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Bathynotus: A key trilobite taxon for global stratigraphic boundary correlation between Cambrian Series 2 and Cambrian Series 3

Jin Peng [a,b,*], Yuanlong Zhao [b], Jinliang Yuan [c], Lu Yao [b], Hong Yang [b]

[a] *Department of Earth Sciences, Nanjing University, Nanjing 210093, China*
[b] *College of Resource and Environmental Engineering, Guizhou University (Caijiaguan Campus), Guiyang 550003, China*
[c] *Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China*

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Abstract

The Cambrian trilobite *Bathynotus* is a special morphology of Redlichiid, which is characterized by a wider thorax axis and an 11th macropleural segment bearing a long, backwardly directed spine. Additionally, its 12th and 13th pleural segments are narrow and they terminate at a fulcrum where they fuse together and to the posterior edge of the long macropleural spine. The genus is widely distributed, occurring in North America, Siberia, the Altay-Sayan fold belt of Russia, South China, the Tarim Basin of China, and Australia. It occurs primarily in deposits of the upper part of the continental slope, at the transition between stable platform settings and subsiding margins of the late Early Cambrian. Here, we recognize three species of *Bathynotus* from China, including *B. holopygus* which is widespread around the world. Although six species of *Bathynotus* have been reported from Siberia and the Altay-Sayan fold belt area of Russia, data presented here suggest that only three of these species are valid. *Bathynotus* exhibits a short geological range, with its first occurrence late in the unnamed Cambrian Series 2 and the last appearance datum of *Bathynotus* at the boundary of Cambrian Series 2 and Cambrian Series 3. The late appearance datum (LAD) of *Bathynotus* provides an important global stratigraphic marker of the boundary between Cambrian Series 2 and Cambrian Series 3.
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Keywords: *Bathynotus*; Age; Cambrian Series 2; Boundary; Correlation

1. Introduction

Bathynotus (Hall, 1860) is a special morphology of Redlichiid trilobite, which has a wider thorax axis and an 11th macropleural segment bearing a long, backwardly directed spine. Additionally, the pleurae of the 12th and 13th are narrow, terminating at the fulcrum where they are fused with the macropleural spine. The genus has been found in Cambrian strata in many parts of the world. It has long been a dramatic index fossil for the subdivision of Cambrian System. However, there has been much controversy about its taxonomy and precise age [1–4]. According to the previous reports, the genus *Bathynotus* is diverse, with a total of 14 species described. However, a recent study indicates that many species of *Bathynotus* may not be valid. Here, we provide a discussion of all specimens of *Bathynotus* previously reported in the literature from different regions in the world, with the exception of six species from the Siberian platform and Altay-Sayan fold belt of Russia, which were described based on a few cranidium specimens. We compare those specimens with a large collection of well-preserved complete specimens and serialized larvae from the lower part of the Kaili Formation, eastern Guizhou, China. We argue that there are

* Corresponding author. Tel.: +86 851 8115975; fax: +86 851 4733001.
E-mail address: gzpengjin@126.com (J. Peng).

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only three valid species of *Bathynotus*, namely, the type species of *Bathynotus*, *B. holopygus* (Hall, 1859), *B. kueichouensis* (Lu in Wang et al., 1964) and *B. elongatus* (Zhao, Gong and Huang, 1987). All occurrences of *Bathynotus* lie within the late Early Cambrian or unnamed Cambrian Series 2. The view that the genus also occurs within early Middle Cambrian strata in a single area is also discussed.

Although the Global Stratotype Section and Point (GSSP) for the boundary between Cambrian Series 2 and Cambrian Series 3 has not yet been established, the first appearance datum (FAD) of *Oryctocephalus indicus* is clearly recognized to define the base of Cambrian Series 3. The boundary between Cambrian Series 2 and Cambrian Series 3 marks a turning point in trilobite evolution, coinciding with the mass extinction of the global Redlichiid fauna and the radiation of the corynexochida and ptychopariida. Because *Bathynotus* is a dramatic representative of the Redlichiid and exhibits a short geological range [5–8], study of its taxonomy and precise age is of great significance as the late appearance datum (LAD) of *Bathynotus* in the Lower Cambrian provides an important datum for global stratigraphic correlation between Cambrian Series 2 and Cambrian Series 3.

