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Ostracods from the upper Silurian Si Ka Formation, northern Vietnam, and their paleobiogeographical significance

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Abstract. The first detailed, systematic record of Silurian ostracod crustaceans from Vietnam is presented. Ostracods from the upper Silurian (upper Ludlow–lower Pridoli) Si Ka Formation of Ha Giang Province, northern Vietnam comprise *ca*. 10 species, including two new species of hollinoideans, two beyrichioideans, three species of eridostracine, at least one putative paraparchitoidean, and two indeterminate palaeocopid species. The fauna co-occurs with macroplant and fish fragments, and pterineid bivalves, in lithofacies that are interpreted as estuarine. The presence of beyrichioideans is consistent with their reported occurrence in marine, marginal-marine and estuarine ostracod assemblages elsewhere in the late Silurian and Devonian. One of the beyrichioidean species possibly represents *Qujingsia nonaculeata*, a species known from the Ludlow–Pridoli of South China, thus endorsing the supposed late Silurian age of the Vietnam fauna and its paleogeographical position on the South China paleo-plate. The other beyrichioidean is *Beyrichia* (*Beyrichia*), a globally distributed taxon in the Silurian and Early Devonian. Three species of eridostracine are referred to *Cryptophyllus*, a genus with a global distribution and temporal range from the Ordovician to Carboniferous. Hollinoidean taxa, whilst endemic at the genus-level, show affinities with glossomorphitine and sigmoopsinae taxa from Europe.

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Keywords: ostracod, paleobiogeography, paleoecology, Silurian, stratigraphy, Vietnam

Introduction

The lower Paleozoic succession of northern Vietnam is a classical area for paleontology, first studied at the time of the French Colonial survey (e.g. Mansuy, 1915; Saurin, 1956). From the 1960s onwards there was renewed interest in these rocks (see Tong-Dzuy *et al.*, 2013 for a summary). Most recently a team of Vietnamese, Japanese, French and British scientists has begun the detailed evaluation of the paleontology of the Paleozoic rock formations of northern Vietnam including its graptolite (Rushton *et al.*, 2017), conodont (Komatsu *et al.*, 2018), shelly (Wong Hearing *et al.*, 2021) and palynological assemblages (Legrand *et al.*, 2021). Herein we describe a Silurian ostracod assemblage from the Si Ka Formation of northernmost Ha Giang Province (Figure 1). This is the first detailed record of a Silurian ostracod assemblage from Vietnam that includes systematic paleontological description of the taxa, comprising hollinoideans, beyrichioideans, eridostracines, paraparchitoideans, and two indeterminate palaeocopid species. We also document the environmental setting and assess the paleobiogeographical significance of the ostracods.

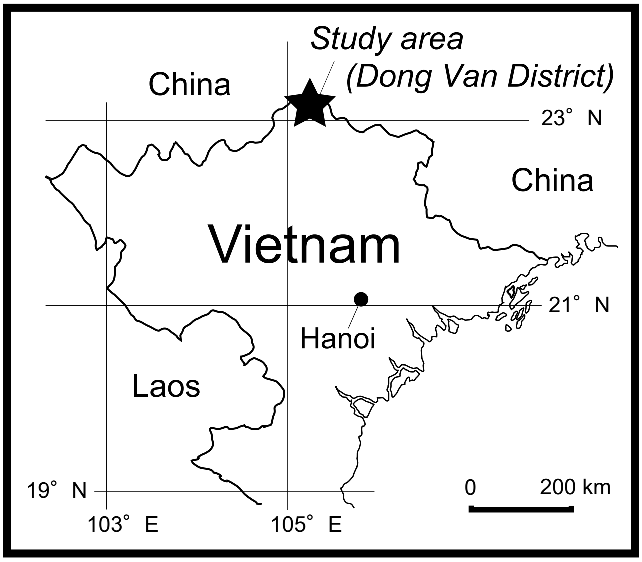

Figure 1. Geographical location of the Si Ka Formation in Dong Van District, Ha Giang Province, northern Vietnam.

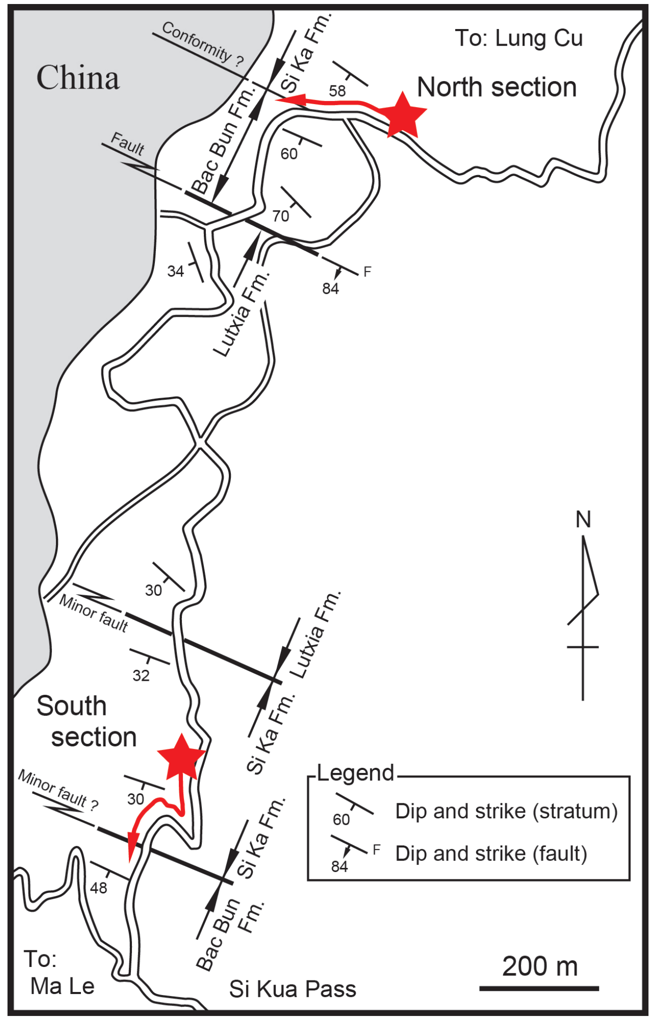

Figure 2. Geographical locus of the North and South sections through the Si Ka Formation, on the road between Ma Le and Lung Cu, Lung Cu commune, Dong Van District, Ha Giang Province, northern Vietnam. For simplicity here, the boundaries between the formations, including those associated with faults, are marked by straight lines.

Geological setting

The Si Ka Formation is exposed in the northernmost part of Vietnam, in Ha Giang Province on the border with China (Figures 1, 2). It was deposited in fluvial, estuarine and coastal settings during the late Silurian (Komatsu *et al.*, 2021), in a subtropical climate on the South China paleo-plate (Tong-Dzuy and Vu, 2011; Cocks and Torsvik, 2013). Structurally and lithostratigraphically, the Si Ka Formation lies in the eastern Bac Bo Zone that extends eastwards from the northwest–southeast trending Song Chay Fault, delimited to the south and east by the Quang Ninh Zone (Tong-Dzuy *et al.*, 2013).

Previously the Si Ka Formation has been considered of Early Devonian age, but recent palynological investigation has provided a refined late Silurian, late Ludlow to early Pridoli age (Legrand *et al.*, 2021), an assignment herein endorsed by one of the ostracods in the formation (see below). The Si Ka Formation unconformably overlies the lower Paleozoic Lutxia and Than Sa formations, and is succeeded by the shelf marine-deposited mudstones of the Lower Devonian Bac Bun Formation (Tong-Dzuy and Vu, 2011; Tran and Vu, 2011; Tong-Dzuy *et al.*, 2013). Collectively the Si Ka and Bac Bun formations have been included in the Song Cau Group.

The lower and middle part of the Si Ka Formation comprises red, pearl green and grey mudstones and sandstones that accumulated in fluvial and floodplain settings (Figures 3, 4). In contrast, the upper 25 m of the formation is dominated by organic-rich, dark grey mudstones intercalated with silty mudstone layers that represent estuarine deposits. It is these latter deposits (Figure 4) that contain ostracods, together with plant debris and palynomorphs, fragmentary fish bones, lingulid brachiopods, gastropods, bivalves and ichnofossils.

