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First record of ostracods from the Upper Ordovician red-coloured marine sandstones of the Tierenkeawati Formation in Tarim Basin, NW China: implications on palaeoenvironment and palaeobiogeography

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Abstract

Ostracods are described for the first time from the red-coloured marine sandstones of Arisu section (Arisu red beds) of the Upper Ordovician Tierenkeawati Formation in Kalpin area of northwestern Tarim Basin, Xinjiang Uygur Autonomous Region (Xinjiang), Northwest China. Twenty-two species belonging to thirteen genera are described and figured. The ostracod fauna suggests a probable Sandbian–Katian age for these beds. The palaeoecological assemblage of ostracod fauna implies the deposition in a nearshore-offshore environment during a regression when the Arisu red beds of the Tierenkeawati Formation were laid down in the Tarim Basin. Many cosmopolitan and provincial genera were present in diversified ostracod fauna of the Arisu red beds, suggesting the possible biogeographic relationships among the Tarim, Tibet, and South China plates, as well as Europe and North America continents during the Late Ordovician. Ostracods experienced faunal exchanges between Laurentia and the Tarim Plate during the Late Ordovician Period.

Keywords: Ostracods, Late Ordovician, Arisu section, Tierenkeawati Formation, Kalpin area, Tarim Basin, GOBE, STTS

1 Introduction

Ostracods are one of the most widespread and diverse group of crustaceans since the Early Ordovician and are still thriving today (Horne et al. 2002; Siveter 2008). After the origin of the clade, ostracods experienced critical turnover of composition in the Late Ordovician Period, which is also considered to be a key interval for the Great Ordovician Biodiversification Event (GOBE)

and the Paleozoic Evolutionary Fauna (Frey et al. 2004). Ordovician time was one of the favorable periods for ostracods, particularly in marine environments, from coastal sea to deep sea settings. They play an important role in stratigraphic subdivisions and consequently for biogeographic correlations (e.g., Swain 1957; Tinn and Meidla 2002; Mohibullah et al. 2011; Salas 2011; Taha 2018). Moreover, ostracods are one of the best fossils to reconstruct palaeoenvironment and palaeogeography of the Ordovician (e.g., Williams et al. 2003; Landing et al. 2013; Taha 2018; Zhang et al. 2018) due to their sensitivity to ambient factors such as oxygenation, salinity, bathymetry, temperature, hydrodynamics and nutrients.

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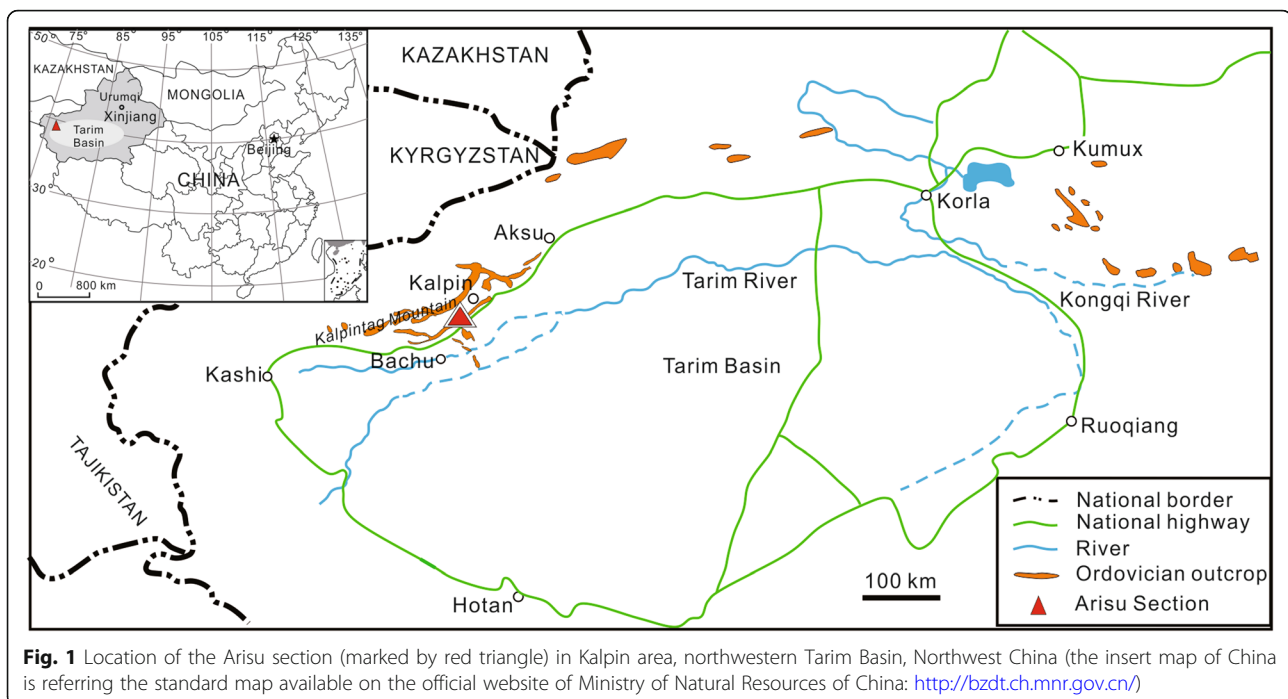