2. Taxonomy of *Bathynotus*

Since *Bathynotus* (Hall, 1860) was erected, 14 species, one conformis species and some unnamed species have been established based on the materials from America, Russia, Australia and China. Among these, six species from Russia are *B. namanensis* (Lermontova, 1940), *B. granulatus* (Lermontova, 1940) [9,10], *B. anabarensis* (Lazarenko, 1958) [8,11], *B. fortis* (Semashko, 1969), *B. rotundus* (Semashko, 1969) [12], and *B. angularis* (Ogienko, 2001) [13]. Additionally, Lermontova erected the genus *Bathynotellus* similar to *Bathynotus* in 1940 [9]. However, holotype specimens of all six species show only fractured cranidia. We suggest that they are incomplete specimens. Because these species have not yet been well documented, it is not clear whether these six species belong to *Bathynotus* or to another trilobite taxon [4]. Therefore, further work is needed to clarify their taxonomic position. As for *Bathynotellus*, its morphological features are very similar to those of *B. holopygus* (Hall, 1859) without distinct discrepancy. Since it appears to be very similar to a larval specimen of *B. holopygus* (Hall, 1859; see Fig. 1c and d), we suggest that it should be assigned to *B. holopygus* (Hall, 1859). Thus, the type species of *Bathynotellus, B. yermolaevi* (Lermontova, 1940), should be a synonym of *B. holopygus* (Hall, 1859).

The type species of *Bathynotus* comes from the Cambrian strata of northeastern North America. Hall (1859) established *B. holopygus* based on the specimens from the Georgia Formation in Vermont, USA [5,6]. *Bathynotus holopygus* represents the only species of *Bathynotus* found in North America (Fig. 1a–d).

In Australia, only one conformis species of *Bathynotus, B.* cf. *B. holopygus*, occurs in the Cambrian strata of Northern Territory [14,15].

Bathynotus has been well documented in China, and is widespread in the northwest Tarim Basin and in South China, where it occurs in abundance. Before 1990, six species of *Bathynotus* had been established from the materials collected in China. They are *B. kueichouensis* (Lu in Wang et al., 1964) [16], *B. nanjiangensis* (Zhang, 1981) [17], *B. hubeiensis* (Sun, 1982) [18], *B. hunanensis* (Liu, 1982) [19], *B. gaotanensis* (Zhang and Li, 1984) [20], and *B. elongatus* (Zhao, Gong and Huang, 1987) [7]. Zhao et al. [2] examined in detail the complete exoskeleton specimens of *Bathynotus* from the lower part of the Kaili Formation of eastern Guizhou, Southwest China. They compared and discussed the six species that were previously recorded, and presented three species of *Bathynotus*, namely, *B. kueichouensis* (Lu in Wang et al., 1964), *B. gaotanensis* (Zhang and Li, 1984), and *B. elongatus* (Zhao, Gong and Huang, 1987). They also described a new species, *B. sinensis* (Zhao, Gong and Huang, 1990) and some undescribed species. In total, four species of *Bathynotus* occur in the Kaili Formation, namely *B. kueichouensis*, *B. elongatus*, *B. gaotanensis* (Zhang and Li, 1984) and *B. sinensis* nov. sp.

When Yuan et al. reported the trilobite fauna from the Kaili Formation, Taijiang, Guizhou, China in 1997 [21], they thought that *B. hubeiensis* (Sun, 1982) had been described based on the incomplete specimens of *B. kueichouensis* [18], and found that the features of *B. gaotanensis* (Zhang and Li, 1984) were very similar to those of *B. kueichouensis*. Therefore, both *B. gaotanensis* and *B. hubeiensis* should be synonyms of *B. kueichouensis*. Thus, seven species of *Bathynotus* from China that were previously identified should be only five species, including *B. kueichouensis* (Lu), *B. nanjiangensis* (Zhang), *B. hunanensis* (Liu), *B. elongatus* (Zhao, Gong and Huang), and *B. sinensis* (Zhao and Huang, 1990).