Material and methodology

Ostracods have been recovered from mudstone samples from eight horizons in the upper part of the Si Ka Formation (Figure 5), together with specimens from additional loose material collected adjacent to the outcrop but not localised to a specific horizon. Most of the

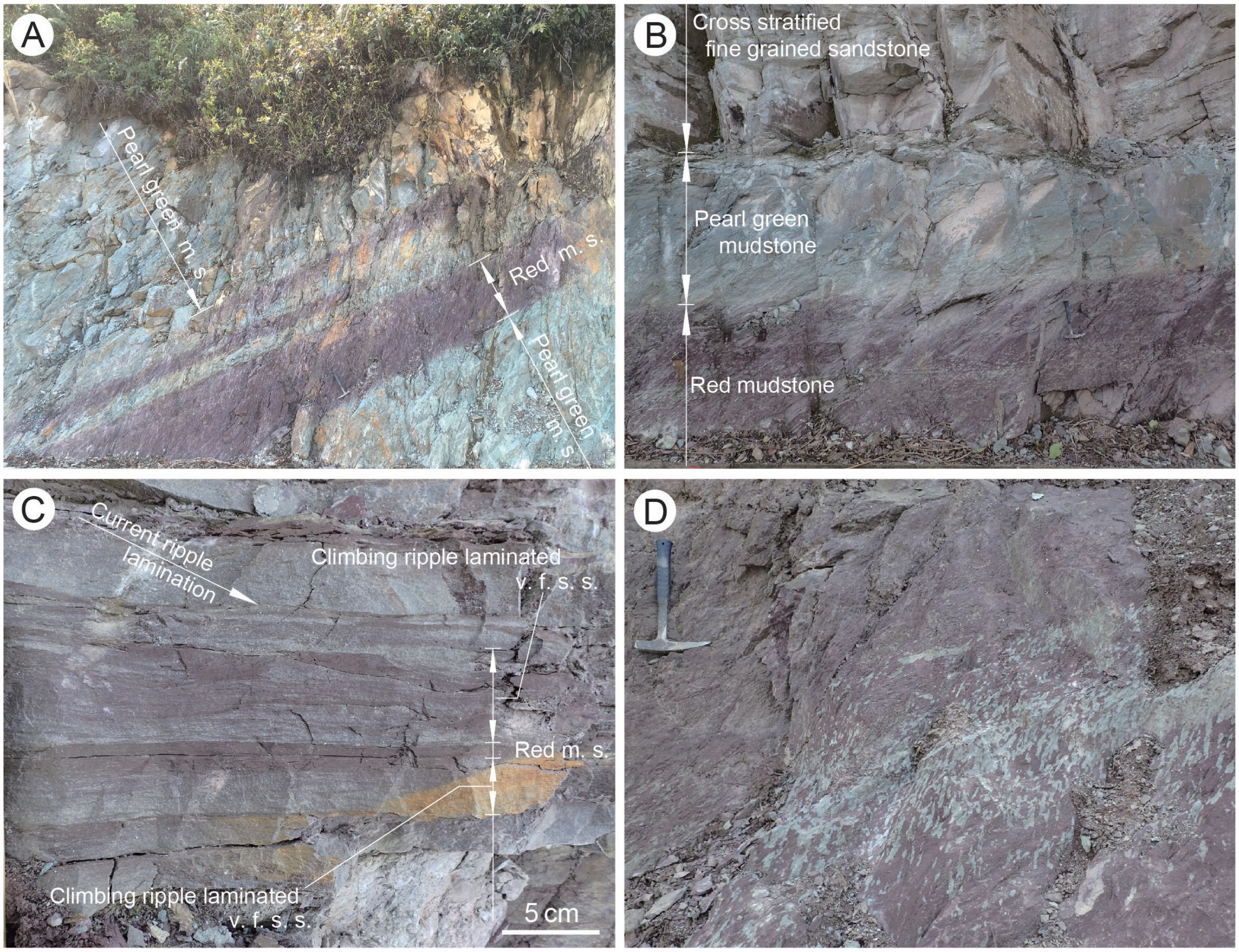

Figure 3. Sedimentology of the middle part of the Si Ka Formation in the South Section (A–D). **A,** vari-coloured floodplain mudstones; **B, C,** fluvial deposits representing channel fill cross-stratified sandstone and vari-coloured floodplain mudstones; **D,** well developed calcretes in floodplain deposits. Ostracods do not occur in these fluvial lithofacies. Hammer for scale in A, B and D is 33 cm long.

specimens are tectonically distorted, part obscured by the rock, or degraded by tropical weathering. The best ostracod specimens, preserved as decalcified moulds on rock slabs, were cast with the silicone rubber 'Silcoset 101' (method of Siveter, 1982). Due to the heavily weathered rock surface and high porosity the specimens were first consolidated using a solution of 1% 'Paraloid B-72' (available from ZOIC PALAEOTECH) in acetone. To further prevent the silicone from adhering to the specimen 'Ambersil HD' silicone release agent was applied to the consolidated surface prior to applying the Silcoset with a syringe. The resulting silicone casts were mounted on aluminium stubs (164 stubs in total) electronically coated with gold and stereo-images taken using a Hitachi S-3600N environmental scanning electron microscope in the University of Leicester School of Geography, Geology and the Environment. All ostracod fossils (rock slabs and SEM stubs), including those figured (with the prefix BT), are stored in the collections of the Geological Museum, General Department of Geology and Minerals of Vietnam (DGMV), Hanoi.

Systematic paleontology

by M. Williams, D. J. Siveter and H. Bush

Class Ostracoda Latrielle, 1802
Order Palaeocopida Henningsmoen, 1953

Remarks.—For a review of the morphology of early Paleozoic palaeocopids see Vannier *et al.* (1989). In discussing lobation and sulcation for the taxa documented here, we use the terminology L1–L4 (lobes 1 to 4, from anterior to posterior) and S1 to S3 (sulci 1 to 3 from ante-

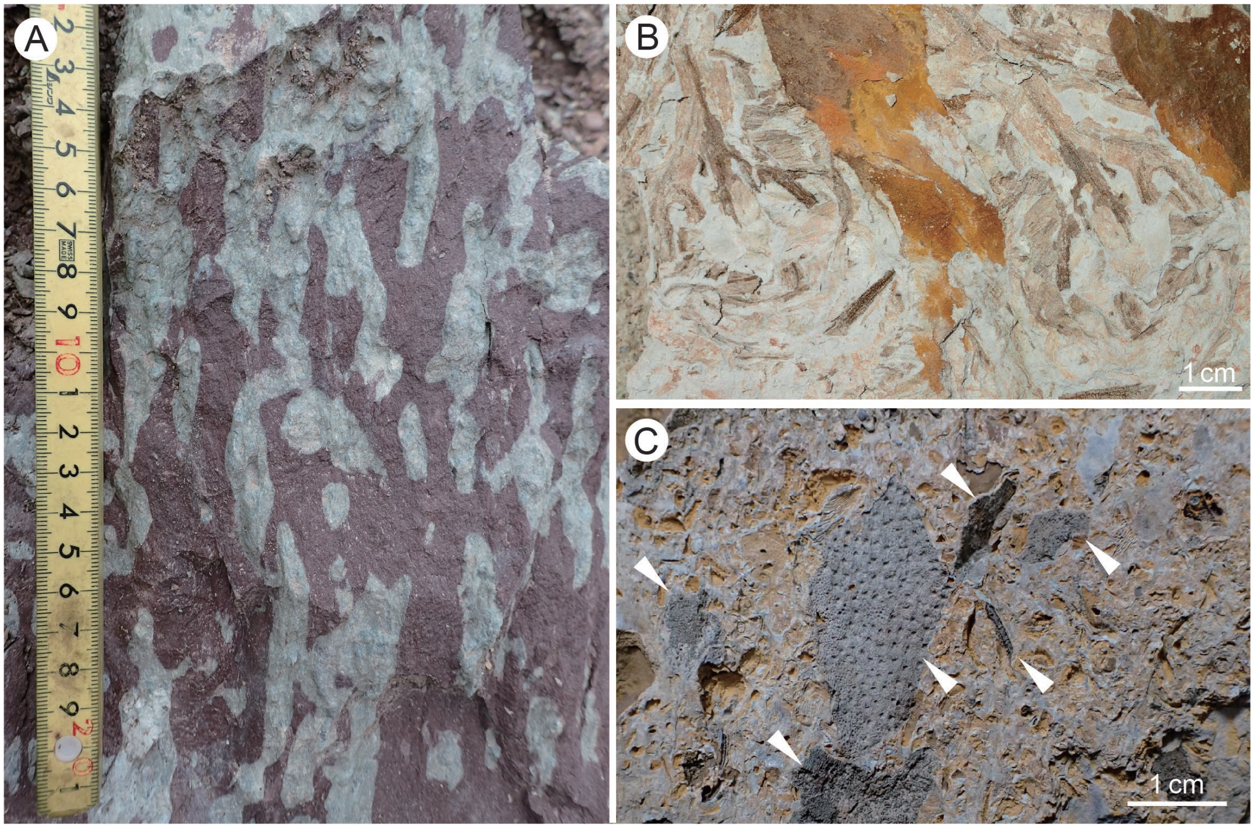

Figure 4. Sedimentology of the middle and upper Si Ka Formation in the South Section (A–C). **A,** branched tubular calcretes in flood-plain deposits; **B,** land plant debris in weathered organic mudstones; **C,** fragmented fish bones (arrowed) in pearl green mudstones. Ostracods occur in the fish and plant-bearing horizons.

