Geological Magazine

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The latest encrinurid trilobites from the Lower Devonian of Xinjiang, Northwest China

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Original Article

Cite this article: Ma J, Yin J, Liu Y, Du X, Liu S, and Zong R (2023) The latest encrinurid trilobites from the Lower Devonian of Xinjiang, Northwest China. *Geological Magazine* **160**: 1578–1585. https://doi.org/10.1017/S0016756823000596

Received: 17 April 2023
Revised: 3 August 2023
Accepted: 12 September 2023
First published online: 9 October 2023

Keywords:
conodonts; Encrinurinae; Lochkovian; Silurian–Devonian boundary; western Junggar

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Abstract

Encrinurids are common in Ordovician and Silurian strata but whether they survived into the Early Devonian is still controversial. This paper documents the encrinurid *Batocara* sp. near the Silurian–Devonian boundary in western Junggar, Xinjiang. The highest horizon of *Batocara* sp. is located above the first appearance datum of the Devonian conodont *Caudicriodus*, confirming that encrinurids may cross the Silurian–Devonian boundary. The presence of *Caudicriodus angustoides bidentatus*, *Zieglerodina planilingu* and plate-type loboliths of scyphocrinoids above the highest horizon of *Batocara* sp. indicates that encrinurids here extend only into the lower part of the first conodont zone of the Lochkovian (i.e., *Caudicriodus hesperius* Biozone). Encrinurids are widely distributed and easily recognized, and unlike graptolites and conodonts are not controlled by lithofacies. Therefore, it might be possible to use the highest horizon of encrinurids as indicator fossils to identify the approximate position of the Silurian–Devonian boundary in areas or sections where graptolites and conodonts are not present, and at least in northwest China.

1. Introduction

Encrinurinae (Encrinuridae, Phacopida) is a cosmopolitan trilobite subfamily that has been reported from North and South America, Europe, Asia, Australia and the Arctic region (see, Temple & Tripp, 1979; Temple & Wu, 1990). Encrinurinae first appeared in the early Floian or late Tremadocian of the Early Ordovician (Pärnaste, 2006) and reached their maximum diversity in the Silurian when they were a major component of the trilobite fauna (Bault *et al.* 2022). However, the time when encrinurids disappeared is still controversial and inconclusive. Most scholars believe that encrinurids became extinct to the end of Silurian (Ormiston, 1977; Boucot, 1985; Chlupác, 1994), so they were used to determine the Silurian–Devonian boundary (SDB). Nevertheless, some reports suggest that encrinurids can survive into the Devonian (Maksimova *et al.* 1973; Fletcher, 1975; Biske *et al.* 1977; Bourque & Lesperance, 1977; Nikiforova, 1977; Maksimova, 1980; Strusz, 1980; Zhang, 1983; Owens *et al.* 2010). But these so-called 'earliest Devonian encrinurids' were not age constrained by index graptolites or conodonts, and do not have an undoubted earliest Devonian age. Here, we document encrinurids preserved with earliest Devonian conodonts from western Junggar, Xinjiang, NW China, which provides sufficient evidence for the survival of encrinurids into the Early Devonian. On this basis, the implications of encrinurids for determining the position of the Silurian–Devonian boundary are discussed.

2. Geological setting and materials

Western Junggar is an important part of the Central Asian Orogenic Belt, occupied by Paleozoic accretionary complexes in the south and volcanic arcs in the north (Windley *et al.* 2007; Xiao *et al.* 2008; Chen *et al.* 2010). The well-exposed SDB occurs in strata of the Boshchekul-Chingiz volcanic arc (Hou *et al.* 1979; Wang, 1991; Xiao *et al.* 1991, 1992; Zeng & Xiao, 1991; Cai *et al.* 1993; Ni *et al.* 1998; Zong & Gong, 2020). The strata near the SDB mainly consist of pyroclastic rocks with a few carbonate rocks (Gong & Zong, 2015), named the Wutubulake and Mangeer formations in ascending order (also referred to as the Wutubulake Member of the Kekexiongkuduke Formation and the Mangeer Member of the Hoboksar Formation, Cai, 1999). Both formations yield abundant benthic animal fossils such as corals, brachiopods, trilobites, crinoids and bryozoans (Zeng & Xiao, 1991; Xiao *et al.* 1992; Zong & Gong, 2020). In addition, rich plants and a few graptolites are also found in the Wutubulake Formation (Cai *et al.* 1993; Ni *et al.* 1998). In the past, based on a few studies of graptolites and benthic animals, the ages of the Wutubulake and Mangeer formations were generally considered as Pridoli and Early Devonian, respectively (Cai *et al.* 1993; Ni *et al.* 1998; Cai, 1999).