Shergold and Whittington [3] restudied all species of *Bathynotus* found globally and suggested that all species of *Bathynotus* from China and *B.* cf. *B. holopygus* from Australia were a synonym of the type species, *B. holopygus*. They explained that the many species of *Bathynotus* established could be resulted from distortion that was caused by post-burial flattening, which made some specimens to become long and narrow, and others broader and shorter. But this explanation is not completely correct. We agree that the type species of *Bathynotus, B. holopygus*, is widespread globally, and that *B. sinensis* should be assigned to *B. holopygus* (Fig. 1a–c). And for two other species, *B. kueichouensis* (Figs. 1i–l and 2e–h) and *B. elongatus* (Figs. 1e–h and 2a–d), from the lower part of the Kaili Formation of eastern Guizhou, their description based on their entire exoskeletons should be accepted [4].

In the recent years, we have conducted fieldwork on the exposures of the Kaili Formation near Balong and Chuangdou villages, Jianghe County, Guizhou Province for the study of the boundary between Cambrian Series 2

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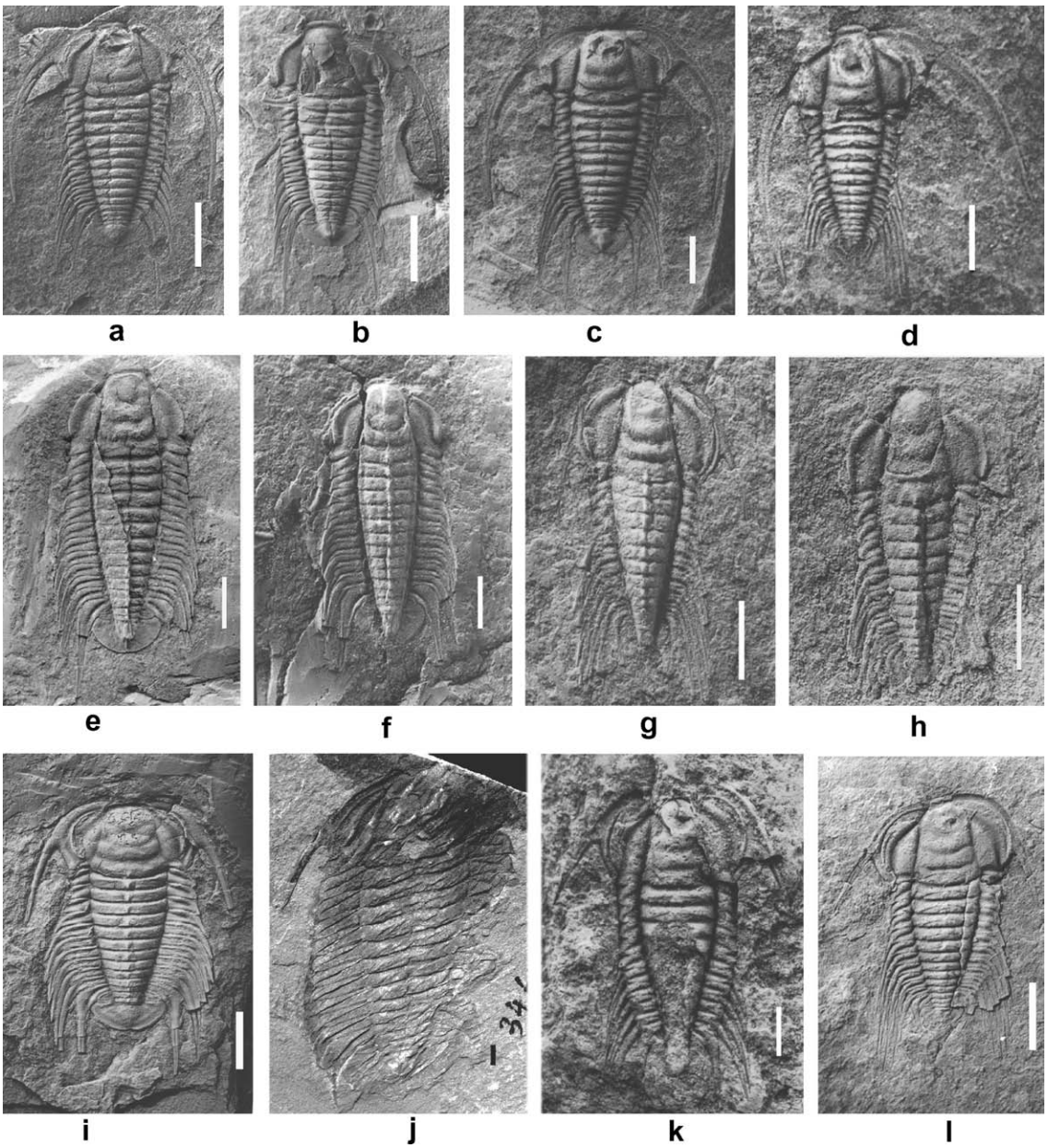