rior to posterior). Using this approach, the anterior sulcus is S1 (between L1 and L2), the adductorial sulcus is S2 (between L2 and L3), and the posterior sulcus is S3 (between L3 and L4). L2 is often referred to as the preadductorial lobe/node (Vannier *et al.*, 1989, text-fig. 6).

Superfamily Hollinoidea Swartz, 1936
Family Tetradellidae Swartz, 1936
Subfamily Glossomorphitinae Hessland, 1954
Genus ***Cutympanum*** gen. nov.

ZooBank lsid: urn:lsid:zoobank.org:act:01BAF71B-5581-45EE-9C59-059395F9DF1C

Etymology.—Latin, *cuprum* (copper), and *tympanum* (drum), alluding to the traditional bronze drums of the Lo Lo people of northern Vietnam. The outcrop of the Si Ka Formation from which this species is derived is the Lung Cu - Ma Le section in the Lung Cu commune, Dong Van District, Ha Giang Province, where 90% of the people are Lo Lo. Gender neutral.

Type-species.—*Cutympanum hagiangensis* sp. nov., from the Si Ka Formation, northern Vietnam.

Diagnosis.—Bilobate to very weakly trilobate glossomorphitine, adductorial sulcus (S2) teardrop-shaped to weakly sigmoidal, anterior sulcus (S1) very weakly developed and essentially limited to the dorsal-most part of the valve, sometimes not apparent. Anterior lobe (L1) subdued. Preadductorial lobe (L2) elongate and extending from the dorsal border to become confluent ventrally with the broad anterior lobal area. Heteromorph velum expanded anteroventrally, ventrally and posteroventrally, separated from the lobal surface by a weak furrow.

Remarks.—*Cutympanum* bears comparison with several early Paleozoic glossomorphitines including *Vittella* Schallreuter, 1964, *Collibolbina* Schallreuter, 1967 and *Jeanlouisella* Vannier, 1986. All these genera are preplete, have a well-developed adductorial sulcus, and an expanded velum in heteromorphs. *Cutympanum* differs by possessing a weak anterior sulcus (S1) that subdivides the anterior lobal area in its dorsal part: in the former three genera there is a combined anterior lobal area (L1 and L2). *Cutympanum* differs from *Gracquina* Vannier, 1986 in the distinctly lower elevation of its lobes, its short

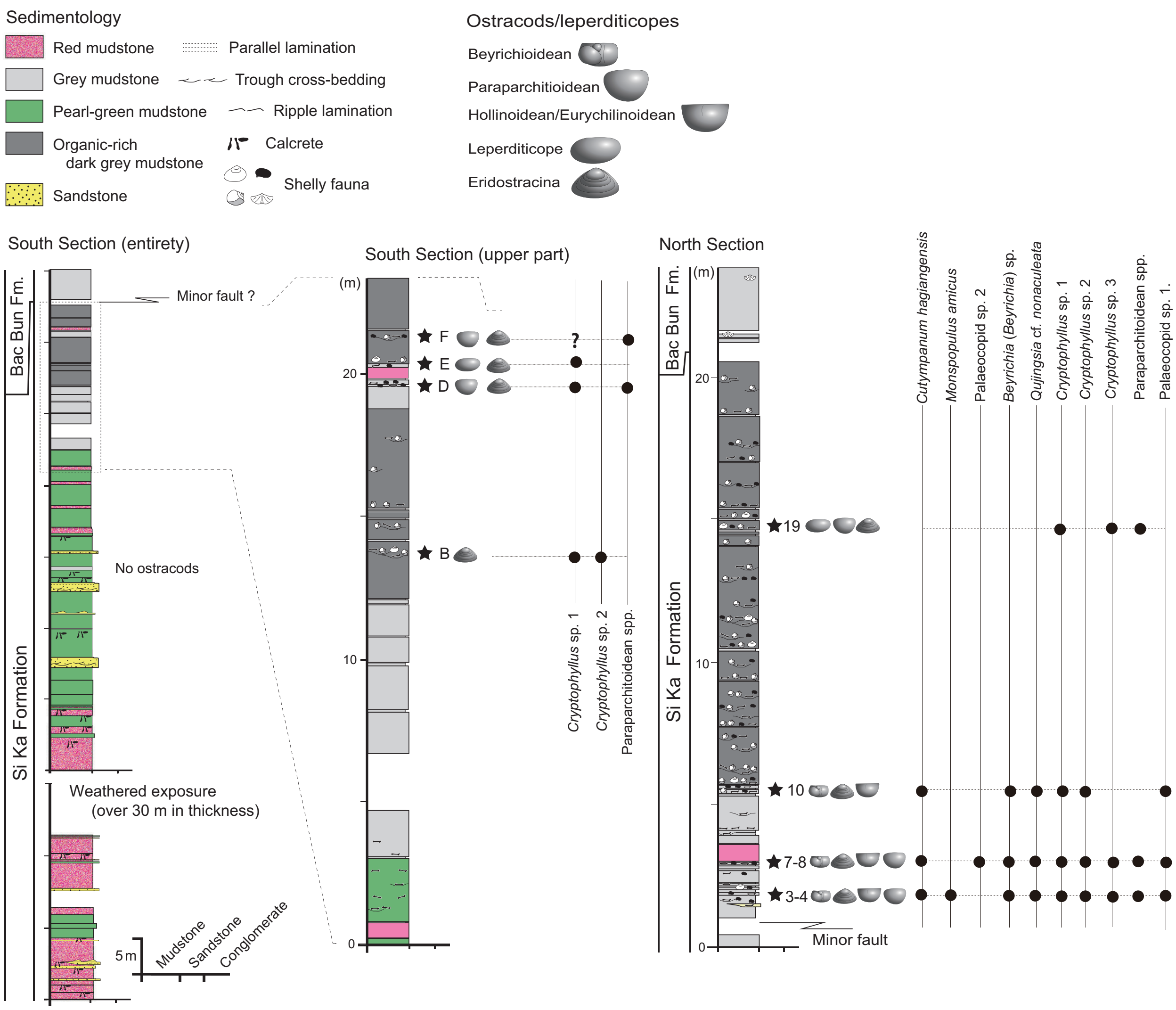

Figure 5. Stratigraphical distribution of the ostracods described herein, in the North and South sections of the Si Ka Formation. Black star indicates an ostracod-bearing horizon.

anterior sulcus (S1) and by lacking a well-developed posterior sulcus (S3).

Cutympanum hagiangensis sp. nov.

Figure 6A, C, E–G

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Hollinoidean sp. 1. McGairy *et al.*, 2021, fig. 2e.

Etymology.—From Ha Giang Province, northern Vietnam.

Holotype.—BT1/531d, Probable adult (tecnomorphic) left valve; length 1.6 mm, height 1.0 mm (Figure 6F). Horizon 3-4, North Section (Figure 2).

Material and measurements.—At least 20 valves from the North Section, horizons 3-4, 7-8 and 10 (Figure 5). Numbered specimens are BT1/531a, BT2/531a, BT3/531a, BT4/531a, BT6/531a. Length 0.8–2 mm, Height 0.5–1.2 mm (based on 16 specimens).

Diagnosis.—As for the genus (monospecific).