Fig. 1 Location of the Arisu section (marked by red triangle) in Kalpin area, northwestern Tarim Basin, Northwest China (the insert map of China is referring the standard map available on the official website of Ministry of Natural Resources of China: <http://bzdt.ch.mnr.gov.cn/>)

Ordovician strata are widely distributed and exposed in northwestern Tarim Basin, Northwest China, especially in the Arisu section in Kalpin area (Fig. 1), and its lithostratigraphy and biostratigraphy have been studied in detail (e.g., Zhou 2001; Wu 2003; Chen et al. 2012, 2013; Zhang and Munneke 2016; Han et al. 2017). However, Ordovician ostracod successions of Kalpin area have so far been little known, except for ostracods from the Caradocian (Wu 2003). Recently we discovered ostracods in red-coloured marine siliciclastic sediments (referred to as Arisu red beds) from the lower part of the Upper Ordovician Tierkeawati Formation in Kalpin area (Fig. 2).

The goal of this paper is to report the ostracods occurring in these Arisu red beds of the Upper Ordovician Tierkeawati Formation in northwestern Tarim Basin, Xinjiang, Northwest China, and to discuss their biostratigraphical, palaeoecological and palaeogeographical implications.

2 Geological setting and stratal section description

Tarim Basin, the largest basin of China, is located in the south of Xinjiang, Northwest China (Fig. 1); the area is the location of the Taklamakan Desert, the largest desert of China. The tectonics, lithostratigraphy and biostratigraphy of Tarim Basin have been studied in detail for petroleum exploration (e.g., Qiao 1986; Zhou and Chen 1992; Jia et al. 2004; Wang et al. 2007; Zhen et al. 2011; Li et al. 2017). The Ordovician strata are widely distributed and exposed in northwestern and northeastern

margins of the Tarim Basin, especially in the Kalpin area (Fig. 1). The Upper Ordovician sequence is usually subdivided into two lithostratigraphic units from the Katian to the Hirnantian Stages, i.e. the Yingnan Formation and the Tierkeawati Formation (Huang et al. 2009; Chen et al. 2013; Zhang et al. 2019). The Yingnan Formation is unconformably overlain by the Tierkeawati Formation in the Kalpin area (Fig. 2) as a result of the Kwangsian Orogeny (Huang et al. 2009; Chen et al. 2013), which elevated the Tarim Basin to form land from early to middle Katian time (Zhou et al. 1992). Lithology of the Yingnan Formation varies from east to west in the Kalpin area. In the east, the Yingnan Formation is composed mainly of dark grey carbonaceous, calcareous and silty shales, intercalated with a few calcilutites, and contains rich graptolites and chitinozoans in association with well-preserved small-sized trilobites and inarticulate brachiopods (Zhou et al. 1992). In the west, the Yingnan Formation is composed of dark grey calcareous shales in the lower part, and thin- to thick-bedded nodular limestone, bioclastic limestone in the upper part (Zhao et al. 2000; Han et al. 2017; Fig. 2). The Tierkeawati Formation consists of greyish green argillaceous siltstone intercalated with thin- to thick-bedded sandstone. A few chitinozoans and acritarchs have been documented, and accordingly the Tierkeawati Formation was assigned to late Katian Stage, corresponding to the *Dicellograptus complexus* graptolite biozone (Huang et al. 2009; Tang et al. 2012; Chen et al. 2013; Zhang et al. 2019).

The Arisu section (40°15'47.95"N, 78°51'15.87"E) is located in the north of the Kalpintag Mountain, about