Fig. 1. The trilobite *Bathynotus* from the lower part of the Kaili Formation (Cambrian Series 2 and Series 3), Kaili area, Guizhou, South China. (a–d) *Bathynotus holopygus* (Hall, 1859) from Yanyin Section of the Kaili Formation in Danzhai County, Kaili area. (a) Dorsal exoskeleton, A1-14-1-15; (b) dorsal exoskeleton, A1-11-1-75; (c) dorsal exoskeleton, meraspid specimen, A1-14-1-26-2b; (d) dorsal exoskeleton, meraspid specimen, A1-9-2-36; (e–h) *Bathynotus elongatus* (Zhao, Gong and Haung, 1987), from Wuliu-Zengjiayan Section of Kaili Formation at Balang, Jianghe County (formerly Taijiang County), Kaili area. (e) Dorsal exoskeleton, GTB-7-1-95; (f) dorsal exoskeleton, GTB-7-2-100; (g) dorsal exoskeleton, meraspid specimen, GTB-8-1-23; (h) dorsal exoskeleton, meraspid specimen, GTB-6-1-24. (i–l) *Bathynotus kueizhouensis* (Lu in Wang et al., 1964) from the Wuliu-Zengjiayan and the Jianshan Section of the Kaili Formation at Balang and Chuandong, Jianghe County (formerly Taijiang County). (i) Dorsal exoskeleton, GTB-6-3-25; (j) dorsal exoskeleton, GJCJ-34.60-5, tectonic distortion; (k) dorsal exoskeleton, meraspid specimen, GTB-4-2-60; (l) dorsal exoskeleton, meraspid specimen, GTB-8-1-47. Scale bars are 2 mm in (c and d), (g and h), (k and l) (all meraspid specimens); scale bars for all holaspid specimens are 5 mm.

and Cambrian Series 3. We have collected abundant *Bathynotus* specimens (Fig. 2) from 36.86 to 51.60 m of the Wuliu-Zengjiayan Section, at a 14.76 m interval (for 76 collections spanning 20 cm each) immediately underlying the FAD of *O. indicus* at 52.8 m. We collected 1148 specimens in total, including both holaspids (251) and meraspids (897). We also collected many *Bathynotus* specimens from 9.1 to 43.35 m of the Jianshan Section, at an interval of 32.25 m in thickness, immediately underlying the FAD of *O. indicus* 44.25 m, including specimens that were affected by tectonic distortion (see Fig. 1j). Although numerical tabulation of these collections has not yet finished, these specimens include both holaspid and meraspid ontogenetic stages of *Bathynotus* (Fig. 2).