Material for the present study was collected from the upper part of the Wutubulake Formation to the base of the Mangeer Formation in the Mangkelu II section in the northern part

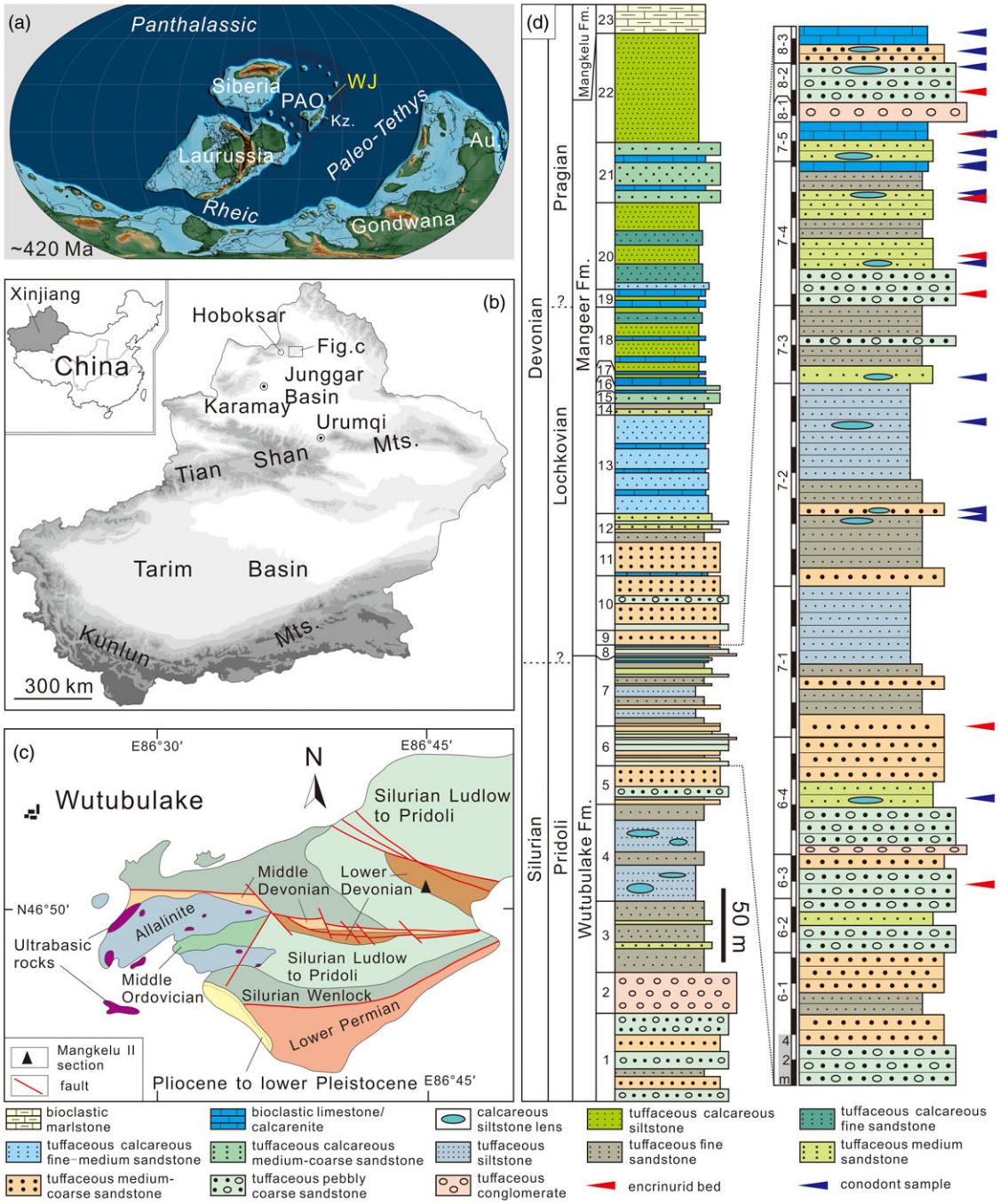

Figure 1. (Colour online) **Geological background and location map of the study area.** (a), Paleogeographical location of western Junggar in the Silurian–Devonian transition (modified from Scotese, 2021). (b), (c), Location of the Mangkelu II section and the geological map of study area (modified from Zong & Gong, 2020). (d), Stratigraphic column of Mangkelu II section. Abbreviations: WJ, western Junggar, Kz., Kazakhstan, PAO, Paleo-Asian Ocean, Au., Australia.

