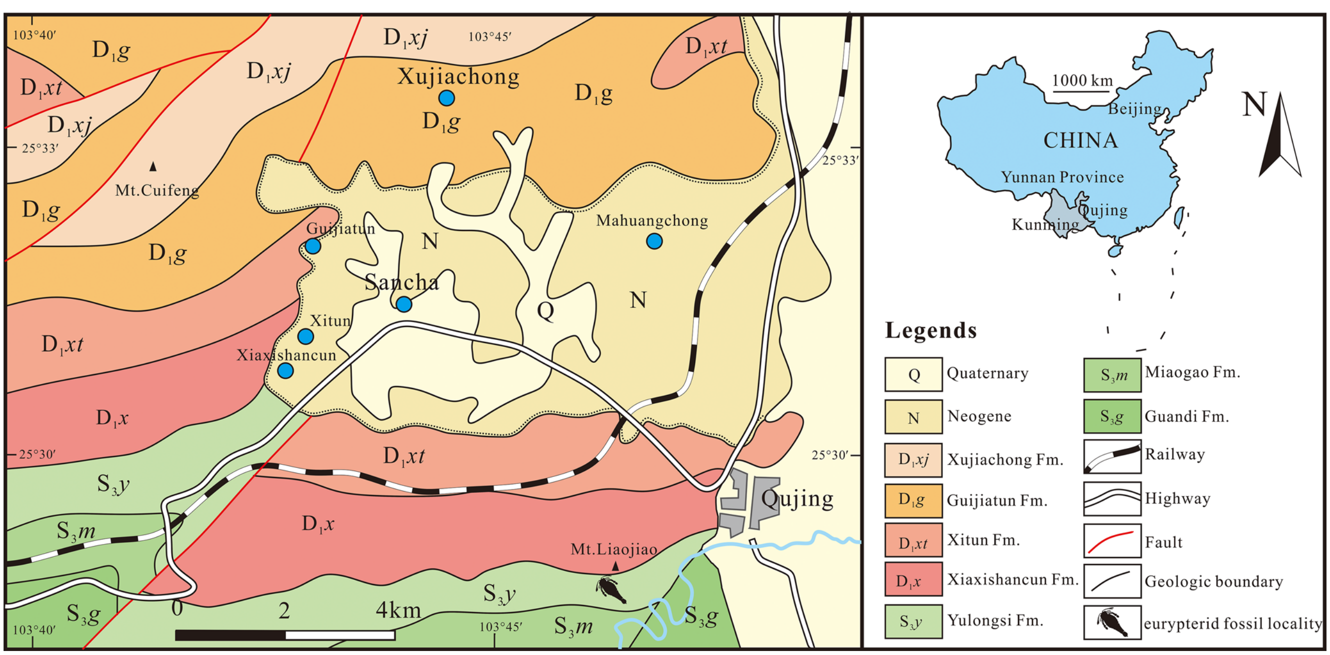

Figure 1. Generalized map showing geologic features of the Qujing area and the eurypterid fossil locality (modified from Hao et al., 2007, fig. 1).