Specimens of *B. kueichouensis* (Figs. 1i–l and 2e–h) show a wide conic glabella that is shorter than the width of the

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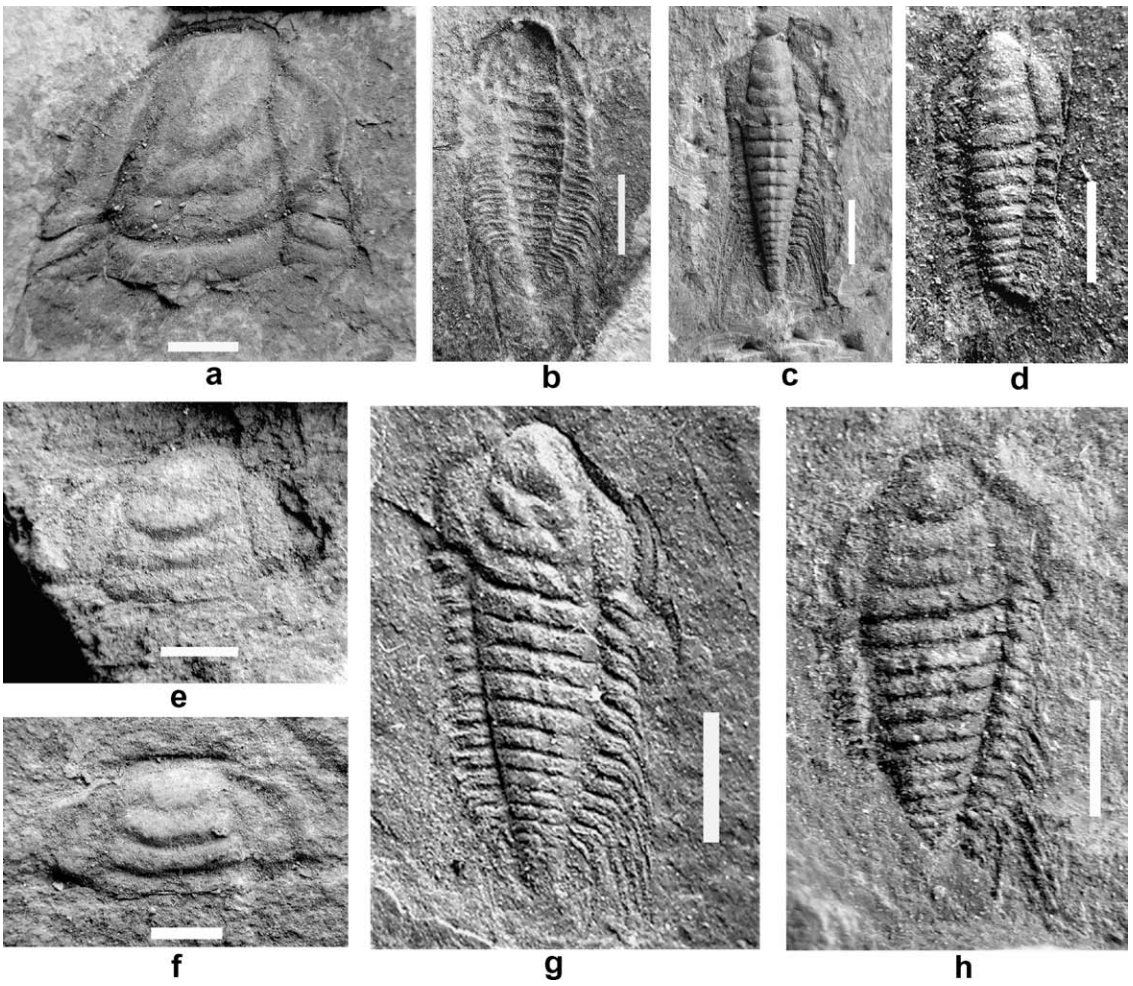

Fig. 2. The trilobite *Bathynotus* from the Wuliu-Zengjiayan Section of the Kaili Formation at Balang, Jianghe County (formerly Taijiang County), Guizhou, South China. (a–d) *Bathynotus elongatus* (Zhao, Gong and Haung, 1987). (a) Cranidium, GTB-38.50-2; (b) dorsal exoskeleton GTB-38.50-1; (c) dorsal exoskeleton, meraspid specimen GTB-30.80-1; (d) dorsal exoskeleton, meraspid specimen, GTB-29.30-1. (e–h) *Bathynotus kueizhouensis* Lu, in Wang et al. (1964). (e) Cranidium, meraspid specimen GTB-27.15-14; (f) cranidium, meraspid specimen GTB-27.8-1; (g) dorsal exoskeleton, meraspid specimen GTB-29.20-1; (h) dorsal exoskeleton, meraspid specimen, GTB-30.80-3. Scale bars in (a) and (b) are 5 mm, for the rest are 2 mm.