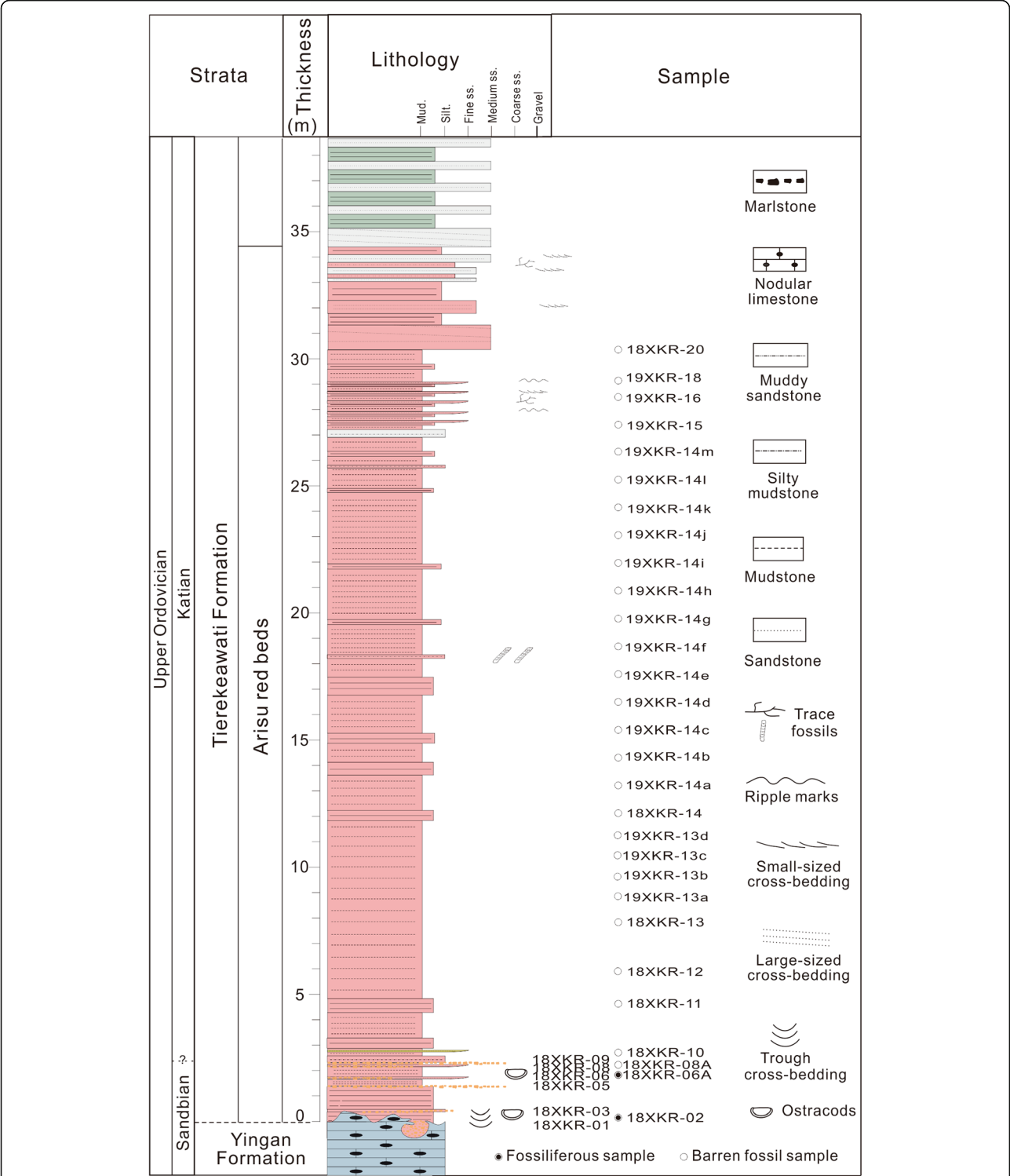


Fig. 2 Lithological column of the Tierenkeawati Formation and samples collected from the Arisu red beds in Kalpin area, northwestern Tarim Basin, Northwest China. 18XKR- and 19XKR-number represent sample numbers, respectively sampling in year 2018 and year 2019

31 km southwest of the Kalpin County (Fig. 1). Late Ordovician and Early Silurian rocks are well exposed in the Arisu section along a narrow and deep erosional stream-cut gorge. The Tierenkeawati Formation disconformably overlies the Yingan Formation (Fig. 3). In the lower part of the Tierenkeawati Formation, we have discovered red-