Description.—Lateral shape preplete. Pronounced, teardrop-shaped to weakly sigmoidal adductorial sulcus (S2), extends halfway from the dorsal margin towards the ventral margin. Preadductorial lobe (L2) small, distinct, confluent ventrally with broad anterior lobal area, but demarcated by a small anterior sulcus (S1) that is limited to the dorsal-most part of the valve. Posterior lobal area with small node immediately posterior of the adducto-

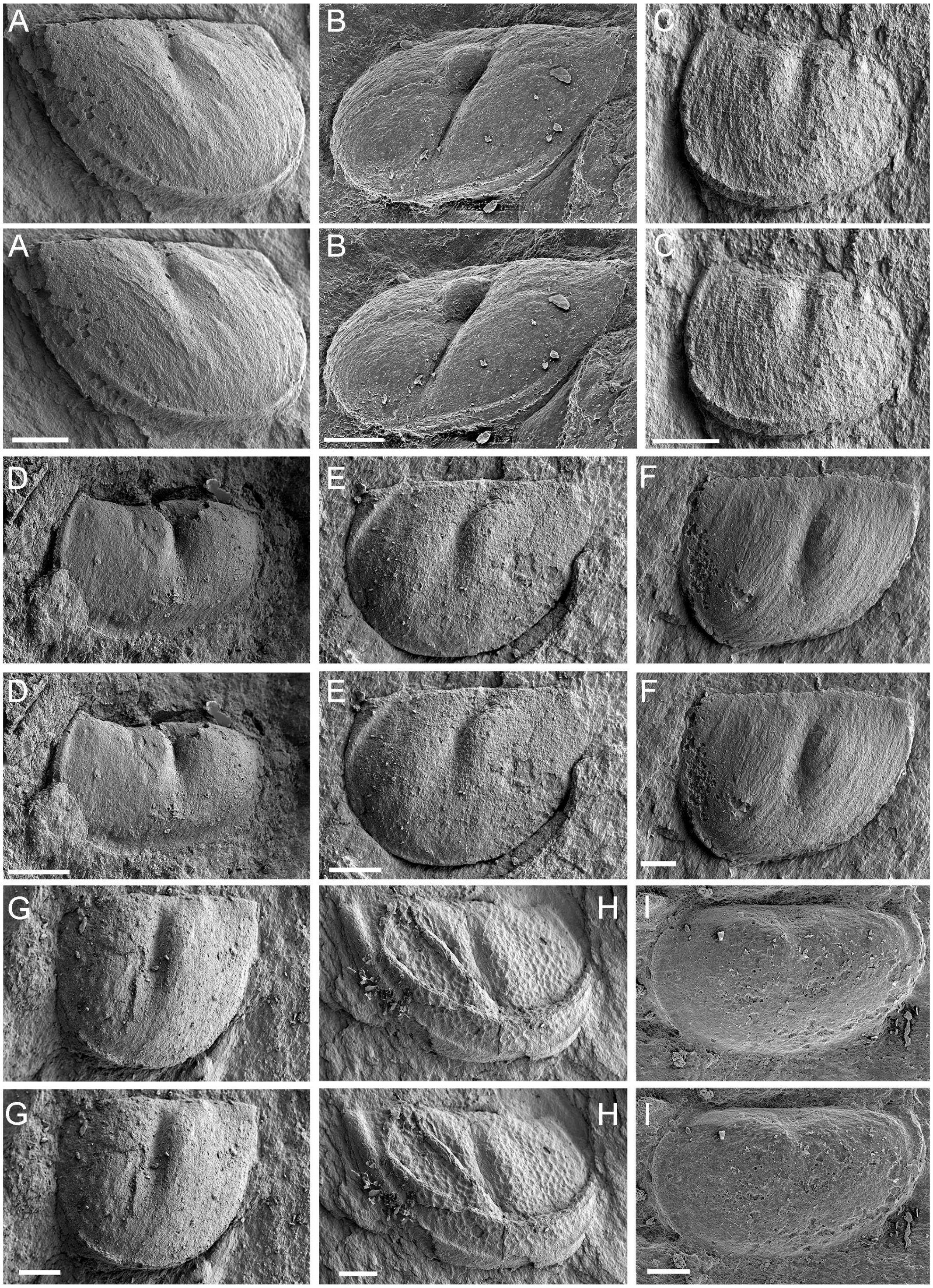

Figure 6. Hollinoidean (A–C, E–G, H), and indeterminate palaeocopid (D, I) ostracods from the Si Ka Formation, North Section. All images are stereo pairs. **A, C, E–G,** *Cutympanum hagiangensis* sp. nov.; A, lateral view of juvenile right valve (BT3/531a), horizon 3-4; C, lateral view of juvenile left valve (BT1/531a), horizon 3-4; E, lateral view of heteromorphic left valve (BT2/531a), horizon 3-4; F, lateral view of tecnomorphic left valve (BT4/531a, holotype), horizon 3-4; G, lateral view of juvenile left valve, tectonically shortened (BT6/531a), horizon 3-4; **B**, *Cutympanum*?, lateral view of juvenile left valve (BT17/531a), horizon 7-8; **D,** Palaeocopid sp. 2, lateral view of partially obscured tecnomorphic right valve (BT15/531a), horizon 3-4; **H,** *Monspopulus amicus* sp. nov., lateral view of tecnomorphic right valve (BT3/531b), horizon 3-4; **I,** Palaeocopid sp. 1, lateral view of left valve, horizon 3-4 (BT22/531a). All scale bars are 250 μm, except ‘I’, 200 μm.

rial sulcus. Velum narrow and entire in tecnomorph. Heteromorph velum broader anteroventrally, ventrally and posteroventrally (Figure 6E). Surface of valves unornamented.

Remarks.—The anterior sulcus is always weakly developed (Figure 6A, C) and sometimes is not evident (Figure 6E, F). Comparably aged faunas from China do not appear to contain glossomorphitines similar to *Cutympanum* (e.g. Jiang *et al.*, 1983; Wang, 1989). A preplete palaeocopid with a narrow velum, slit-like adductorial sulcus and more prominent preadductorial node might be a deformed specimen of *Cutympanum* (Figure 6B).

Subfamily Sigmoopsinae Henningsmoen, 1953
Genus ***Monspopulus*** gen. nov.

ZooBank lsid: urn:lsid:zoobank.org:act:B0A52670-4BE0-4825-BEB6-DD234216C649

Etymology.—Latin *mons* (mountain) and *populus* (people), alluding to the Lo Lo people being part of the Yi ethnic group that live in the mountain landscapes of northern Vietnam. Gender masculine.

Type species.—*Monspopulus amicus* sp. nov.

Diagnosis.—Quadrilobate sigmoopsinid; lobes L2 and L3 are well-developed either side of a deep, straight adductorial sulcus (S2). All lobes with characteristic low elevation. Well-developed histial ridge demarcates the ventral extension of the lobes and sulci. Velar ridge entire, demarcates lateral surface from broad ventral surface. Lateral and ventral surfaces reticulate.

Remarks.—We assign this species to Sigmoopsinae because it is quadrilobate, bears a distinctive histium that demarcates the ventral termination of the lobes and sulci, and is velate (see Meidla, 1996 for a definition of Sigmoopsinae). *Monspopulus* is most similar to *Pseudotallinnella scopulosa* Sarv, 1959, the type species of that genus, but differs in the distinctly lower elevation of its lobes, especially the anterior lobe (L1). Schallreuter (1979) and Meidla (1996) treated *Pseudotallinnella* as a subgenus and synonym of *Kiesowia* Ulrich and Bassler, 1908, respectively, based on the tendency of species to subdivide the lobes into discrete nodes. We do not see this tendency in the single specimen of *Monspopulus* described here.

Monspopulus amicus sp. nov.

Figure 6H

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Hollinoidean sp. 2. McGairy *et al.*, 2021, fig. 2i.

Etymology.—latin *amicus* (friend), referring to the Lung Cu commune.

Holotype.—BT3/531b, left valve; from the North Section, horizon 3-4 (Figure 5).

Material and measurement.—1 complete right valve (the holotype). Length 1.9 mm, height 1.1 mm.

Diagnosis.—As for the genus (monospecific).