basal lobe of the glabella, narrow fixigena that are subtriangular in outline, a curved and round eye ridge, short genal spines extending only to the horizontal position of the 4th segment of the thorax, a wide pygidial margin, and a terminal axial ring that is trans-broad and subtriangular in outline. These specimens are distinct from the typical species of *Bathynotus.* Specimens which were affected by tectonic distortion still show reformation characteristics similar to those of undeformed specimens (see Fig. 1j). Other specimens of *B. elongatus* (Figs. 1e–h and 2a–d) are characterized by thin and elongated exoskeletons, long glabellae, short genal spines, which are longer in meraspid specimens approaching almost one-half of the length of the entire exoskeleton (Fig. 1g and h) [2], narrow fixigena, eye ridges laterally sloping close to the axial furrow of the glabella, a terminal axial ring that is distinct, convex and longer, flat lateral lobes of the pygidium, and a pygidial margin that is not developed (Figs. 1e–h and 2a–d). Comparison with the type species of *Bathynotus, B. holopygus*, reveals that there is an obvious disparity between these species. Moreover, an ontogenetic series of specimens of this species (Fig. 2a–d) indicate that it is distinct from *B. kueichouensis.* This species bears thin and elongated exoskeletons in its natural form, rather than in the form which resulted from tectonic distortion. Clearly, there are three species of *Bathynotus* presented in the Kaili Formation; they are *B. holopygus*, *B. elongatus* and *B. kueichouensis.* However, the type species of *Bathynotus, B. holopygus*, only occurs in the Yanyin Section of the Kaili Formation, more than 100 km away from Jianhe County, in northwestern Danzhai County, Guizhou Province.

There are three species of *Bathynotus* that exhibit a global distribution; however, six species of *Bathynotus* reported from Russia require further work to clarify their taxonomic position.

3. Occurrence and age of *Bathynotus*

According to the previous work, *Bathynotus* is known to be widespread in three large Cambrian faunal realms,

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including Australia-Pacific Ocean realm, Siberia and Laurentia. It occurs mainly in the Siberia platform and Altay-Sayan fold belt of northwestern Siberia. In Laurentia, the type species of *Bathynotus, B. holopygus* (Hall, 1859), occurs only in the Georgia Formation at Parker Quarry, Georgia, NW Vermont [22–24], and in the Pioche Formation of Nevada, western North America [6]. In the Australia-Pacific Ocean realm, *Bathynotus* occurs in the Arthur Creek Formation, and Northern Territory, Australia [3,14,15]. In China, *Bathynotus* is widely distributed in South China, including eastern Guizhou [2,4,7,16], western Hunan [19], southeastern Hubei [18], southern Anhui [20], and western Zhejiang [25]. *Bathynotus* is especially abundant in the Kaili Formation of eastern Guizhou, where a total of 1500 specimens have been collected. *Bathynotus holopygus* only occurs in deeper water facies far from shallow platforms, and *B. kueichouensis* and *B. elongatus* occur in deep-water facies adjacent to shallow platforms. At the same time, it also occurs in the Tarim Basin, Xinjiang, which is located within the Tianshan Geosyncline [17,26]. Obviously, *Bathynotus* occurs primarily in the active belts at the margins of shallow-water platforms [2].