of western Junggar (Fig. 1). This section was first reported by Zong and Gong (2020) who placed the boundary between the Wutubulake Formation and the overing Mangeer Formation between bed 12 and bed 13; however, we make a minor revision to the lithostratigraphic subdivision, moving the boundary between two formations down to between bed 7 and bed 8 (Figs. 1d, 2a–c). The Wutubulake Formation consists generally of fine-grained pyroclastic rocks in turbidite facies, intercalated with thick-bedded coarse-grained pyroclastic rocks and a small amount of calcareous siltstone, with bioclastic or sandy limestone lenses (or thin layers) in the upper part (Fig. 2d–h). The coarse pyroclastic rocks contain allochthonous corals, brachiopods, crinoid stems and trilobites (Fig. 2f, g), and the fine pyroclastic rocks contain rare plants and graptolites. The lower part of the Mangeer Formation consists of coarse pyroclastic rocks, commonly intercalated with thin-bedded calcareous sandstone and bioclastic limestone, yielding corals, brachiopods, trilobites, gastropods, echinoderms and cephalopods, and two layers with plate-type loboliths (Fig. 2i, j; Zong & Gong, 2020). In the upper part of the Mangeer Formation, the granularity of the pyroclastic rocks is slightly finer and the calcium content is increased, with bioclastic limestone and sandy limestone thicker and more abundant and reef limestone formed locally. Therefore,

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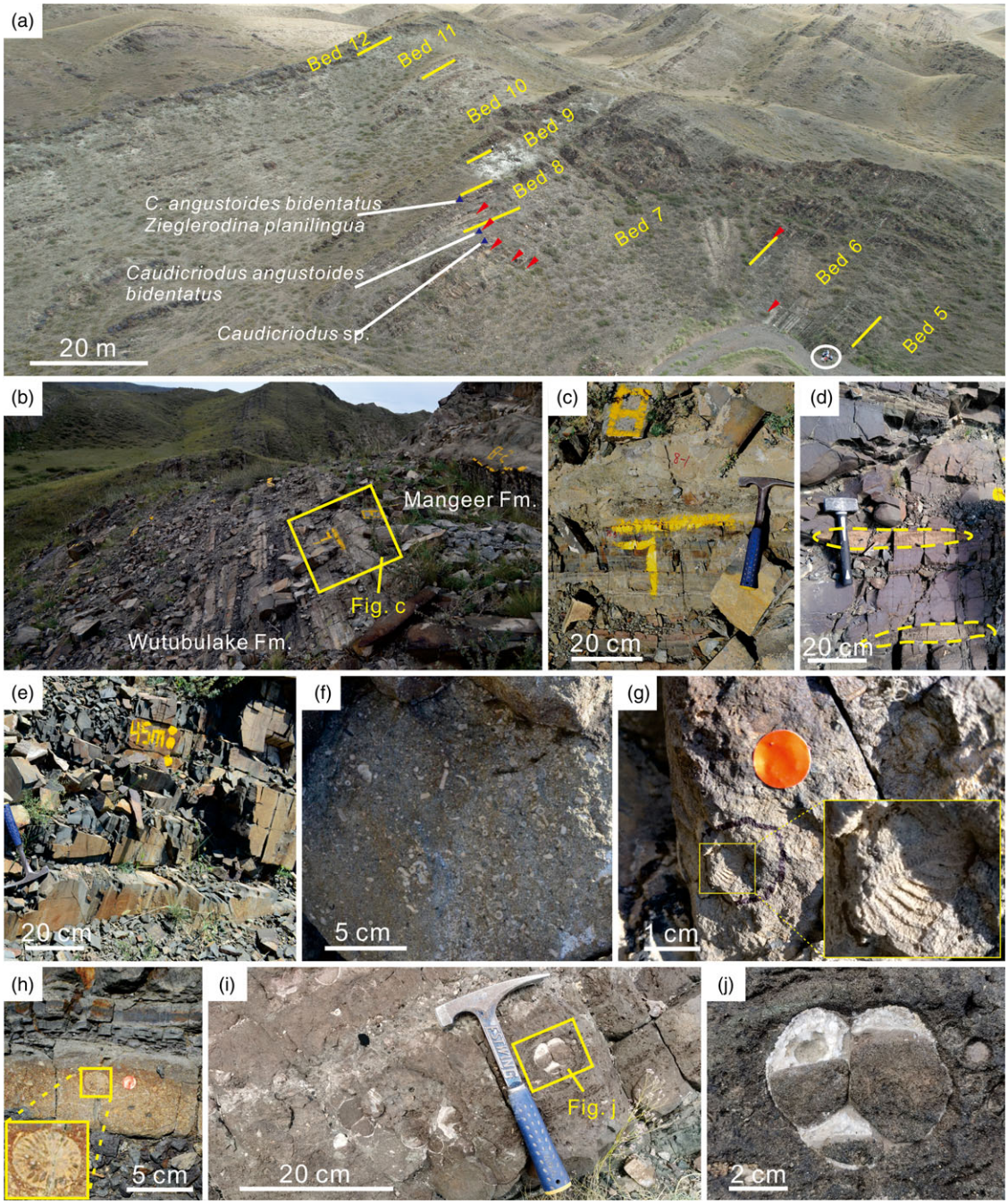