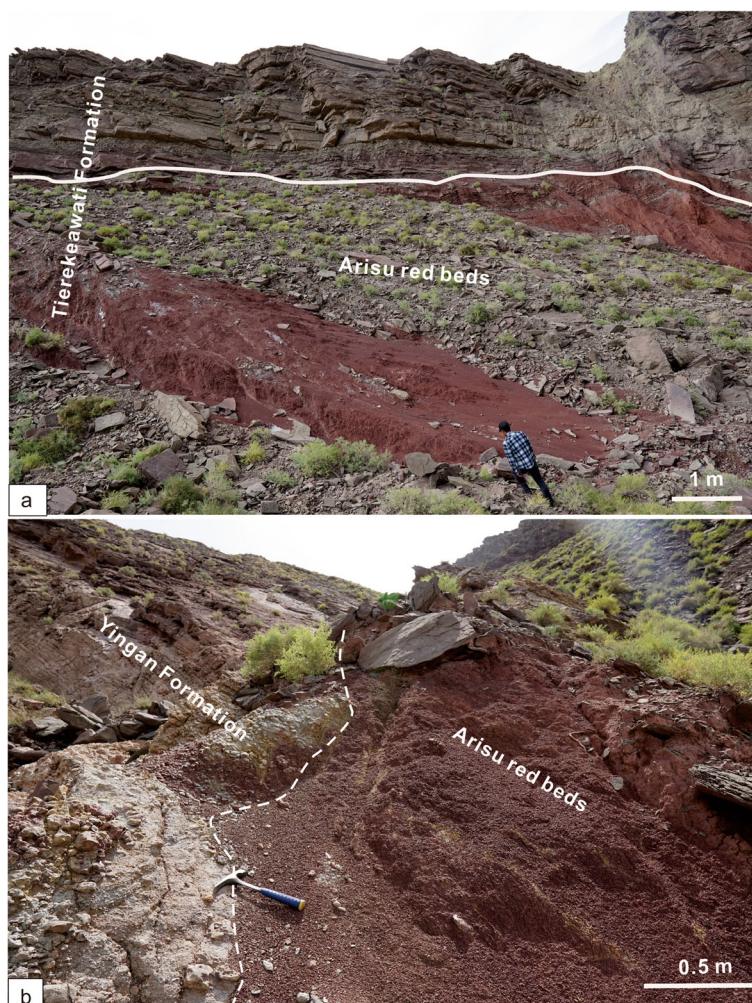


Fig. 3 **a** Field overview for the Arisu red beds of the lower Tieraekawati Formation; **b** Field photo shows the disconformity contact between the Yingan Formation and the Arisu red beds of the Tieraekawati Formation

coloured siliciclastic sediments comprising a mixture of shales, marls, siltstones and sandstones in the Kalpin area (Figs. 2 and 3), which varies from the previously described lithology of the Tieraekawati Formation. The red siliciclastics form a deposit about 34 m thick, composed of mainly purplish red mudstones intercalated with green to grey thin-bedded marlstones and grey thin- to medium-bedded sandstones at the top (Fig. 2). Trace fossils are common in the upper part of the deposit and ostracods are found in the lower part. In this study, the Arisu red beds is a temporary name for these red-coloured clastics of the lower Tieraekawati Formation, until a new lithostratigraphic unit is introduced in future work.

3 Material and methods

Thirty five samples, each about 1.5 kg in weight, were collected from the Arisu section (Figs. 1 and 2). For

mudstones and siltstones, ostracods were extracted after dilute hydrogen peroxide (H_2O_2) (15%) processing. About 270 specimens were thus obtained from the Arisu section, mostly from fossiliferous sample 18XKR-02 in the lower part of the Arisu red beds (Fig. 2).

4 Results

The ostracod faunas obtained from the Arisu red beds of the Tieraekawati Formation are composed by Palaeocopida (e.g., Aparchitoidea, Drepanelloidea, Hollinoidea), Metacopida (e.g., Healdioidea, Longisculoidea, Thlipsur-oidea), and Podocopida (e.g., Bairdioidea). In total 22 species belonging to 13 genera were recognized (Figs. 4 and 5). All specimens figured in this study are deposited in Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, and they are numbered from 171074 to 171101.