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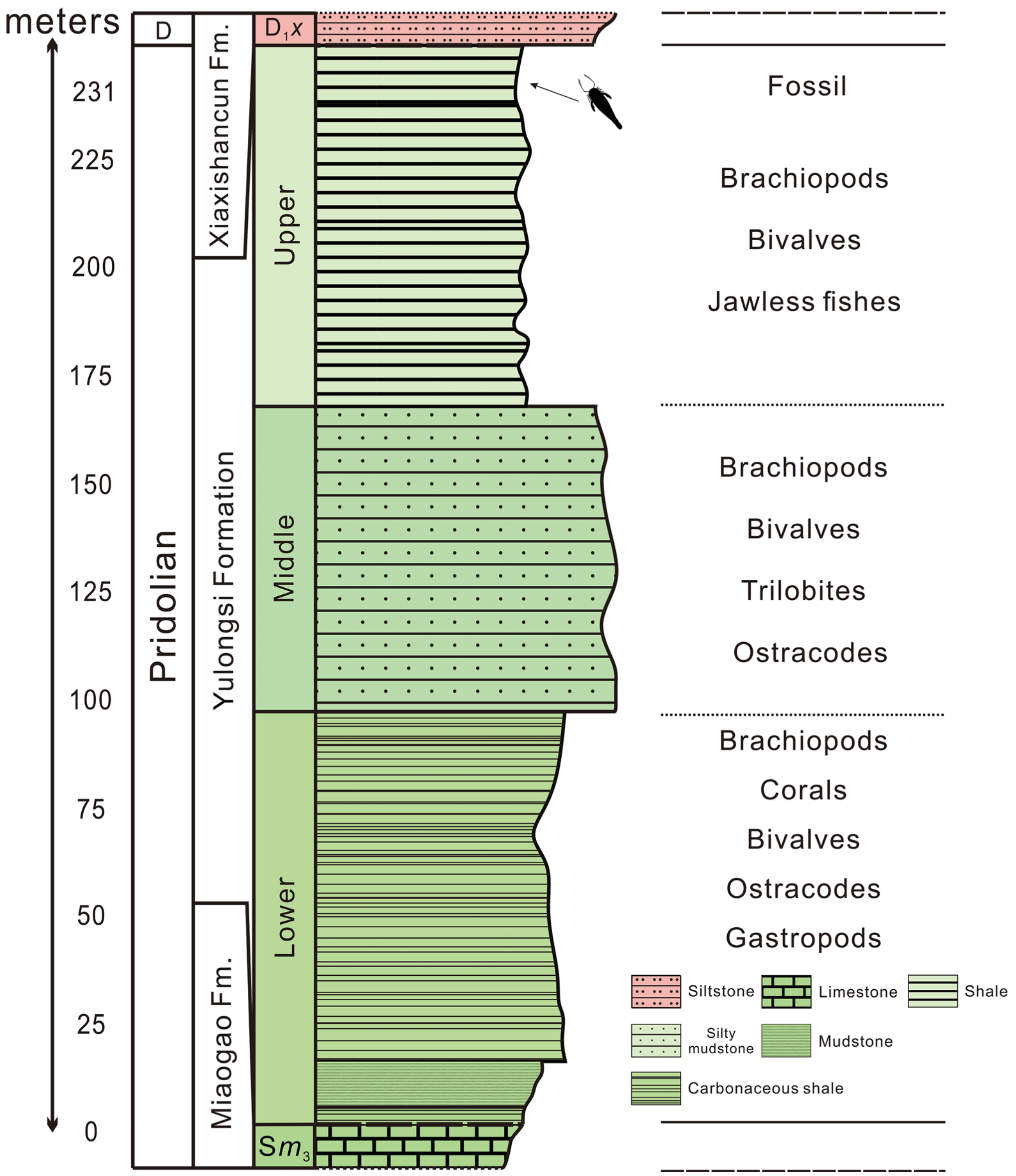

Figure 2. Schematic stratigraphic column for the Yulongsi Formation showing distribution of eurypterids at localities in the Qujing area.

Genus *Erettopterus* Salter in Huxley and Salter, 1859
[= *Truncatiramus* Kjellesvig-Waering, 1961]

Type species.—Pterygotus bilobus Salter, 1856.

Remarks.—Erettopterus was diagnosed by Ciurca and Tetlie (2007) through the possession of a bilobed telson, although previous authors have also considered a deep anterior notch in the metastoma and a lack of enlarged, differentiated denticles in the chelicera to be diagnostic of the genus (Kjellesvig-Waering, 1964; Waterston, 1964). Although the available material does not preserve the telson, several other characteristics, including the relatively undifferentiated cheliceral denticles and the distribution of cuticular ornamentation of the tergites—with an ornament of dense lunule scales across the tergite anteriorly giving way to a smooth unornamented surface posteriorly (also observed by Ciurca and Tetlie, 2007)—indicate that the species can be assigned to the genus with some confidence.

Erettopterus qujingensis new species
Figures 3–5, Table 2

Type material.—Holotype YN-415005; paratypes YN-415001–4, 6–10.

Diagnosis.—Erettopterus with chelicera bearing three principal denticles and distal (terminal) denticle; cheliceral denticles exhibiting size differentiation, central principal denticle longer and broader than others; proximal denticles of free ramus angled inversely; metastoma broad oval in shape with rounded shoulders and a deep median notch.

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Occurrence.—Upper part of the Yulongsi Formation (Pridolian); south of Liaojiao Mountain near Qujing City, Yunnan, southwestern China.