Description.—Lateral shape preplete. Anterior lobe (L1) weakly developed and confluent ventrally with flat anterior lobal area. Anterior sulcus (S1) weak. Preadductorial lobe (L2) narrow, extends from dorsal margin to ridge-like histium. Adductorial sulcus (S2) long, extending more than half of the valve height from the dorsal margin to be terminated against the histium. Post-adductorial lobe (L3) extends from dorsal margin to histium, clearly demarcated posteriorly by the posterior sulcus (S3). Posterior lobe (L4) weakly developed and verging with histium. Histium is entire, extending anterodorsally to posterodorsally. It is wider ventrally especially mid-ventrally. Extra lobal area ventral to the histium. Velum narrow and entire. Lateral and ventral surfaces are reticulate.

Remarks.—The single known specimen of this species is well preserved and sufficiently distinct to enable the erection of a new taxon. The specimen has a narrow velum and is a probable tecnomorph.

Superfamily Beyrichioidea Matthew, 1886
Genus ***Beyrichia*** (***Beyrichia***) McCoy, 1846
Beyrichia (***Beyrichia***) sp.

Figure 7A–D, H, I, ?G

Beyrichioidean sp. 2. McGairy *et al.*, 2021, fig. 2h.

Material and measurements.—At least 16 tecnomorphic valves, all of which are tectonically distorted. Some valves are squat/antero-posteriorly compressed (Figure 7A–D), others are more elongate/dorso-ventrally compressed (Figure 7H, I). Numbered specimens are from the North Section, horizons 3-4, 7-8 and 10 (Figure 5), BT11/531b, BT13/531a, BT15/531b, BT18/531a, BT18/531b, BT18/531c, BT19/531a. Length 1.1–2.3 mm, height 0.7–1.3 mm (based on 9 specimens).

Description.—Syllobium is widest dorsally, with an anterior cusp and tiny posterior cusp just above the dorsal margin. Syllobium narrows ventrally and has a well-marked callus and syllobial groove. The latter continues, below a zygal arch joined to a well-developed preadductorial node (L2), to its confluence with a narrow prenodal sulcus. Anterior lobe is fairly flat, has a cusp posteriorly projecting above the dorsal margin; ventrally has a wide connection with the syllobium. Velar ridge is more or less of constant width between cardinal corners. All lobes

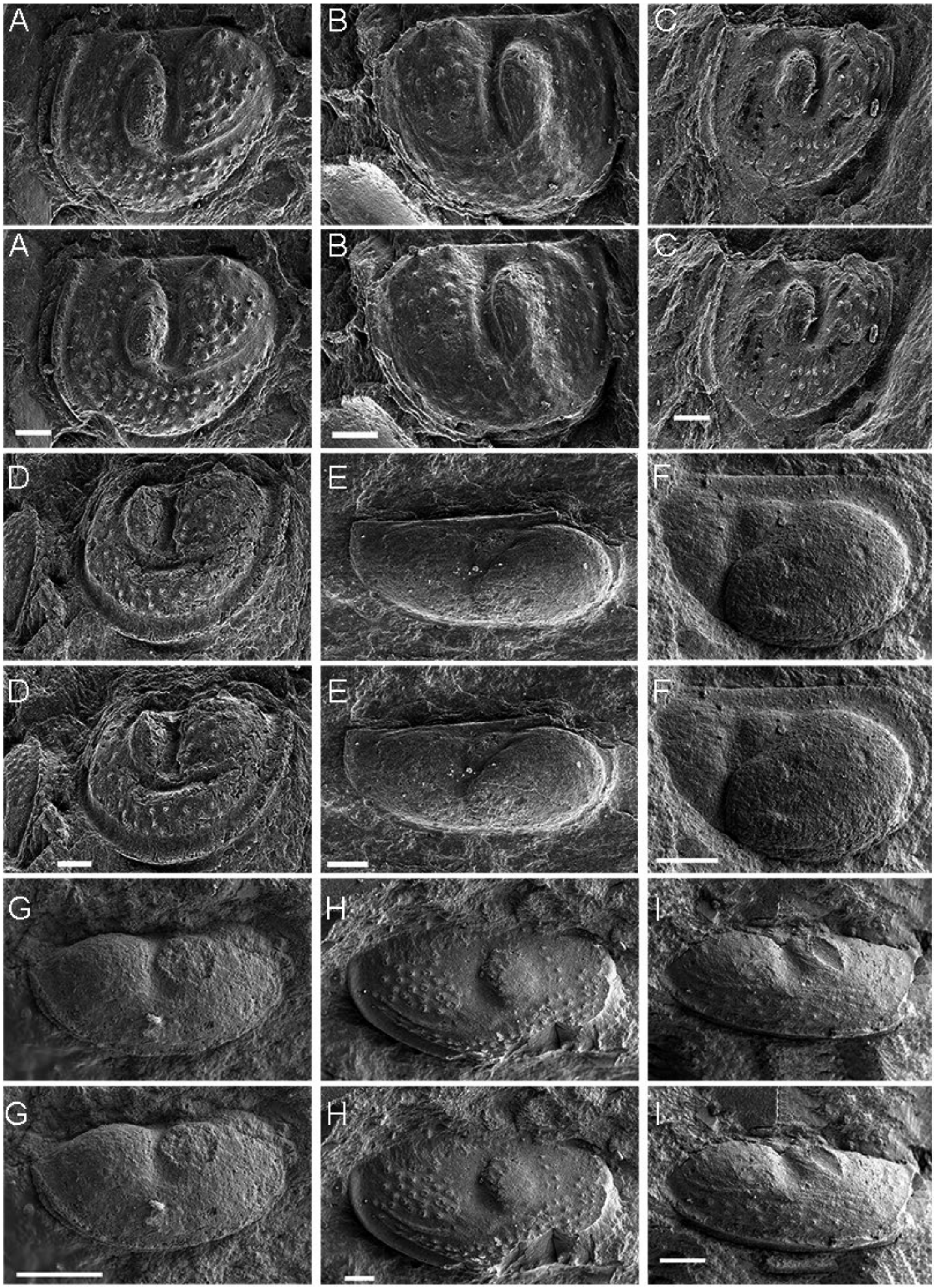

Figure 7. Beyrichioidean ostracods (A–I) from the Si Ka Formation, North Section. All images are stereo pairs. **A–D, G–I,** *Beyrichia* (*Beyrichia*) sp., all tecnomorphs: A, lateral view of left valve (BT18/531a), horizon 7-8; B, lateral view of right valve (BT19/531a), horizon 10; C, lateral view of left valve (BT18/531b), horizon 7-8; D, lateral view of left valve (BT18/531c), horizon 7-8; G, lateral view of right valve (BT11/531b), horizon 7-8; H, lateral view of right valve (BT13/531a), horizon 7-8; I, lateral view of right valve (BT15/531b), horizon 7-8; **E, F,** *Qujingsia* cf. *nonaculeata* Hansch and Wang, 1991; E, lateral view of heteromorphic right valve (BT10/531a), horizon 3-4; F, lateral view of heteromorphic right valve, partly obscured (BT11/531a), horizon 7-8. Scale bar: 250 μm.

evenly covered with tubercles.

Remarks.—The overall lobal morphology of this species is that of *Beyrichia* (*Beyrichia*). The occurrence of a well-developed zygal arch clearly also recalls species of *Beyrichia* (*Scabribeyrichia*) Martinsson, 1962 and *Eobeyrichia* Henningsmoen, 1954, taxa in which the zygal arch is evident in adult tecnomorphs and even in heteromorphs. The Si Ka material contains no confirmed heteromorphs and the species is currently best assigned to *Beyrichia* (*Beyrichia*). One of the figured valves (Figure 7G) shows scant ornament, possibly due to factors of preservation; it is probably conspecific with the other figured *Beyrichia* (*Beyrichia*) specimens. *Beyrichia* is ubiquitous in the Silurian of many parts of Europe, especially the Baltic and Britain, and also the Russian Federation. The genus is also known in, for example, the Silurian of northwestern, Arctic and eastern maritime areas of N America, and China. In the morphology of its lobes and zygal arch, there is some similarity with the single specimen of Lower Devonian *Craspedobolbina* sp. 1 described from Guangxi Province by Wang (1989), except that specimen is reticulate as opposed to the tuberculate ornament of the Vietnamese material.

Genus ***Qujingsia*** Hansch and Wang, 1991
Qujingsia cf. ***nonaculeata*** Hansch and Wang, 1991

Figure 7E, F

Beyrichioidean sp. 1. McGairy *et al.*, 2021, fig. 2g.