Figure 2. (Colour online) **Lithological features and fossils near the Silurian–Devonian boundary of Mangkelu II section in western Junggar, Xinjiang.** (a), The stratigraphic division of the Mangkelu II section and the levels of trilobites (red arrows) and important conodonts (blue arrows). (b), (c), The boundary between the Wutubulake Formation and the overlying Mangeer Formation is located between bed 7 and bed 8, Fig. c shows the local amplification of Fig. b. (d), Calcareous siltstone lens in tuffaceous medium sandstone in bed 7-4 of the Wutubulake Formation. (e), Tuffaceous siltstone in bed 7-2 of the Wutubulake Formation. (f), Tuffaceous pebbly coarse sandstone containing crinoid stems in bed 6-3 of the Wutubulake Formation. (g), Tuffaceous medium-coarse sandstone containing encrinurids pygidium at the bottom of bed 7-1 of the Wutubulake Formation. (h), Bioclastic limestone interlayer in bed 7-5 of the Wutubulake Formation. (i), (j), Plate-type lobolith of scyphocrinoid in bed 8-3 of the Mangeer Formation.

a regressive sequence is formed from the Wutubulake Formation to the Mangeer Formation. The Silurian–Devonian boundary of this section was provisionally located in bed 8 according to a preliminary study of trilobites and plate-type loboliths (Zong & Gong, 2020). However, based on our new conodont data, the SDB needs to be moved down to at least bed 7.

All specimens are stored in the State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences.

3. Results

Near the SDB, encrinurids were found in seven beds, namely bed 6-3 (15.5 m), bed 7-1 (27.4 m), bed 7-4 (62 m), bed 7-4 (65 m), bed 7-4 (69.5 m), bed 7-5 (74.5 m) and bed 8-2 (77.9 m), preserved in bioclastic limestone (Fig. 3a–c), tuffaceous sandstone and pebbly coarse sandstone (Fig. 3d–j). The specimens include cranidia, free cheeks, thoracic segments and pygidia, with pygidia being the most common; no articulated exoskeletons were found. Occurring with

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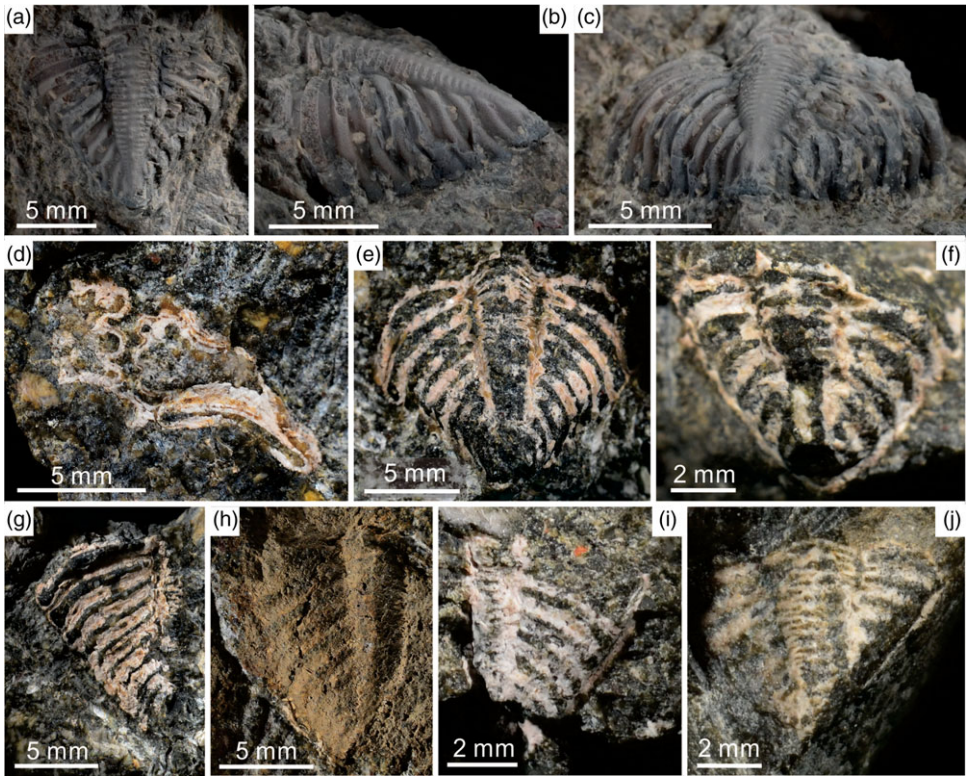