Description.—SWPU: YN-415005 (Fig. 4.1). An isolated free ramus, total preserved length 33 mm, maximum preserved width of ramus 4.1 mm. Terminal denticle incomplete, however the gentle curvature of the preserved ramus margin suggests the denticle may have been curved rather than angular in morphology. Primary denticle (d1´) is more robust than others, length 3.1 mm, width at base 1.8 mm, upright with posterior curvature. Anterior principal denticle (d2´) length 2.1 mm, width at base 1.1 mm, upright with posterior curvature. Third principal denticle (d3´) length 2.1 mm, width at base 1.2 mm, entire denticle angled towards ramus distal termination. Five intermediate denticles are interspersed between the primary denticles and a multitude of smaller denticles; the first *(i1')* occurs just posterior of the terminal denticle and is at least 1.0 mm in height, width at base at least 0.3 mm, upright with little apparent curvature. Second intermediate denticle (*i2'*) occurs 2 mm anterior of the primary denticle, length 1.5 mm, width at base 0.8 mm, upright with posterior curvature. Third intermediate denticle (*i3'*) located immediately posterior of primary denticle, length 1.7 mm, width at base 0.9 mm, upright. Fourth intermediate denticle (*i4'*) located 1.5 mm anterior of third principal denticle, height 1.5 mm, width at base 1.2 mm, entire denticle angled towards ramus distal termination. Fifth intermediate denticle (*i5'*) located 1.7 mm posterior of third primary denticle, height 1.3 mm, width at base 0.7 mm, denticle slightly angled towards ramus distal termination (Table 2).

SWPU: YN-415001 and YN-415002 (Fig. 3, part and counterpart). Material comprising at least two individuals. The large individual is represented by a series of three tergites and an isolated metastoma of either the same individual or one of a similar size. The smaller individual, preserved alongside the large metastoma, comprises a crumpled carapace, partial prosomal appendage VI, and seven articulated tergites.

The tergites of the large specimen are laterally incomplete, with the first tergite having a length of 44 mm and a preserved width of 107 mm, the second tergite a length of 50 mm and a preserved width of 108 mm, and the third a length of 72 mm and a preserved width of 72 mm. The last tergite is clearly folded in on itself part-way along its length, likely the result of