Material and measurements.—Two heteromorph specimens: an almost complete right valve (Figure 7E) and the anterior half of a right valve (Figure 7F), from horizons 3-4 and 7-8 (Figure 5), numbers BT10/531a and BT11/531a respectively. A juvenile specimen (not numbered) from horizon 3-4 (rock slab RG046). Length of specimen BT10/531a is 1.5 mm. A larger specimen from horizon 3-4 (rock slab RG014) measures 1.8 mm long. This species is also known from horizon 10 in the North Section (Figure 5).

Description.—Carapace is elongate; lobes are relatively flat. Syllobium is wide, gently and evenly curved at the dorsal margin. Adductorial sulcus is narrow. The crumina is large, anteroventral, developed entirely within the lobal area, substantially encroaches onto the preadductorial node and anterior lobe, extends close to dorsal margin. Velum is narrow, flange-like either side of the crumina, and is possibly continuous subcruminally. No ornament evident on lobes, crumina or velum.

Remarks.—One of the most taxonomically significant features of this species is its cruminal morphology. The crumina is large, anteroventral, entirely developed within the lobal area and subcruminally the velum may well be continuous and completely unaffected by the crumina (it is difficult to confirm that aspect with the limited material available).

The material from the Si Ka Formation is most similar to the late Silurian *Qujingsia nonaculeata* Hansch and Wang, 1991 from the Kuanti and Miaokao formations of Yunnan Province, southern China. The Vietnamese material is also of similar age (Ludlow–Pridoli) to the Chinese species. The Vietnamese material may well be conspecific; only the limited amount of material (there being no tecnomorphs and lack of knowledge of subcruminal morphology) prevents a firm attribution. It is also similar to the Lower Devonian (Lochkovian–Pragian) *Beyrichia* (*Beyrichia*) *cuifengshanensis* Jiang *in* Jiang *et al.*, 1983, from the Xitun Formation of China and the Lower Devonian (Lochkovian) *Qujingsia* sp. from the Khao Loc Formation, of Tong Vai, Ha Giang Province, Vietnam (Racheboeuf *et al.*, 2005).

The overall morphology of this species also recalls a complex of genera typified by "*Kloedenia*" of traditional American usage (e.g. Swartz and Whitmore, 1956; Berdan, 1972), many of which were included in the Welleriellidae Abushik, 1971 (also Abushik, 1990). The Si Ka species recalls, for example, '*Zygobeyrichia*' *dubia* Abushik, 1971 from the Lower Devonian of Ukraine and especially *Kloedeniopsis hartnageli* Berdan, 1972 from the upper Silurian (Pridoli) of New York. It differs from such forms, inter alia, by its more subdued lobation and more expansive crumina.

Family Uncertain

Palaeocopid sp. 1

Figure 6I

Material and measurements.—At least 8 valves from horizons 3-4, 7-8, 10. Length 0.9–1.8 mm, height 0.5–0.8 mm (based on three specimens).

Description.—Amplete to weakly preplete and elongate, unisulcate palaeocopid with strongly convex anterior and posterior lobal areas and a flattened marginal rim.

Remarks.—These specimens bear resemblance to the North American Ordovician taxon *Ectoprimitoides* Berdan, 1988 (see for e.g. Williams and Siveter, 1996, fig. 7e). There is also a superficial resemblance to the European Ordovician taxon *Bolbina* Henningsmoen, 1953, but there is no evidence of domiciliar dimorphism in the specimens we have examined. Pending further and better-preserved material the taxon is described in open nomenclature.

Palaeocopid sp. 2

Figure 6D

Eurychilinoidean sp. McGairy *et al*., 2021, fig. 2f.

Material and measurement.—BT15/531a, anteriorly incomplete (partially obscured) tecnomorph, right valve from the North Section, horizon 7-8 (Figure 5). Length 0.8 mm, height 0.6 mm.

Description.—Amplete, very weakly bisulcate. Anterior lobal area broadly convex. Adductorial sulcus (S2) pronounced and deep, extends ventrally from the dorsum to a little less than half the valve height. Weak posterior sulcus (S3) subdivides the posterior lobal area in its dorsal portion. Valves velate, narrow at posterodorsal corner, broadening ventrally where it becomes distinctly concave. Termination point of velum anteriorly is uncertain. No dolonal antrum visible, therefore considered to be a tecnomorph. Valve surface smooth.

Remarks.—The single right valve resembles eurychilinoideans because it possesses a well-developed adductorial sulcus, gently inflated posterior and anterior lobal areas, and a velum which broadens ventrally where it becomes distinctly concave (compare with material described by Kesling, 1960). However, the single valve has too few characters for a firm assignment.

Order Uncertain

Eridostracina Adamczak, 1961 emend. Olempska, 2012

Remarks.—These supposed ostracods show moult retention (see Olempska, 2012). This is the first record of eridostracines from the Paleozoic of Vietnam.

Family Cryptophyllidae Adamczak, 1961 (=? Rhabdostichidae Rusconi, 1954)

Genus ***Cryptophyllus*** Levinson, 1951

Remarks.—There are a multitude of lower and middle Paleozoic species referred to *Cryptophyllus* (for a review see Olempska, 2012), from regions as far apart as North America (Harris, 1957), China (Song *et al*., 2017), and Australia (Jones, 1962). These are characterised by moult retention, and in the case of *Cryptophyllus* the individual lamellae are simple and unmodified. *Cryptophyllus* species show variation according to number of lamellae retained and overall shape (amplete, postplete, elongate) that is evident in the three species from the Si Ka Formation (Figure 8). Because of the general simplicity of *Cryptophyllus* carapaces, their lack of diagnostic characters, and the poor preservation of the Vietnamese specimens that show no details of the hinge, muscle scars or other structures, we avoid describing the specimens with formal names.

Cryptophyllus sp. 1

Figure 8A, D, E

Eridostracine sp. 1. McGairy *et al*., 2021, fig. 2a.

Material and measurements.—At least 21 valves, from horizons 3-4, 7-8, 19, B, D, E, and possibly F (Figure 5). Numbered specimens are: BT5/531a, BT14/531a, BT20/531a. Length 1.5–2.1 mm, height 0.8–1.5 mm (based on 10 specimens).

Description.—Ovate, amplete from lateral view. Up to 6 lamellae retained, typically ranging from 2 to 6: individual lamellae are simple without ventral ridges or rims. Weak umbo, surface lacks ornament.

Remarks.—The ovate amplete shape of this species recalls *Cryptophyllus* species such as *C. ovalis* (Eichwald, 1860).

Cryptophyllus sp. 2

Figure 8F–I

Eridostracine sp. 2. McGairy *et al*., 2021, fig. 2c.

Material and measurements.—At least 7 valves, from horizons 3-4, 7-8, 10, B (Figure 5). Numbered specimens are: BT7/531a, BT8/531a, BT12/531a, BT16/531a. Length 1.4–2.3 mm, height 0.8–1.3 mm (based on 7 specimens).

Description.—Elongate, amplete lateral shape. Up to 5 lamellae retained, typically 4 to 5 lamellae: individual lamellae are simple. Weak umbo. No surface ornament.

Remarks.—An elongate amplete shape is evident already in Ordovician *Cryptophyllus* from the Oil Creek Formation of Oklahoma (Harris, 1957).

Cryptophyllus sp. 3

Figure 8B, C

Eridostracine sp. 3. McGairy *et al*., 2021, fig. 2b.

Material and measurements.—At least 7 valves, from horizons 3-4, 7-8 and 19 (Figure 5). Numbered specimens are: BT9/531a, BT9/531b. Length 1.3–2.5 mm, height 1.1–1.5 mm (based on 6 specimens).

Description.—Elongate posteriorly with postplete lateral shape. Up to 7 lamellae retained; individual lamellae are simple without ventral ridges and rims. Umbo weak. Surface lacks ornament.