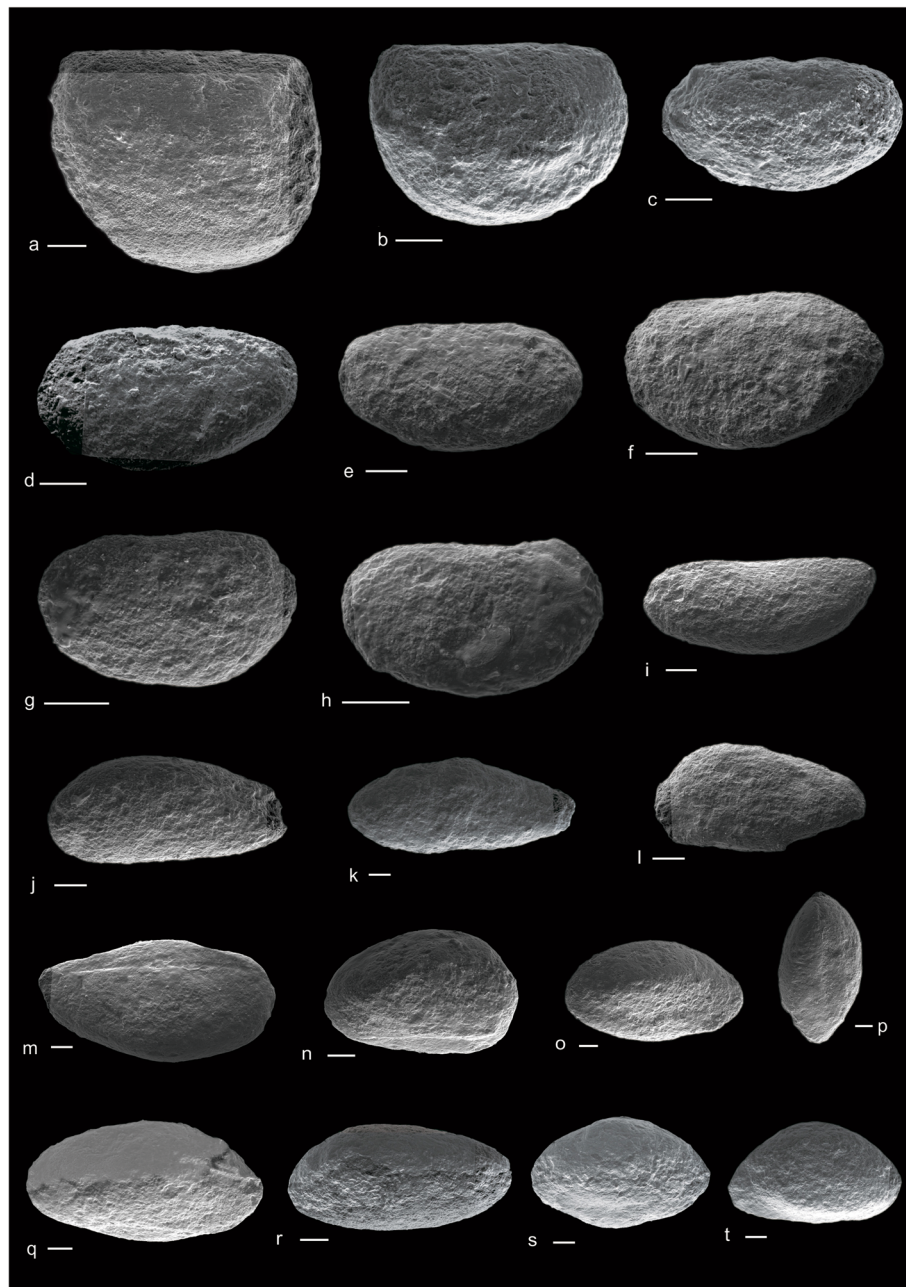


Fig. 4 Scanning electron micrographs of ostracods (l) from the Arisu red beds of the Terekeawati Formation in Kalpin area, northwestern Tarim Basin, Northwest China. Scale bar is 100 μm . **a** *Aparchites* sp. Right lateral view of complete carapace, 171074, Late Ordovician; **b** *Paraeuprimitia* cf. *pulchra* Sun, 1978 (Guan et al. 1978). Left lateral view of complete carapace, 171075, Late Ordovician; **c** *Euprimitia* cf. *symmetrica* (Hou 1956). Right lateral view of complete carapace, 171076, Late Ordovician; **d** *Primitia monstrata* Shi and Wang 1985. Right lateral view of complete carapace, 171077, Late Ordovician; **e** *Primitia monstrata* Shi and Wang 1985. Left lateral view of complete carapace, 171078, Late Ordovician; **f** *Primitia* cf. *monstrata* Shi and Wang 1985. Right lateral view of complete carapace, 171079, Late Ordovician; **g** *Primitia* cf. *wangjiawanensis* Sun, 1983 (Wang et al. 1983). Right lateral view of complete carapace, 171080, Late Ordovician; **h** *Primitia* cf. *wangjiawanensis* Sun, 1983 (Wang et al. 1983). Right lateral view of complete carapace, 171081, Late Ordovician; **i** *Primitia* sp. Right lateral view of complete carapace, 171082, Late Ordovician; **j** *Predarwinula arguta* Sun 1987. Right lateral view of complete carapace, 171083, Late Ordovician; **k** *Predarwinula* cf. *arguta* Sun 1987. Right lateral view of complete carapace, 171084, Late Ordovician; **l** *Krausella* sp. Left lateral view of complete carapace, 171085, Late Ordovician; **m** *Krausella* cf. *calvini* (Kay 1940). Right lateral view of complete carapace, 171086, Late Ordovician; **n** *Nikitinella* cf. *pinnaformis* Wang 2015. Right lateral view of complete carapace, 171087, Late Ordovician; **o** *Longiscula* cf. *vulgaris* Sun 1987. Right lateral view of complete carapace, 171088, Late Ordovician; **p** *Longiscula* cf. *vulgaris* Sun 1987. Dorsal view of complete carapace, 171089, Late Ordovician; **q** *Longiscula subcylindrica* (Ulrich 1889). Right lateral view of complete carapace, 171090, Late Ordovician; **r** *Longiscula subcylindrica* (Ulrich 1889). Left lateral view of complete carapace, 171091, Late Ordovician; **s** *Fenxiangia rhombiformis* Jiang, 1995 (Jiang et al. 1995). Right lateral view of complete carapace, 171092, Late Ordovician; **t** *Fenxiangia rhombiformis* Jiang, 1995 (Jiang et al. 1995). Right lateral view of complete carapace, 171093, Late Ordovician

5 Discussion

5.1 Age comparative analysis

The ostracod assemblages from the Arisu red beds of the Tierenkewati Formation are characterized by *Primitia*, *Predarwinula*, *Krausella*, *Longiscula*, *Fenxiangia*, *Euprimitia*, *Paraeuprimitia* and *Nikitinella*, most of which are typical genera of the Ordovician. *Primitia monstrata* Shi and Wang 1985 (Fig. 4d–f) was first reported from the Upper Ordovician (Katian) Chedao Formation in Gansu Province, Northwest China (Shi and Wang 1985). *Predarwinula arguta* Sun 1987 (Fig. 4j) was originally described from the Upper Ordovician (Sandbian–Katian) Pagoda Formation in Hubei Province, South China (Sun 1987). *Fenxiangia rhombiformis* Jiang, 1995 (Jiang et al. 1995) (Fig. 4s, t) firstly appeared in the Upper Ordovician (Sandbian–Katian) ‘Saergantag’ Group in North Tarim Basin, Northwest China (Jiang et al. 1995). *Longiscula subcylindrica* (Ulrich 1889) (Fig. 4q, r) and *Anticostus jolieti* (Copeland 1973) (Fig. 5c) were discovered from the Upper Ordovician (late Katian) in Anticosti Island, East Canada (Taha 2018).