Figure 3. (Colour online) **Encrinurid trilobite *Batocara* sp. from the Wutubulake and Mangeer formations (near the Silurian-Devonian boundary) of Mangkelu II section, western Junggar, Xinjiang.** (a)–(c), pygidium, BGEG-MII/T007, bed 7-5 (74.5 m), dorsal view (a), left lateral view (b), and posterior view (c). (d), Incomplete cranidium, BGEG-MII/T010, bed 7-4 (69.5 m), dorsal view. (e)–(f), Complete pygidia, BGEG-MII/T004, BGEG-MII/T015, bed 7-4 (62 m), bed 8-2 (77.9 m), dorsal view. (g)–(j), Incomplete pygidia, BGEG-MII/T012, BGEG-MII/T006, BGEG-MII/T013, BGEG-MII/T011, bed 7-4 (62 m), bed 7-4 (62 m), bed 8-2 (77.9 m), bed 7-4 (69.5 m), dorsal view, and (h) is an internal mold.

the encrinurids are crinoid stem, bryozoan, brachiopod and coral fragments. These encrinurids are relatively uniform in size and are mostly worn on the surface, suggesting allochthonous burial. Based on the non-mucronate pygidium, the wide pygidial pleura and the narrow pygidial axis, as well as the number of pygidial axial rings and pleural ribs, we assign these encrinurids to *Batocara* Strusz, 1980. It is not possible to identify the specimens at species level due to the poor preservation and lack of adequate and complete cranidia.

Fifteen conodont samples were collected from limestone and calcareous siltstone interlayers or lenses in this section (Fig. 1d), and conodonts were found in all samples except for five horizons, namely bed 6-3 (22.5 m), bed 7-2 (52 m), bed 7-3 (55.5 m), bed 7-4(69.9 m) and bed 7-5 (73 m). However, the conodonts in most samples were broken and could not be identified, and elements with important stratigraphic value were scarce. There are only three samples having age-indicative conodonts, i.e., *Caudicriodus* sp. from bed 7-4 (72.1 m), *Caudicriodus angustoides bidentatus* from bed 7-5 (74.5 m) and *Caudicriodus angustoides bidentatus* and *Zieglerodina planilingua* from bed 8-3 (82.5 m) (Fig. 4).

4. Discussion

4.a. Evidence for Early Devonian encrinurids

The strata containing encrinurids near the SDB are classified as Silurian by most scholars (e.g., Chlupáč *et al.* 1972; Holloway & Neil, 1982; Liao *et al.* 1995; Duan & An, 2004; Zhang & Sun, 2007). However, some scholars suggesting that a few encrinurids crossed the SDB. There are scattered reports of Early Devonian encrinurids in some areas since the 1970s, such as Tien-Shan in central Aisa (Biske *et al.* 1977), Podolia in Ukraine (Nikiforova, 1977), Central Kazakhstan (Maksimova, 1975), Québec in Canada (Bourque & Lesperance, 1977) and New South Wales in Australia (Fletcher, 1975). Unfortunately, the Early Devonian age claimed for these encrinurids was based either on benthic organisms, or on graptolites or conodonts not belonging to index species. Whether these occurrences are all of Early Devonian age is doubtful (Liao *et al.* 1995) and some occurrences regarded as earliest Devonian have been revised by subsequent studies (Liao *et al.* 1995; Zhang & Sun, 2007). For example, the supposed Early Devonian *Encrinurus* sp. from Tien-Shan occurs in the same horizon as the conodont *Ozarkodina steinhornensis praeoptima* (Biske *et al.* 1977), but using the species of the *Ozarkodina eosteinhornensis-steinhornensis* group (now *Zieglerodina*) to define the Silurian–Devonian boundary is considered unreliable (Barrick *et al.* 2021). The supposed Early Devonian encrinurids from Podolia are from the Tajna Beds, the base of which was once considered to coincide with the Silurian–Devonian boundary. However, that position for the boundary was based on the first appearance datum (FAD) of the graptolite *Monograptus uniformis angustidens* (Nikiforova, 1977), rather than on the Devonian index graptolite *Monograptus uniformis uniformis* (Martinsson, 1977). The first appearance datum of *M. uniformis uniformis* in the Tajna Beds is higher than the occurrence of encrinurids (Nikiforova, 1977). Moreover, chitinozoans in the Tajna Beds (later renamed the Tajna Formation) show that this unit is at least in part of Silurian age (Paris & Grahn, 1996). The claimed Early Devonian encrinurids from the Indian Point Formation in Québec are from a horizon above those containing *Monograptus*