Globally, the occurrence of *Bathynotus* in Cambrian realms is restricted to a brief stratigraphic interval that is the late Early Cambrian in age and occurred at the top of the unnamed Cambrian Series 2. The view that *Bathynotus* occurrence may have been diachronous globally is wrong, because this genus likely originated in terminal Early Cambrian time and disappeared in the initial Middle Cambrian [2,3]. The type species of *Bathynotus*, *B. holopygus*, occurred in the *Olenellus* Zone of the Georgia Formation, Vermont, in the latest Early Cambrian [5,23,27]. It also occurs in the Pioche Formation of the Great Basin, Nevada, USA. The two North American occurrences of *Bathynotus* are of the same age, occurring in the upper *Olenellus* Zone of the Dyeran Stage. In the Pioche Formation of Nevada, *Bathynotus* occurs approximately 2 m below the extinction (LAD) of *Olenellus* [28].

In China, *Bathynotus* has been found in many localities, and it is always associated with *Kunmingaspis, Chittidilla* [2,17,25,29] and *Nangaops* [25] or *Redlichia, Mufushania* and *Chittidilla* [18,21,27,30], which are characteristic fossils that define the stratigraphic interval at the top of the Lower Cambrian, or the terminal Cambrian Series 2, and their ages all belong to late Early Cambrian or later Cambrian Series 2. It is likely that these occurrences represent the same time-span as the range of *Bathynotus* occurrences in North America [31].

In Australia, *Bathynotus* occurs in collections from the Arthur Creek Formation, where it is not associated with other fossils, and its age is therefore uncertain. Öpik, however, assumed that *Bathynotus* cf. *B. holopygus* occurred there in the earliest Middle Cambrian because of the occurrence of *Lancastria* (Kobayashi, 1935) elsewhere in the Arthur Creek Formation. In Vermont, *Lancastria* is associated with the type species of *Bathynotus* [32], but occurred in the initial Middle Cambrian in Australia. Obviously, the supposed early Middle Cambrian occurrence of *Bathynotus* in Australia lacks sufficient evidence.

Six species of *Bathynotus* from Russia were described from five localities, including the Zaledeevo Formation in the vicinity of the Namana River – a tributary of the Angara River [8], the Chara Formation at the Olekma River – a tributary of the Lena River in the Aldan region, the Shumnoy Formation at the Sukharina River in the Igarka region, belonging to the Siberian Platform and Minusinsk, on the Enisey River, south of Krasnoyarsk and east of Novokuznetsk, in western Sayan, and the Mundybash Formation in the Kuznetsk Alatau region. According to the previous reports, *Bathynotus* from the former two localities is late Early Cambrian in age, and that from the latter three localities is Middle Cambrian in age. In Altay-Sayan, Russia, *Bathynotus* from Minusinsk is associated with *Paradoxides, Schistocephalus* and some species of *Anabaraspis*. *Bathynotus* from the Altay-Sayan fold belt co-occurs with *Schistocephalus* in the *Oryctocara* Zone. Indeed, *Paradoxides* was also found in the *Oryctocara* Zone [33–35]. However, *Anabaraspis* occurs in a location below the *Oryctocara* Zone, a key representative of the *Anabaraspis* Zone. Some species of *Anabaraspis* range into the overlying *Oryctocara* Zone [34,35]. In China, *Ovatoryctocara granulate* and *Oryctocephalops* from the *Oryctocara* Zone also occur in the lower part of the Kaili Formation in Guizhou, which was defined as the base of the Middle Cambrian or Cambrian Series 3, below the FAD of *O. indicus.* They coexist with *Redlichia* and *Bathynotus*. As a result, *Bathynotus* from the Altay-Sayan fold belt should be late Lower Cambrian in age or designated to the unnamed Cambrian Series 2. According to Astashkin et al. [8], only *Bathynotus* sp. (*B. anabarensis*; Lazarenko, 1958) from the Shumnoy Formation on the Sukharina River in the Igork area, northwestern Siberia, may differ in age from those mentioned above, because it was found in the *Tomagnostus fissius–Paradoxides sacheri* Zone of the Late Amganian Stage of Middle Cambrian or Cambrian Series 3 [3,8]. Nevertheless, analysis of the fossil assemblage from the Shumnoy Formation, especially from the fraction containing *Bathynotus*, indicates that the position of *Bathynotus* occurrence is in the middle part of ca. 239 m-thick Shumny Formation, assigned to the *T. fissius–P. sacheri* Zone. Its age is uncertain because there are no fossils associated with *Bathynotus* from the *T. fissius–P. sacheri* Zone, or with *Erbia sibirica, Erbia granulosa, Chondragraulos minussensis, Kounamkites routundatus, Peronaspis scutalis*, of which *E. sibirica, E. granulosa* is common in the *Anabaraspis* Zone. The stratigraphic position of *K. routundatus* and *P. scutalis* is obviously higher than that of the above mentioned two species, and the middle part of the Shumnoy Formation cannot be absolutely assigned to the *Tamagnostus fissusi–P. sacheri* Zone; therefore, *Bathynotus* may occur below the *Anabaraspis* Zone. Furthermore, the Shumnoy Formation is a diachronous unit across the Lower and Middle Cambrian, and the age of *Bathynotus* from this area should