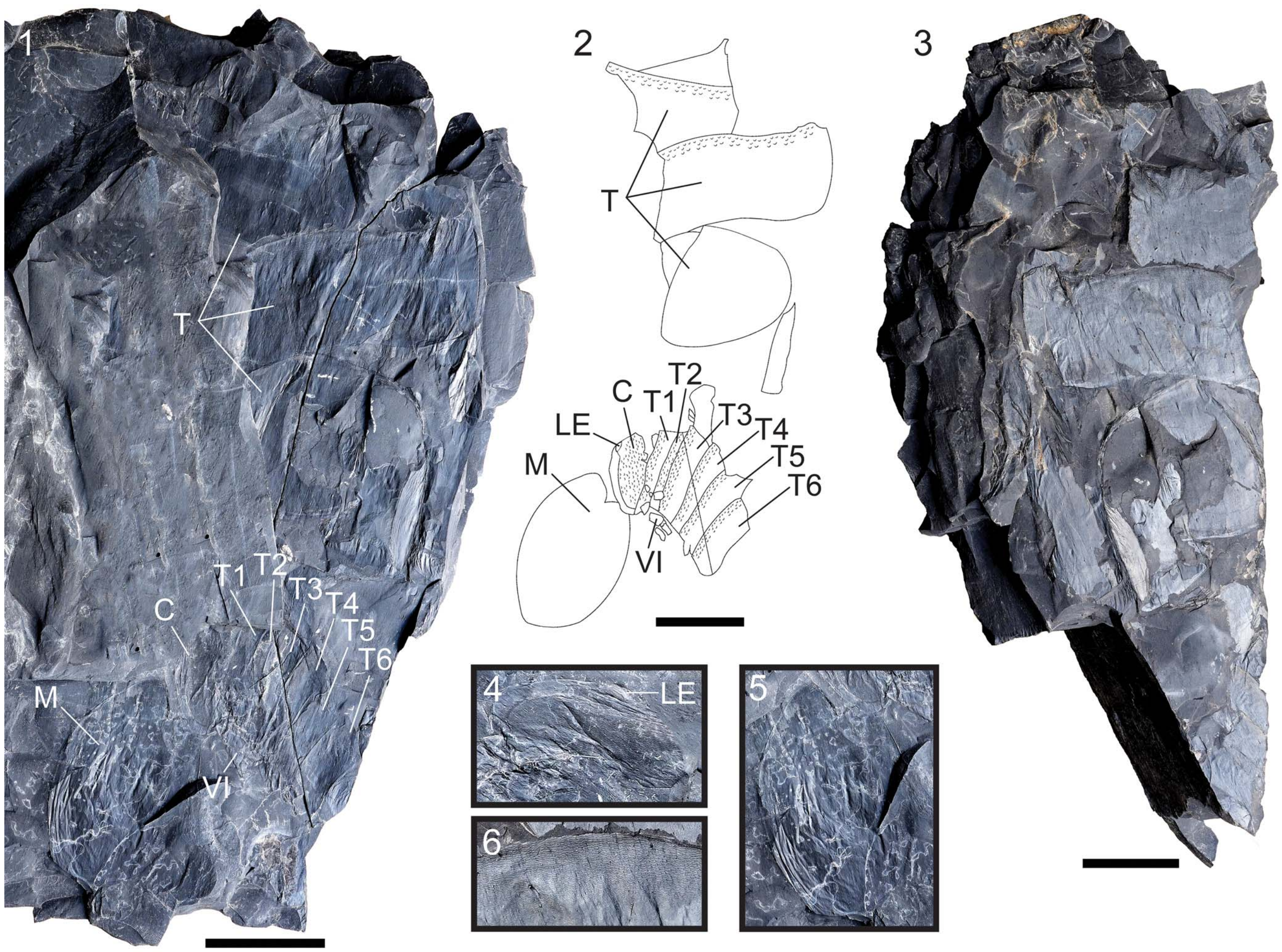

Figure 3. *Erettopterus qujingensis* n. sp. (**1**) Part YN-415001; (**2**) interpretive drawing of YN-415001; (**3**) counterpart YN-415002; (**4**) prosomal carapace of small specimen on YN-415001; (**5**) metastoma on YN-415001; (**6**) detail of anterior tergite ornamentation on YN-415002. C = carapace, LE = lateral compound eye, M = metastoma, T = tergites, VI = prosomal appendage VI. Scale bars = 50 mm.

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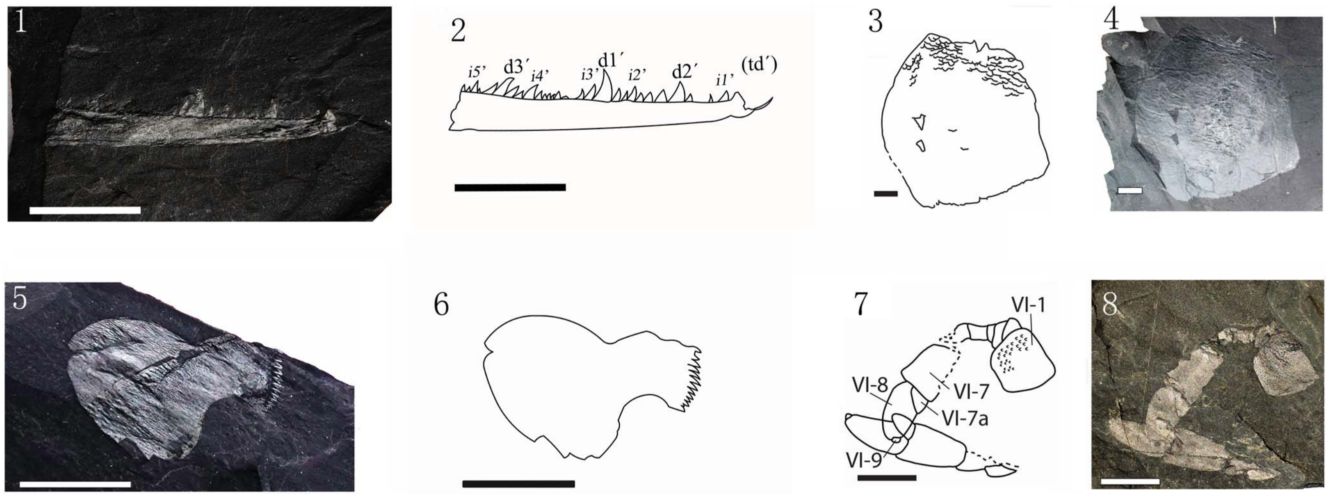

Figure 4. *Erettopterus qujingensis* n. sp. (**1, 2**) Holotype YN-415005, (**1**) free ramus of chelicera, (**2**) interpretive drawing of free ramus of chelicera; (**3, 4**) YN-415004, (**3**) interpretive drawing of partial metastoma, (**4**) partial metastoma; (**5, 6**) YN-415003, (**5**) isolated coxa of prosomal appendage VI, (**6**) interpretive drawing of partial metastoma; (**7, 8**) YN-415006, (**7**) interpretive drawing of prosomal appendage VI, (**8**) isolated pair of prosomal appendage VI. td´ = terminal denticle on free ramus; d1´–d3´ = principal denticles on free ramus; *i1'–i5'* = intermediate denticles on free ramus; VI-1, VI-7–VI-9 = prosomal appendage VI podomeres 1, 7–9; VI-7a = modified part of VI-7. Scale bars = 10 mm.

taphonomic deformation. The anterior 12 mm of each tergite is covered in small scales, getting progressively deeper and more angular posteriorly (Fig. 3.5). The metastoma is rhombiovate (sensu Tollerton, 1989), 84.3 mm long, with a maximum width at its midline of 55.1 mm giving an L:W ratio of 1.53, a lateral angle of 54°, and an angle of cordation 73°. The anterior shoulders are rounded with an angular anterior 13 mm deep notch.