Moreover, most similar morphological species have been documented from the Upper Ordovician, for instance, *Paraeuprimitia* cf. *pulchra* Sun, 1978 (Guan et al. 1978) (Fig. 4b), *Primitia* cf. *wangjiawanensis* Sun, 1983 (Wang et al. 1983) (Fig. 4g, h) and *Predarwinula* cf. *arguta* Sun 1987 (Fig. 4k) discovered in the Upper Ordovician (Sandbian–Katian), Hubei Province, South China (Guan et al. 1978; Wang et al. 1983; Sun 1987) are similar to *Paraeuprimitia pulchra*, *Primitia wangjiawanensis* and *Predarwinula arguta* Sun 1987, respectively. *Nikitinella* cf. *pinnaformis* Wang 2015 (Fig. 4n) and *Rectella?* cf. *proposita* Abushik and Sarv 1983 (Fig. 5b) are similar to *Nikitinella pinnaformis* and *Rectella?* *proposita* Abushik and Sarv 1983 (Abushik and Sarv 1983) from the Upper Ordovician (Katian) in Zhejiang Province, South China (Wang 2015). *Euprimitia* cf. *symmetrica* (Hou 1956) (Fig. 4c) is similar to *Euprimitia symmetrica* (Hou 1956) from the Upper Ordovician (Sandbian–Katian) Yenwushan Formation in Jiangshan area, Zhejiang Province, South China (Hou 1956). *Fenxiangia* cf. *puriformis* Jiang, 1995 (Jiang et al. 1995) (Fig. 5a) is similar to

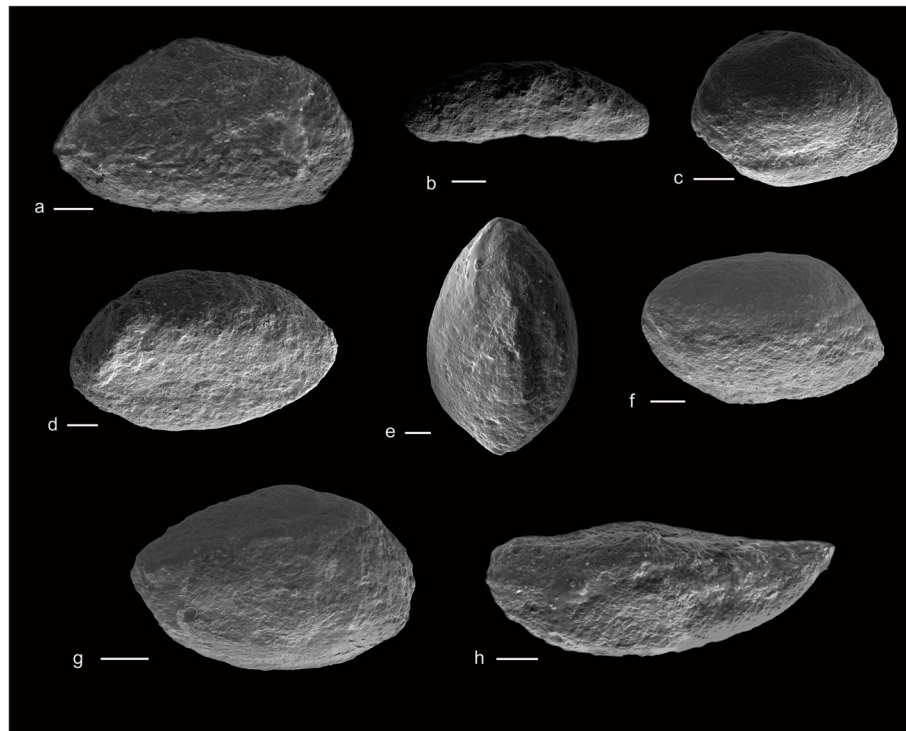


Fig. 5 Scanning electron micrographs of ostracods (II) from the Arisu red beds of the Tierenkewati Formation in Kalpin area, northwestern Tarim Basin, Northwest China. Scale bar is 100 μ m. **a** *Fenxiangia* cf. *puriformis* Jiang, 1995 (Jiang et al. 1995). Left lateral view of complete carapace, 171094, Late Ordovician; **b** *Rectella?* cf. *proposita* Abushik and Sarv 1983. Left lateral view of complete carapace, 171095, Late Ordovician; **c** *Anticostus jolieti* (Copeland 1973). Left lateral view of complete carapace, 171096, Late Ordovician; **d** *Bairdia* cf. *altitumida* Wang 2015. Right lateral view of complete carapace, 171097, Late Ordovician; **e** *Bairdia* cf. *altitumida* Wang 2015. Dorsal view of complete carapace, 171098, Late Ordovician; **f** *Bairdia* cf. *confragosa* Jiang, 1995 (Jiang et al. 1995). Right lateral view of complete carapace, 171099, Late Ordovician; **g** *Bairdia* sp. Right lateral view of complete carapace, 171100, Late Ordovician; **h** *Steusloffina* cf. *cuneata* (Steusloff 1895). Left lateral view of complete carapace, 171101, Late Ordovician