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Table 1
Correlation of the boundary interval between undefined Cambrian Series 2 and Series 3 in South China, western North America, and Siberia, Russia.

South China	Western North America	Siberia, Russia
Cambrian Series 3		
Taijiangian	Delamaran	Amgaian
Oryctocephalus indicus Zone	*Oryctocephalus indicus* Zone	*Kounamkites* Zone
Peronopsis taijiangensis	*Microoryctocara nevadensis*	*Peronpsis recta*
Oryctocephalus indicus	*Oryctocephalus indicus*	*Oryctocephalus reynoldsiformis*
Oryctocephalus latilimbatus	*Oryctocephalus indicus* (*O. americaus*)	*Oryctocephalus indicus* (*O. reticulates*)
Oryctocephalus (*Eoryctocephalus*) *yui*		*Ovatoryctocara granulata*
Oryctocephalus indicus		
Cambrian Series 2		
Duyunian	Dyeran	Amgaian
Bathynotusholopgus–Ovatoryctocara granulata Ass. Zone	Upper *Olenellus* Zone	*Oryctocara* Zone
Bathynotus kueizhouensis	*Olenellus*	*O. ovata*
B. holopygus	*Bathynotus holopygus*	*Bathynotus* sp.
B. elongatus		*Oryctocephalops frishcenfeldi*
Redlichia (*R.*) *takoensis longispina*		*Ovatoryctocara granulata*
Ovatoryctoara granulata		
Orcytocephalops guizhouensis		

be the same as that from Siberia. Further investigations are needed to determine the precise age of *Bathynotus* from these localities.

In comparison with the specimens from the three larger Cambrian realms and according to the investigations of its functional morphology, *Bathynotus* has been shown to be a pelagic trilobite characterized by its predatory habit and wide distribution [36]. Therefore, its age should be consistent for all the specimens around the world. We suggest that *Bathynotus* occurring globally are late Early Cambrian or unnamed Cambrian 2 in age. We also consider that the proposed occurrence of *Bathynotus* in an individual area of Siberia at the base of the Middle Cambrian is not true; however, further work is needed to resolve the stratigraphic position of *Bathynotus* at this location.

4. *Bathynotus* for global boundary correlation between Cambrian Series 2 and Cambrian Series 3

Oryctocephalus indicus (Reed, 1910) is an excellent guide species marking the base of Cambrian Series 3 [37–44]. At present, the Wuliu-Zengjiayan Section of Kaili Formation appears to be the most viable candidate for establishing the GSSP for the base of Cambrian Series 3. The trilobite assemblages occurring below and above FAD of *O. indicus* have distinct disparity, which is coincident with the mass extinction of many widespread trilobite groups and with the evolution of new taxa at the Early–Middle Cambrian boundary. This faunal turnover provides an excellent datum for global correlation of this stratigraphic interval. The widespread genus *Bathynotus* is an important representative of trilobite assemblages below FAD of *O. indicus*, and therefore, its precise age has a great significance. In addition to the FAD of *O. indicus*, the LADs of *Bathynotus* and *Redlichia* in Lower Cambrian strata provide the basis for the global correlation between Cambrian Series 2 and Cambrian Series 3 [31,35,37,41] (Table 1).

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