The prosomal carapace of the smaller specimen is crumpled, with a preserved length of 32 mm and preserved width of 41 mm. The overall shape of the prosomal shield is difficult to determine, but the available undistorted margins suggest it may have been subquadrate. An anterolaterally positioned lateral compound eye is preserved, overlapping the carapace margin and oval in outline (Fig. 3.3), 8 mm long by 2 mm wide. Podomeres of prosomal appendage VI are preserved alongside the first few tergites; although generally fragmentary, it is possible to identify the elongated podomere 7 of a swimming paddle with a length of 18 mm and a distal width of 10 mm. Six tergites are preserved in their entirety; the first is 8 mm long, 43 mm wide; the second

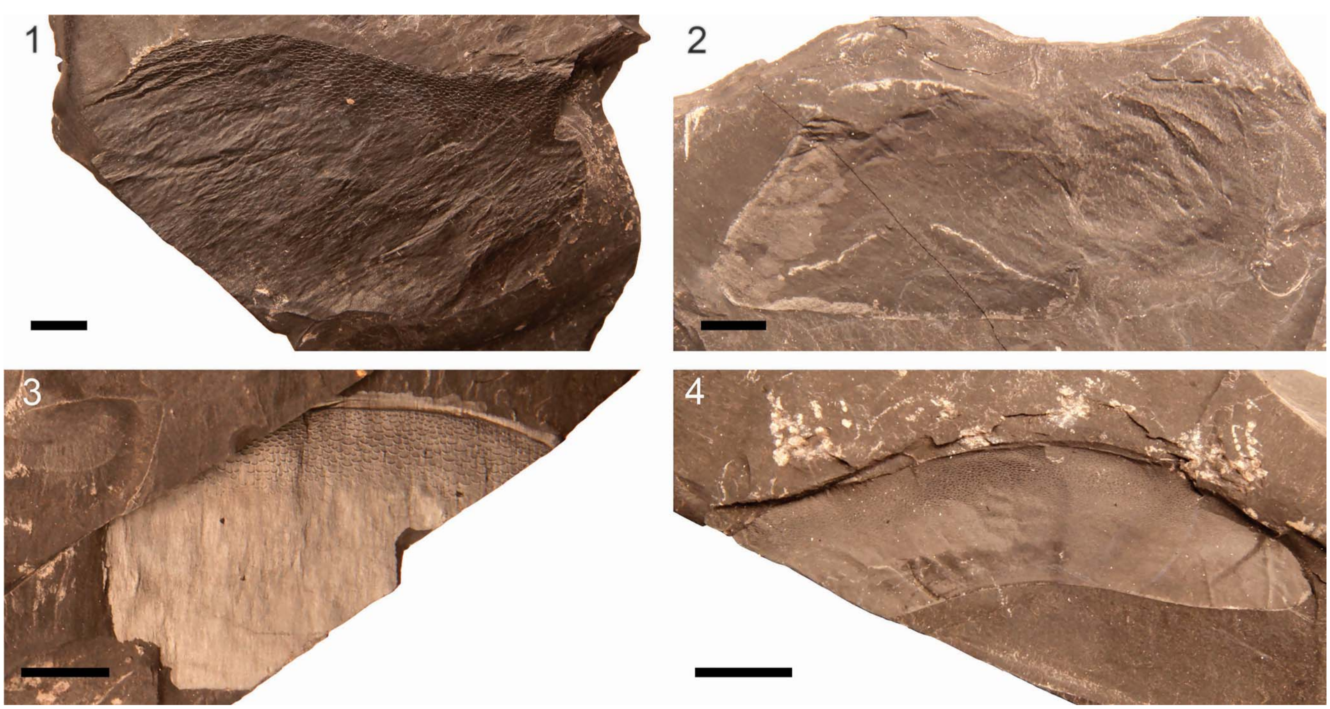

Figure 5. *Erettopterus qujingensis* n. sp. (**1**) Isolated tergite YN-415009; (**2**) isolated tergite YN-415007; (**3**) isolated tergite YN-415010; (**4**) isolated tergite YN-415008. Scale bars = 10 mm.

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Table 2. Denticle dimensions for holotype YN-415005, free ramus of *Erettopterus qujingensis* n. sp. All measurements are in millimeters.

	d1´	d2´	d3´	*i1´*	*i2´*	*i3´*	*i4´*	*i5´*
Length	3.1	2.1	2.1	1.0	1.5	1.7	1.5	1.3
Width	1.8	1.1	1.2	0.3	0.8	0.9	1.2	0.7
angled towards	posterior	Posterior	inverse	posterior	posterior	upright	inverse	inverse

11 mm long, 47 mm wide; the third 12 mm long, 48 mm wide; the fourth 12 mm long, 48 mm wide; the fifth 14 mm long, 47 mm wide; and the sixth is 15 mm long, 45 mm wide. The seventh tergite is also partially preserved, with an observed length of 12 mm and an observed width of 34 mm. The anterior 5 mm of each tergite is covered in dense scales.