Fenxiangia puriformis from the Upper Ordovician (Sandbian–Katian) ‘Saergantag’ Group in North Tarim Basin, Northwest China (Jiang et al. 1995).

Overall, the age of ostracods from the Arisu red beds of the Tierেকেawati Formation in this study is inferred as Sandbian–Katian Age.

5.2 Palaeoenvironmental and palaeogeographical implications

Detailed palaeoenvironmental studies of Ordovician ostracods are rare in general. Several researchers (e.g., Bandel and Beker 1975; Wang 1988) noted the co-occurring relationship between ostracod fauna and marine lithofacies of the Paleozoic. Two associations (i.e., *Leperditella* Association and *Anisocyamus* Association) were recognized from the Middle Ordovician Bromide Formation in southern Oklahoma area, America (Williams and Siveter 1996): the *Leperditella* Association was characterized by leperditiope and some palaeocope (e.g., leiope and eridostracan) ostracods and was restricted to lithofacies of very shallow or marginal marine environments; by contrast, the *Anisocyamus* Association was dominated by palaeocope, metacope, binodicope and podocope ostracods, occupying subtidally deposited marine sediments with wide geographical distribution from shallow to deeper marine. Five ostracod associations, i.e., the leperditiid, palaeocopid, smooth-podocopid, spinose-podocopid, and entomozocean associations, were recognized in the Paleozoic strata of South China Plate by Wang (1988), which represent palaeoenvironments from nearshore to deep settings.

The ostracod fauna from the Arisu red beds of the Tierেকেawati Formation is dominated by metacopids ($\geq 50\%$ of the total number of species), palaeocopids (about 32% of the total number of species), and podocopids ($\leq 18\%$ of the total number of species). Thus, the ostracod assemblage is similar to the *Anisocyamus* Association (Williams and Siveter 1996); and is also ecologically equivalent to the mixture of palaeocopid and smooth-podocopid associations (Wang 1988) and the Eifelian Ecotype (Bandel and Beker 1975), both of which are generally characterized by a rich and diverse ostracod fauna indicative of a nearshore-offshore setting (Bandel and Beker 1975; Wang 1988; Song and Gong 2019). In the middle part of the Arisu red beds, although body fossils are absent, trace fossils provide evidence for the palaeoenvironmental interpretation. Most of these trace fossils are *Thalassinoides*, *Didymaulichnus*, and *Phycodes* (Fig. 6a–c), and can imply a nearshore palaeoenvironment (Bromley 1996; Yang et al. 2004; Zhang and Gong 2013; Shahkarami et al. 2017). Moreover, small-scale cross-bedding and symmetrical ripples in the upper part of the Arisu red beds (Fig. 6d) also indicate

nearshore shallow water. Overall, the Arisu red beds of the Tierেকেawati Formation were deposited during a regressive process, in a nearshore-offshore depositional palaeoenvironment, followed by a shallowing-upward trend.

During Ordovician time, most of the Chinese terranes were located in or near the tropical areas in the north-eastern peri-Gondwana region, including Tarim, South China, North China, Himalaya (South Tibet), Lhasa (North Tibet), and Sibumasu (Burrett et al. 1990; Metcalfe 2011; Zhan et al. 2016). Corals from the Upper Ordovician in Kalpin area, Northwest Tarim had a particularly close connection to the Late Ordovician faunas recorded in South China (Han et al. 2017). Similarly, three cephalopod provinces, the South China–Tarim–Tibet–Sibumasu Province (STTS), the North China Province, and the Australia Province (Fang et al. 2019), were recognized for the Late Ordovician, which suggests close biogeographic relationships between the Tarim and South China Plates. Most ostracods from the Arisu red beds of the Tierেকেawati Formation in Kalpin area, Northwest Tarim Basin are also similar to the Late Ordovician faunas recorded in South China. The Late Ordovician genera, which are common in Tarim Basin, such as *Paraeuprimitia* Sun, 1978 (Guan et al. 1978), *Primitia* Jones and Holl 1865, *Nikitinella* Melnikova 1986, *Longiscula* Neckaja 1958 and *Fenxiangia* Sun, 1978 (Guan et al. 1978), appeared simultaneously in Hubei and Zhejiang Provinces of South China (Guan et al. 1978; Wang et al. 1983; Sun 1987). Besides, *Predarwinula arguta* Sun 1987, firstly described from the Upper Ordovician in Hubei Province, South China (Sun 1987), is also recorded in the Upper Ordovician of southern Tibet Plate (Song et al. 2019), which might imply close biogeographic relations among Tarim, South China, and Tibet Plates during the Late Ordovician. Thus, we deduce that ostracods from Northwest Tarim, like other marine faunas such as corals (Han et al. 2017) and cephalopods (Fang et al. 2019), are similar to the Late Ordovician faunas recorded in South China and all belong to the STTS during the Late Ordovician. In addition, the ostracod fauna from Arisu red beds of the Tierেকেawati Formation in Tarim Basin, belonging to the STTS, can be geo-ecologically compared to the faunas of Europe and North America continents during the Late Ordovician. For instance, *Steusloffina cuneata* (Steusloff 1895) also in the Upper Ordovician of Southwest Scotland (Mohibullah et al. 2011); *Krausella calvini* (Kay 1940) was first discovered in the Late Ordovician Decorah Formation of Iowa area (Kay 1940), and common in the Middle Ordovician Bromide Formation of Oklahoma area, America (Williams and Siveter 1996); *Anticostus jolieti* (Copeland 1973) also appeared from the Late Ordovician (late Katian) Ellis Bay Formation in