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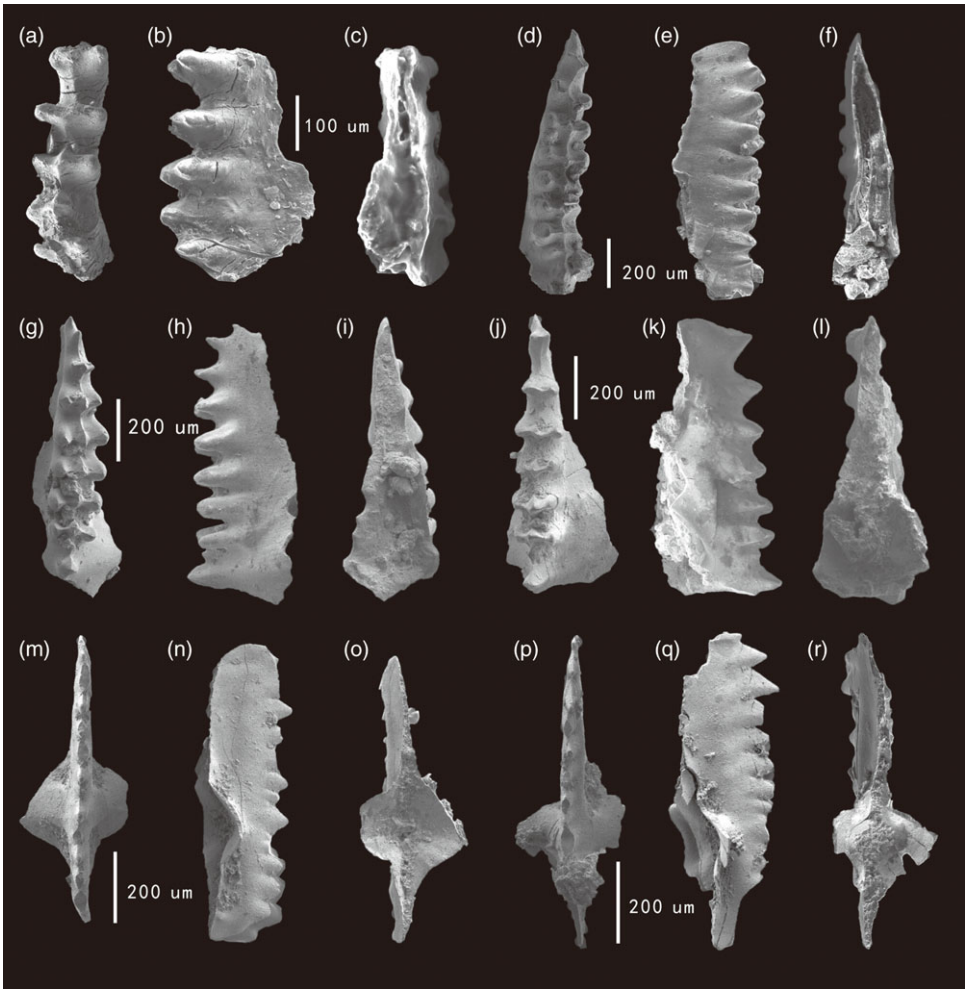

Figure 4. The earliest Devonian conodonts from Mangkelu II section in western Junggar, NW Xinjiang. (a)–(c), *Caudicriodus* sp., BGEG-MII/C/72.1/001, upper, lateral, and lower views of the I element, Bed 7-4 (72.1 m). (d)–(i), *Caudicriodus angustoides bidentatus*, BGEG-MII/C/74.5/018, BGEG-MII/C/74.5/019, upper, lateral, and lower views of the I element, Bed 7-5 (74.5 m). (j)–(l), *Caudicriodus angustoides bidentatus*, BGEG-MII/C/82.5/006, upper, lateral, and lower views of the I element, Bed 8-3 (82.5 m). (m)–(r), *Zieglerodina planilingua*, BGEG-MII/C/82.5/007, BGEG-MII/C/82.5/008, upper, lateral, and lower views of the P elements, Bed 8-3 (82.5 m).

praehercynicus Jaeger, *Monograptus* ex gr. *microdon* Richter, *Monograptus aequabilis aequabilis* (Přibyl)) and *Linograptus posthumus posthumus* (Richter) (Bourque & Lesperance, 1977). This graptolite assemblage is presumed to belong to the Early Devonian *M. uniformis* zone (Lenz, 1972), but the index element *M. uniformis uniformis* has not been found in this assemblage.