SWPU: YN-415004 (Fig. 4.2, 4.3). A partial metastoma was preserved in black shale. The only complete external margins preserved are those of the left side, a small portion of the margin of the lower right, and the center of the anterior notch. The overall shape appears to be rhombiovate; preserved length 81 mm, preserved width 80 mm. The anterior third of the metastoma is ornamented with lunate scales.

SWPU: YN-415003 (Fig. 4.4). An almost completely preserved isolated coxa of appendage VI. The coxa is broad, expanding distally with a marked constriction between the gnathobase and the distal expansion. The length of the coxa is 18.1 mm from the distal portion of the expanded posterior to the gnathobasic edge. The maximum width of the coxa, located towards the posterior of the expanded region, is 14.7 mm; the gnathobasic surface is incomplete with a preserved width of 6.1 mm, and the subsequent constriction is 5.3 mm wide at its narrowest point. The full gnathobasic surface is not preserved, but at least 11 teeth are present, generally uniform in shape and decreasing regularly in size from anterior to posterior. The coxa surface is ornamented with broad lunule scales grading to small tubercles at the coxa midline.

SWPU: YN-415006 (Fig. 4.5, 4.6). A pair of prosomal appendage VI paddles, one comprising nine podomeres (including the coxa) with the other preserving only the five distal podomeres. Paddle of *Hughmilleria* type (sensu Tollerton, 1989). The coxa, which preserved only the expanded distal portion, has a preserved length of 10.6 mm, a preserved width of 8.8 mm, and is ornamented with lunule scales. The second podomere is 2.9 mm long, at least 2.9 mm wide, and is broadly triangular in shape; the third podomere is rectangular, being 2.4 mm long and 3.6 mm wide; fourth podomere is incomplete, preserved dimensions 1.5 mm long, 2.1 mm wide; fifth podomere incomplete, preserved dimensions 2.8 mm long, 2.5 mm wide; sixth podomere incomplete, preserved dimensions 4.3 mm long, 2.2 mm wide, expanding to 4.0 mm wide distally, complex articulation visible at proximal podomere joint; seventh podomere 9.8 mm long, 4.5 mm wide proximally, widening evenly to 7.0 mm distally; modified ‘podomere’ 7a located along the inner paddle margin, triangular in shape, 3.1 mm long, 3.2 mm wide at its base; eighth podomere oval, 9.4 mm in length, 5.7 mm in width; ninth podomere small, 0.7 mm long, 1.1 mm wide, slightly recessed into eighth podomere.

SWPU: YN-415007 (Fig. 5.1). Partial tergite, length 48 mm, preserved width 92.5 mm. Anterior 11 mm ornamented with dense scales.

SWPU: YN-415008 (Fig. 5.2). Partial tergite, length 45.5 mm, preserved width 90 mm.

SWPU: YN-415009 (Fig. 5.3). Partial tergite, length 39 mm, preserved width 53 mm. Smooth articulating facet present across tergite anterior, 2 mm long. Anterior 9 mm of tergite ornamented with dense scales.

SWPU: YN-415010 (Fig. 5.4). Partial tergite, length 15 mm, preserved width 75 mm. Anterior 5 mm of tergite ornamented with dense scales.

Etymology.—The specific epithet is named after the type locality, near Qujing City.

Remarks.—*Erettopterus qujingensis* n. sp. shares a number of characteristics with other well-known *Erettopterus* species, particularly *E. osiliensis* Schmidt, 1883, with the anterior slant to the posterior denticles in the chelicera (Kjellesvig-Waering, 1964). *Erettopterus qujingensis* n. sp. can be distinguished from all other *Erettopterus* species by the shape of the metastoma, which is broader and more rounded than in either *E. osiliensis* or *E. bilobus*, and through the morphology of the ninth podomere of appendage VI, which is larger than in any other known *Erettopterus* species (see Woodward, 1866–1878; Ciurca and Tetlie, 2007; Lomax et al., 2011). The cheliceral morphology of *E. qujingensis* n. sp. is distinct from the pterygotid chelicera described by Wang and Gai (2014) from the Lower Devonian Xitun Formation of Yunnan Province, which exhibits a more robust and highly curved ramus and more differentiation between the cheliceral denticles.