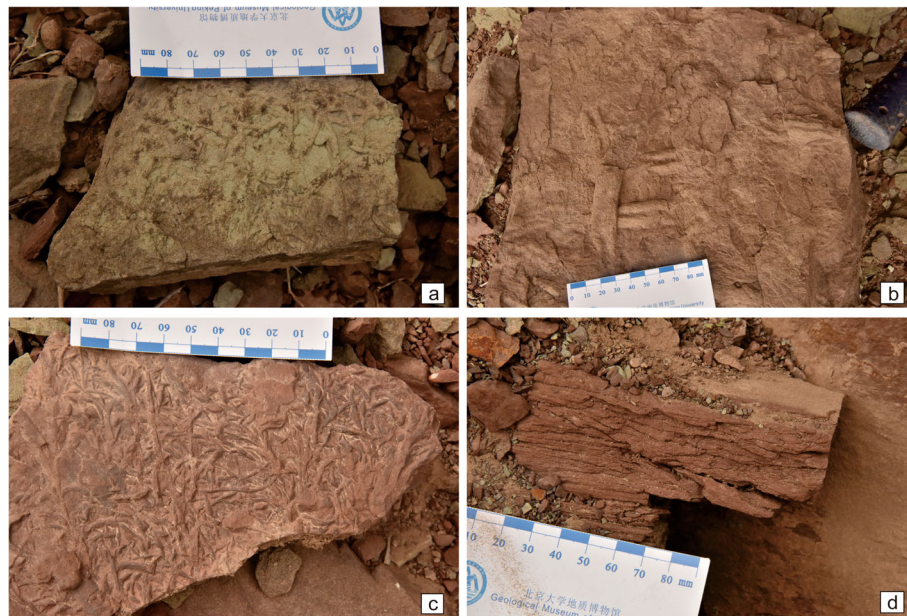


Fig. 6 Field photos of trace fossils (a–c) and sedimentary structure (d) in the Arisu red beds of the Tierkeawati Formation in Kalpin area, northwestern Tarim Basin, Northwest China. **a** *Thalassinoides*; **b** *Didymaulichnus*; **c** *Phycodes*; **d** Small-sized cross-bedding in the upper part of the Arisu red beds

eastern Canada. These findings demonstrate that ostracods experienced faunal exchanges between Laurentia and the Tarim Plate during the Late Ordovician.

6 Conclusions

- 1) Twenty-two species belonging to thirteen ostracod genera are described and figured for the first time from the red-coloured marine sandstones of Arisu section (Arisu red beds) of the Upper Ordovician Tierkeawati Formation in Kalpin area, northwestern Tarim Basin, Northwest China.
- 2) The ostracod fauna suggests a probable Sandbian–Katian age for the Arisu red beds, and implies that the Arisu red beds were deposited in a regressive nearshore–offshore palaeoenvironment followed by a shallowing-upward trend.
- 3) Ostracod faunas of the Arisu red beds are diversified with many global and/or regional genera, suggesting these ostracods belonging to the South China–Tarim–Tibet–Sibumasu Province (STTS) during the Late Ordovician, same as corals and cephalopods.
- 4) The ecological assemblage of ostracods in the Arisu red beds is similar to the *Anisocyamus* Association and also corresponds to the Eifelian Ecotype.
- 5) It is inferred that there were possible biogeographic relationships among Tarim, Tibet, and South China Plates, as well as Europe and North America continents during the Late Ordovician Period.

Abbreviations

GOBE: Great Ordovician Biodiversification Event; STTS: South China–Tarim–Tibet–Sibumasu Province

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Authors' contributions

JJS and YXS conceived the idea of this study and composed the manuscript. PT, XLZ, QJL and ZJL discussed the results and revised the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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