Remarks.—A number of *Cryptophyllus* taxa have a postplete shape. In that sense the Vietnamese material

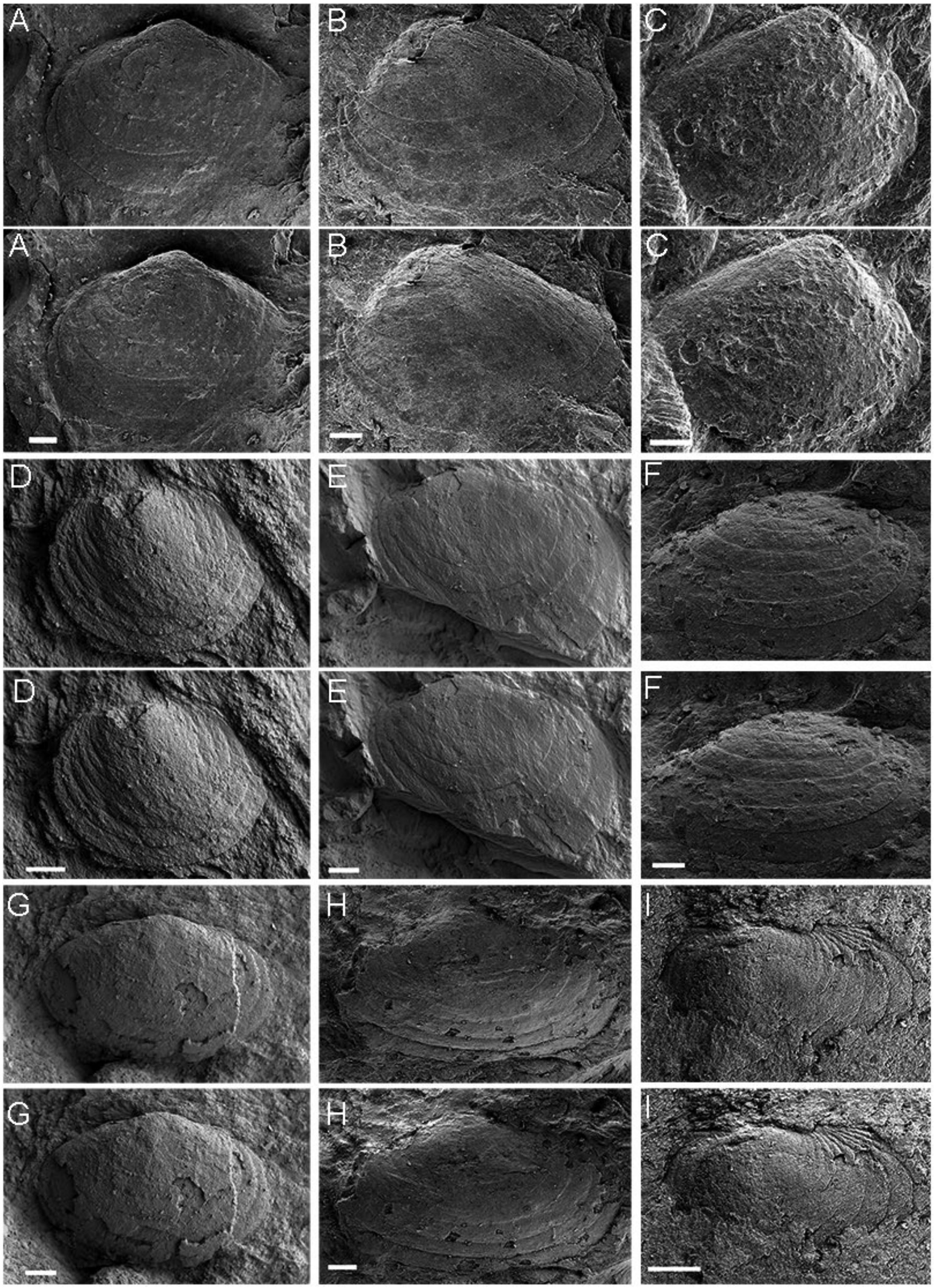

Figure 8. Eridostracine ostracods (A–I) from the Si Ka Formation, North Section. All images are stereo pairs. **A, D, E,** *Cryptophyllus* sp. 1; A, lateral view of valve (BT20/531a), horizon 19; D, lateral view of valve (BT5/531a), horizon 3-4; E, lateral view of valve (BT14/531a), horizon 7-8; **F–I,** *Cryptophyllus* sp. 2: F, lateral view of valve (BT7/531a), horizon 3-4; G, lateral view of valve (BT16/531a), horizon 7-8; H, lateral view of valve (BT8/531a), horizon 3-4; I, lateral view of valve (BT12/531a), horizon 7-8; **B, C,** *Cryptophyllus* sp. 3; B, lateral view of left valve (BT9/531a), horizon 3-4; C, lateral view of right valve (BT9/531b), horizon 3-4. Scale bar: 250 μm.

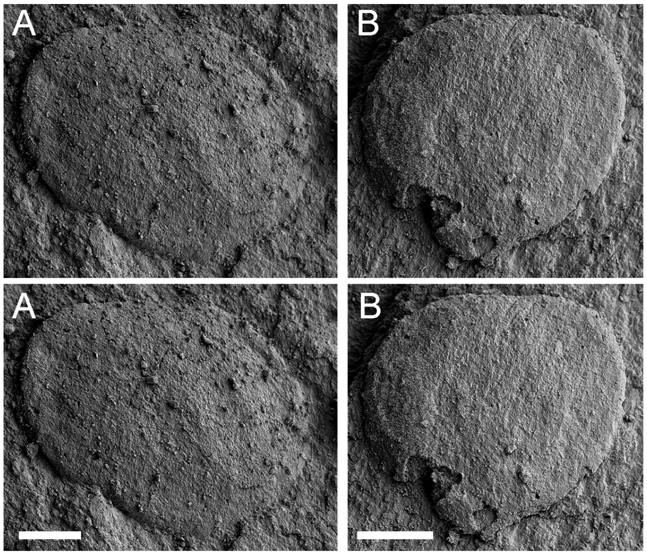

Figure 9. Paraparchitoidean ostracods (A, B) from the Si Ka Formation, North Section. Both images are stereo pairs. **A, B,** Paraparchitoidean sp. 1; A, lateral view of right valve, BT21/531a, horizon 3-4; B, lateral view of left valve, BT21/531b, horizon 3-4. Scale bar: 250 μm.

recalls, for example, *Cryptophyllus* sp. from the Early Devonian of Novaya Zemlya, which is considered to be a component of a restricted marine-shelf assemblage (Abushik and Evdokimova, 1999).

Paraparchitocopa Gramm (*in* Gramm and Ivanov), 1975
Superfamily Paraparchitoidea Scott, 1959, emended Sohn, 1971
Family Paraparchitidae Scott, 1959
Paraparchitoidean sp. 1

Figure 9A, B

Paraparchitoidean sp. McGairy *et al*., 2021, fig. 2d.

Material and measurements.—Multiple specimens from horizons 3-4, 7-8, 19, D, F, and from loose material at an adjacent outcrop. Numbered specimens are BT21/531a,b. Length 0.6–1.8 mm, height 0.5–1.5 mm (based on 9 specimens). Some much larger specimens, measuring 2.3–3.0 mm long and 2.0–2.2 mm high (3 specimens), may be referable to this species.

Description.—Simple, non-lobate, unornamented, weakly preplete valves, with a straight to gently arched dorsal margin. No marginal structures.

Remarks.—Many valves appear to have suffered post-mortem compaction. In its simplicity, this taxon resembles the approximately contemporaneous '*Rozhdestvenskayites*' cf. *auriculiferus* from the late Silurian (Pridolian) of Nevada, USA (Stone and Berdan, 1984). In lacking spines, it is also reminiscent of *Chamishaella* Sohn, 1971. The absence of carapaces means that we are unable to determine dorsal and ventral valve overreach and overlap relationships.

This taxon is present in deposits interpreted as lower estuary, ostracod assemblage 1 (e.g. horizons 3-4, 7-8), and central estuary, ostracod assemblage 2 (e.g. horizon 19; see 'Paleoecology', below). Paraparchitoideans are known from marine deposits of the Silurian (Stone and Berdan, 1984) and Devonian (Jones, 2004). They are widespread in brackish and shallow marine settings of the Carboniferous (Dewey *et al.*, 1990; Dewey and Puckett, 1991; Tibert and Scott, 1999).