A number of ontogenetic stages of *E. qujingensis* n. sp. are represented within the described material, with the large tergites and metastoma of SWPU: YN-415001 and YN-415002 and metastoma SWPU: YN-415004 representing the largest individuals. These specimens indicate that *E. qujingensis* n. sp. could attain lengths >90 cm.

Family Slimoniidae Novojilov, 1962
Genus *Slimonia* Page, 1856

Type species.—*Slimonia acuminata* Salter, 1856

Slimonia sp.
Figure 6

Diagnosis.—Carapace is long rectangular shape. Oval-shaped lateral eyes are preserved in the anterolateral corners and are elongate. Anterior margin of the carapace is ornamented by two rows of small pustules.

Occurrence.—Upper part of the Yulongsi Formation (Pridolian); south of Liaojiao Mountain, near Qujing City, Yunnan, southwestern China.

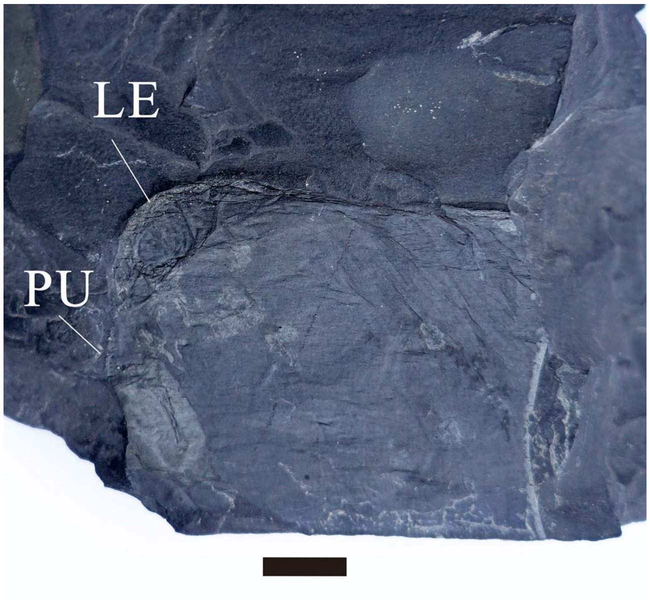

Figure 6. *Slimonia* sp.; partial carapace YN-415011. LE = lateral eye, PU = pustules. Scale bar = 10 mm.

Description.—Partial carapace specimen, preserving right margin, lateral compound eye, and portions of anterior and posterior margins. Carapace 43.7 mm long, preserved width 34.4 mm. Based on curvature of the anterior and posterior margins, the midline of the carapace is preserved, resulting in an estimated carapace width of 44 mm and suggesting a quadrate shape (Tollerton, 1989). The anterior margin of the carapace is ornamented by two rows of small pustules. The lateral eye is positioned anterolaterally, abutting the carapace margin, and is oval in shape, with a length of 8 mm.

Material.—YN-415011 (Fig. 6).

Remarks.—The occurrence of pustules across the anterior carapace margin is diagnostic of *Slimonia* (Lomax et al., 2011), an assignment further supported by the shape and position of the lateral eyes. The prosomal carapace is markedly shorter than in *Slimonia acuminata*; however, because *Slimonia boliviana* Kjellesvig-Waering, 1973, is only known from its telson (Kjellesvig-Waering, 1973) and the prosomal carapace of *Slimonia dubia* Laurie, 1899, is also quadrate in shape (Laurie, 1899), it is not currently possible to determine whether the specimen described here represents a new species.

Discussion

The co-occurrence of *Erettopterus* and *Slimonia* in the Yulongsi Formation is especially interesting given the two genera also co-occur at the famous Wenlock localities of Lesmahagow, Scotland (Lomax et al., 2011). Finding similar eurypterid faunal compositions across different paleocontinents might suggest that eurypterids formed comparable communities globally. Broadly equivalent Silurian eurypterid faunas already have been documented between the Vernon Formation of New York and the Saaremaa Formation of Estonia (Ciurca and Tetlie, 2007). Comparison of associated faunas also would give insight into the similarities of ecosystem structures across the Silurian world. Like the Lesmahagow fauna, a few jawless fishes are also present in the Yulongsi Formation. The *Erettopterus* and *Slimonia* fossils of Lesmahagow occur in the