Strusz (1980) attributed an Early Devonian age to two species of encrinurids from Australia, but it was later proved that these records were the result of incorrect stratigraphic assignment (Campbell in Zhang & Sun, 2007). Owens *et al.* (2010) described the encrinurids from the basal 10 m of the upper member of the Zaamin Formation in the Zaamin River Basin, Uzbekistan. This member yielded the conodonts *Ozarkodina steinchornensis remscheidensis* and *Amydrotaxis johnsoni*, which are common in the Lochkovian (Klapper & Murphy, 1980; Akhmedov, 2001; Wang *et al.* 2005; Zherlygin, 2012), but may extend down into the Pridoli (Murphy *et al.* 2004; Zherlygin, 2012). In addition, the exact horizon of the conodonts in the upper member of the Zaamin Formation is uncertain, so it is still unknown whether the encrinurids occur above or below these so-called Early Devonian conodonts. In China, Duan and An (2004) reported the encrinurid *Encrinuropsis sinicus* Kuo, 1962 from the upper part of the Erdaogou Formation in Jilin Province. This formation was originally regarded as Pridoli in age (Wang & Li, 1986) based on the conodont *Spathognathodus steinhornensis eosteinhornensis*, but Wang *et al.* (2014) considered that the conodont to have been misidentified and that there are no Silurian conodonts in the upper part of the Erdaogou Formation. Based on the conodont *Neopanderodus* sp. and other benthic fossils, Wang *et al.* (2014) inferred that a Lochkovian age for the upper part of the Erdaogou Formation cannot be excluded. However, the exact locations of encrinurids and conodonts are uncertain, so it is controversial whether encrinurids described by Duan and An (2004) appeared in the Early Devonian. The age of encrinurids from the lower part of the Wutubulake Formation in the Mangkelu section of western Junggar, Xinjiang was also considered to be the Early Devonian based on benthic animals such as other trilobites and corals (Zhang, 1983; Wang, 1991), but later studies of graptolites from this formation changed its age to Pridoli (Cai *et al.* 1993; Ni *et al.* 1998).

Caudicriodus sp. (Fig. 4a–c) appears for the first time in bed 7-4 (72.1 m) of the Mangkelu II section in western Junggar, Xinjiang. The specimen differs from the Lochkovian *Caudicriodus woschmidti* or *Caudicriodus hesperius* in the absence of a posterior

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process. However, the specimen is intact (from lower view), and its small size and the presence of well-developed transverse ridges suggest that it may represent a juvenile specimen of the Early Devonian *Caudicriodus* (Drygant & Szaniawski, 2012). According to Jeppsson (1988), *Caudicriodus* (specifically *Caudicriodus woschmidti*) occurs slightly before *Monograptus uniformis uniformis* in some sections, but this fact may be due to facies control (Corradini & Corriga, 2012). The appearance of *Caudicriodus* (or *Icriodus*) is still believed to coincide with the beginning of the Devonian period (Corradini & Corriga, 2012; Slavik & Hladil, 2020; Ferretti *et al.* 2022). *Caudicriodus angustoides bidentatus* (Fig. 4d–i) was found in bed 7-5 (74.5 m) of the Mangkelu II section. This subspecies is widely documented in the middle–upper Lochkovian (Savage, 1976; Boncheva *et al.* 2007; Slavik *et al.* 2012), but it may also extend downwards into the lower Lochkovian as demonstrated by its occurrence together with *Caudicriodus woschmidti* in Inner Mongolia, China (Wang, 2006, 2019). Thus, in the Mangkelu II section of western Junggar, Devonian strata begin at least in bed 7-4 (72.1 m), and the age of the encrinurid *Batocara* sp. in bed 7-5 (74.5 m) and bed 8-2 (77.9 m) is undoubtedly the Early Devonian, providing positive evidence that encrinurids cross the Silurian–Devonian boundary.

4.b. Implications for the Silurian–Devonian boundary

The Silurian–Devonian boundary is defined by the FAD of the graptolite *Monograptus uniformis uniformis* (Martinsson, 1977), but conodonts are often used to determine the SDB in carbonate facies. At present, the FAD of *Caudicriodus hesperius* is widely used to define the boundary (Carls *et al.* 2007; Corradini & Corriga, 2012; Slavik *et al.* 2012; Schönlaub *et al.* 2017; Hušková & Slavík, 2019; Corradini *et al.* 2020). However, both graptolites and conodonts are strongly controlled by lithofacies. They are rare or even absent in some areas lacking carbonate rocks and shales, or in shallow-water facies, so that the Silurian–Devonian boundary cannot be determined accurately in these areas. The FAD of the trilobite *Warburgella rugulosa rugosa* is also regarded as an important auxiliary indicator of the SDB, but the paleogeographic distribution of the *Warburgella rugulosa* group is relatively limited, with reliable records only from Europe, North Africa, North America and Central Asia (see Ormiston, 1977; Maksimova, 1980). A subspecies similar to *W. rugulosa rugosa*, i.e., *Warburgella rugulosa sinensis*, was reported from Qujing, Yunnan, China (Wu, 1977), but was later revised as a separate species, *Warburgella sinensis* (Zhang & Sun, 2007). This means that the real *Warburgella rugulosa* group has not been found in China. Compared to the *Warburgella rugulosa* group, encrinurids are extensive in paleogeographic distribution and readily recognized in a variety of marine rocks and all strata containing encrinurids were dated as Silurian in age (Chlupáč *et al.* 1972; Holloway & Neil, 1982; Liao *et al.* 1995; Duan & An, 2004; Zhang & Sun, 2007). The highest horizon of encrinurids in the Mangkelu II section located above the FAD of *Caudicriodus*, indicating, however, that these trilobites can continued up to the Early Devonian and are not exclusively Silurian. Therefore, the SDB previously determined on the basis of encrinurids in some sections need to be redefined by graptolites or conodonts (e.g., Guo, 1962; Liao *et al.* 1995), and the SDB of these sections are likely to need to be moved downwards.