Discussion

Paleoecological setting of the ostracods

The sedimentary deposits of the Si Ka Formation are interpreted as fluvial and estuarine (Figures 3, 4; Komatsu *et al.*, 2021; McGairy *et al.*, 2021). Ostracods occur in the upper part of the Si Ka Formation in estuarine deposits (Figures 4, 5). These contain an assemblage of land plants and a microflora of trilete spores (Legrand *et al.*, 2021), together with a fauna of fish, bivalves, gastropods, leperditicope arthropods and rare lingulid brachiopods. Typical stenohaline marine indicators, such as acritarchs, corals, trilobites, rhynchonelliform brachiopods and cephalopods are absent. By comparison with fully marine ostracod assemblages of the Silurian (e.g. see Siveter, 1984, 2009; Lundin *et al.*, 1991), the diversity of the Si Ka Formation is low, with about 10 species. There is an absence of podocopine ostracods (see Lundin *et al.*, 1991; Hairapetian *et al.*, 2011) that are typical of fully marine settings of the Silurian. Therefore, the Si Ka ostracods were adapted to coastal and estuarine settings (McGairy *et al.*, 2021). Although beyrichioideans (Figure 7) are typically fully marine ostracods in the Silurian, they are known from marginal marine facies in late Silurian (Miller, 1995; Miller *et al.*, 1997; Floyd and Williams, 2003; Molyneux *et al.*, 2008), and Devonian settings (Knox and Gordon, 1999; Racheboeuf *et al.*, 2005) suggesting some were euryhaline. Eridostracines (Figure 8) are known from littoral settings of the Devonian (Bless, 1983; Olempska, 2012; Song *et al.*, 2017). The ostracod assemblages of the Si Ka Formation were resolved into two assemblages by McGairy *et al.* (2021), a higher diversity assemblage (of up to 10 species, horizons 3-4, 7-8, 10, Figure 5) with beyrichioideans that suggests more marine influence and may be lower estuary, and a lower diversity assemblage (horizons 19, B, D–F, Figure 5) of eridostracines and paraparchitoideans, occurring in facies that may be central estuary. There is overlap in spe-

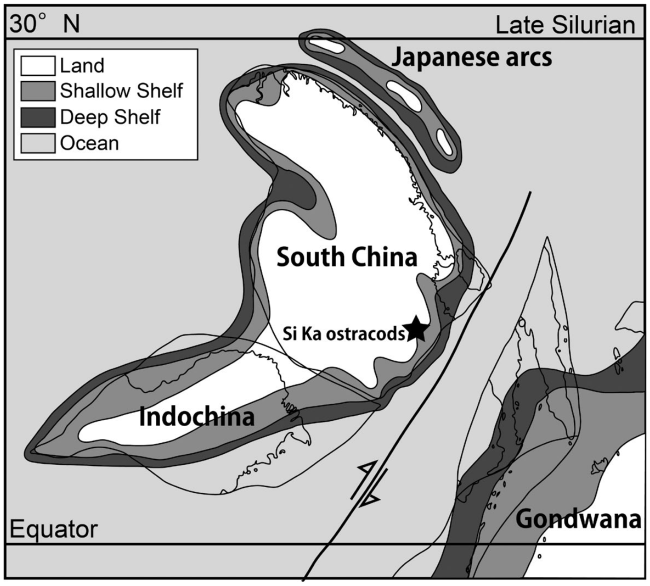

Figure 10. Paleogeography of East Asia in the late Silurian (late Ludlow), with location of the Si Ka ostracod assemblage marked (map modified from Cocks and Torsvik, 2013 and Legrand *et al*., 2021).

cies between these two assemblages, notably the eridostracines and paraparchitoideans, suggesting a range of salinity tolerance.

Paleobiogeography

Traditionally, ostracods have been used as tools for defining early Paleozoic geography, based on their shelf marine habitats and apparently limited capacity for transoceanic dispersal (Schallreuter and Siveter, 1985; Siveter, 1989; Williams *et al.*, 2003). However, more recent studies have noted some surprising paleobiogeographical connections, for example, the occurrence of typical North American taxa in the early Silurian of Iran (Hairapetian *et al.*, 2011), the only Silurian occurrences of the genus *Hollinella* in Japan and the USA (Siveter *et al.*, 2019), and the presence of North American and European taxa in the Late Ordovician faunas of Northwest China (Song *et al.*, 2020), suggesting that some taxa were clearly capable of wider dispersal.

During the late Silurian, Vietnam was a component of the South China paleo-plate and was situated in the subtropics (Cocks and Torsvik, 2013; Figure 10). A previous record of Late Ordovician ostracods from the Phu Ngu Formation of the Nari District in northeast Vietnam recorded a small fauna assignable to the genera *Kinnekullea* and *Laterophores* (Wong Hearing *et al.*, 2021), which are typical of European Ordovician successions. At the generic level, the fauna of the Si Ka Formation also contains some cosmopolitan taxa, most notably the eridostracine *Cryptophyllus*—a globally distributed genus that first occurs in the Ordovician of the USA (e.g. Harris, 1957), and persists until the Carboniferous, for example in Australia (Jones, 1962)—and the widespread beyrichioidean *Beyrichia* (*Beyrichia*), known widely from Europe, North America and China. Although the other taxa of the Si Ka Formation are endemic at the generic-level, or too poorly preserved to reveal wider biogeographical affinities, the presence of hollinoideans that bear comparison with European glossomorphitine and sigmoopsine taxa is notable.

At the species-level, *Qujingsia* cf. *nonaculeata* may well be conspecific with Chinese material from the upper Silurian Kuanti and Miaokao formations of Yunnan Province, China (Hansch and Wang, 1991), supporting the paleogeographical connection of northern Vietnam with South China during the Silurian (Figure 10). *Qujingsia* is also known from the Lower Devonian of northern Vietnam (Racheboeuf *et al.*, 2005). Beyond that, there are few affinities between the Silurian faunas described here, and elsewhere in Asia, for example those of the complex terranes of central Asia (Mikhailova and Siveter, 2021), Turkey (Nazik *et al.*, 2018), Japan (Siveter *et al.*, 2019), Iran (Hairapetian *et al.*, 2011) and the Eurasian Arctic (Abushik and Evdokimova, 1999). This might reflect that several of the Vietnamese ostracod species were adapted to estuarine settings, and thus may have had limited dispersal possibilities in open marine habitats.

As Silurian ostracods are so far unreported elsewhere in Vietnam, we cannot make comparisons with the fossiliferous Silurian formations south of the Ma River Suture Zone, which is the structural demarcation between the early Paleozoic 'South China' and 'Indochinese' paleoplates (Tran, 1995 and references therein). However, we might expect there to be future discoveries of ostracods from the extensive lower Paleozoic deposits of central Vietnam.

Conclusions

A low diversity ostracod fauna from the Silurian Si Ka Formation of northern Vietnam is reported. The fauna comprises 10 species, two new hollinoideans, *viz* the glossomorphitine *Cutympanum hagiangensis* gen. et sp. nov., and the sigmoopsine *Monspopulus amicus* gen. et sp. nov., two indeterminate palaeocopid species, three species of the eridostracine *Cryptophyllus* described in open nomenclature, two species of beyrichioidean, namely *Beyrichia* (*Beyrichia*) sp. and *Qujingsia* cf. *nonaculeata,* and a paraparchitoidean. This fauna represents the earliest well-documented example of ostracods colonising an estuary (McGairy *et al.*, 2021).

The ostracod assemblage contributes to a broader understanding of the faunal diversity of the early Paleozoic assemblages of the South China paleo-plate and builds on previous work documenting ostracods from the Ordovician (Wong Hearing *et al.*, 2021) and Lower Devonian (Racheboeuf *et al.*, 2005) of Vietnam. *Qujingsia* cf. *nonaculeata*, may well be the same as the Chinese species *Q. nonaculeata* and therefore supports a Ludlow–Pridoli age for the Vietnam fauna and supports the supposed paleogeographic position, on the south China plate, of the Vietnam region in question. Beyond that, no clear biogeographical affinity can be identified for the Vietnam ostracods as the fauna contains genera that are widespread, such as *Cryptophyllus* and *Beyrichia* (*Beyrichia*), or comprises endemic taxa.

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Electronic material

ZOIC PALAEOTECH. Fossil preparation tools and supplies. Available from: https://www.zoicpalaeotech.co.uk/

Author contributions

MW, DJS, HB and AM undertook the fossil identifications. TK, PDN, MW, THPH, TY, JL and CGM initiated the project and collected the ostracods. HB, AM, RHG, CPS gathered images of the fossils. TK produced Figures 1–4; AM drafted Figure 5. CPS, RHG and HB drafted Figures 6–9; JL drafted figure 10. MW, TK, PDN, DJS and AM prepared the manuscript with contributions from all authors. All authors agree to be accountable for the final draft of the manuscript.