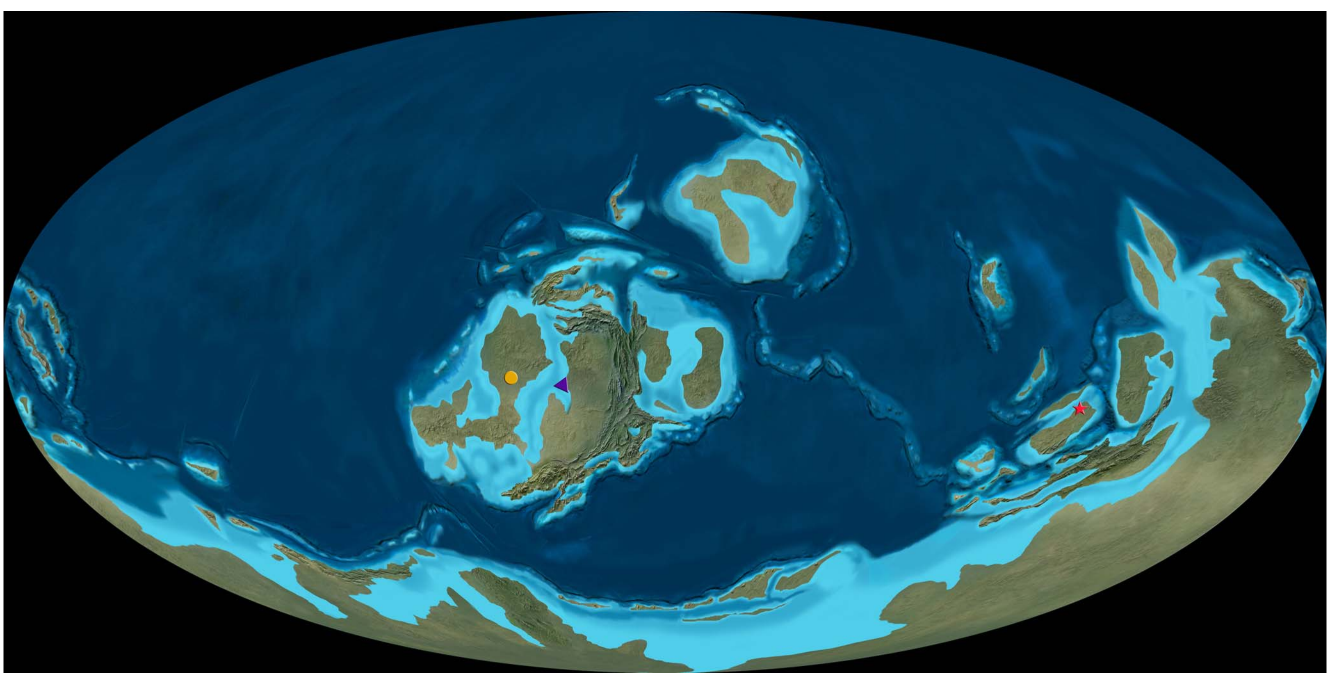

Figure 7. Paleogeographic distribution of Pridolian *Erettopterus* and *Slimonia*. Global paleogeographic reconstruction for the Pridolian (420 Ma) is after Blakey (2020). Circles represent localities of previously described Pridolian *Erettopterus*. Triangle represent localities of previously described Pridolian examples of both *Erettopterus* and *Slimonia* (Tetlie, 2007). Star shows location of the Chinese eurypterids.

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Patrick Burn and Kip Burn formations of the Priesthill Group in the *Jamoytius* Horizon and *Ceratiocaris* and *Pterygotus* beds, respectively. The *Jamoytius* Horizon consists predominantly of dark, organic, intensely laminated silt-mudstone (Žigaitė and Goujet, 2012), indicative of an anoxic environment (Earnest, 1998) as part of a shallow, restricted marginal marine setting or possibly a lake (Žigaitė and Goujet, 2012; Clarkson and Harper, 2016). The Yulongsi Formation shows more similarities to the Kip Burn Formation. For example, in the Qujing region, the dominant lithology of the Yulongsi Formation is a dark gray, laminated mudstone comparable to the dark olive-gray mudstone with laminated siltstone of the Kip Burn Formation. Based on sedimentary and tectonic evidence, the Yulongsi Formation also appears to represent a period of gradual transition from a shallow marine to lagoonal environment (Wang, 2000).

All of the 17 previously known species of *Erettopterus* are known from Europe and North America (Tetlie, 2007), as are two of the three *Slimonia* species—*Slimonia boliviana* was described from a single telson from Pojo, Bolivia (Kjellesvig-Waering, 1973). The specimens described here broaden the distribution of *Erettopterus* and *Slimonia* and is the first Gondwanan record of *Erettopterus*. Moreover, the discoveries further support the notion that pterygotoids had superior dispersal abilities, leading to a more cosmopolitan distribution because of substantial swimming abilities (Tetlie, 2007). These new discoveries from China not only provide a broader picture of the biogeography of the group, but also demonstrate that species in Gondwana occupied similar environments to their Laurentian relatives (Fig. 7).

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