The highest horizon of encrinurids in the Mangkelu II section is bed 8-2 (77.9 m), and the overlying bed 8-3 (82.5 m) yields abundant and diverse trilobites but no encrinurids. The conodonts *Caudicriodus angustoides bidentatus* (Fig. 4j–l) and *Zieglerodina planilingua* (Fig. 4m–r) were also found in bed 8-3 (82.5 m). *Caudicriodus angustoides bidentatus* is restricted to the Lochkovian (Savage, 1976; Wang, 2006; Boncheva *et al.* 2007; Slavik *et al.* 2012; Wang, 2019), and *Z. planilingua* is commonly documented from the Pridoli to the lower Lochkovian (Murphy *et al.* 2004; Corradini & Corriga, 2012; Corriga *et al.* 2014a; Corradini *et al.* 2020). In addition, scyphocrinoid plate-type loboliths were found in bed 8-3 and bed 11 of this section (Zong & Gong, 2020). The appear and disappear abruptly within a relatively short stratigraphic interval, occurring only in strata near the SDB (Haude, 1992). Plate-type lobolith-bearing strata in Baoshan, Yunnan Province, China, also yielded *Monograptus* cf. *uniformis angustidens*, *M. microden* and *Caudicriodus woschmidti*, are restricted to the Lochkovian (Shi & Gong, 1992). In the Tafilalt region of southeastern Morocco, according to conodont biostratigraphy, *Camarocrinus*, *Marhoumacrinus* and their plate-type loboliths are present at the top of the Pridoli and extend into the *Caudicriodus hesperius* zone at the base of the Lochkovian (Corriga *et al.* 2014b; Haude *et al.* 2014).

In view of above, the stratigraphic extension of plate-type loboliths in the Mangkelu II section in western Junggar should remain in the Devonian (Lochkovian) first conodont zone, which limits the highest horizon of encrinurids to the *Caudicriodus hesperius* zone, and most likely to the lower part of that zone, not far above the Silurian–Devonian boundary. Thus, in areas where plankton is absent, or where shale and carbonate rocks are not developed, the topmost horizon of encrinurids may be used as an approximate indicator of the SDB. In the absence of standard graptolites or conodonts, encrinurid-bearing strata can still be roughly assigned to the Silurian.

5. Conclusions

The Lochkovian conodonts *Caudicriodus* sp. and *Caudicriodus angustoides bidentatus* were found below the highest horizon of encrinurids in western Junggar, Xinjiang, NW China, providing evidence that encrinurid trilobites persisted into the earliest Devonian, and did not become extinct at the end of Silurian. The upper stratigraphic limit of encrinurids here is in the *Caudicriodus hesperius* Zone of the lower Lochkovian, as indicated by conodonts and plate-type loboliths occurring higher in the sequence.

Encrinurids are widely distributed, including in carbonate, clastic and pyroclastic facies, and are easily identified. The encrinurids *Batocara* sp. survived into the earliest Lochkovian in at least NW China. These factors mean that the highest horizon of encrinurids which have been confirmed in other areas to associate with graptolites and conodonts near the SDB can be used to define the Silurian–Devonian boundary approximately in those areas or sections that lack index fossils such as graptolites and conodonts.

Acknowledgements. We are grateful for the constructive comments from Greg Edgecombe and David Holloway, which improved the clarity and scope of the manuscript. This study was supported by the National Natural Science Foundation of China (Grant Nos. 42072041, 41702006). We are grateful to Zhihong Wang (Wuhan Geological Survey Center of China Geological Survey), Xinsong Zhang and Weidong Du (Fuzhou University), and Haohong Xie (China University of Geosciences, Wuhan) for their help in the field work.

Competing interests. No conflict of interest exits in the submission of this manuscript, and the manuscript is approved by all authors for publication.

https://doi.org/10.1017/S0016756823000596 Published online by Cambridge University Press

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