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

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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.

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
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 Ptychociding with the mass extinction of the global Redlichiid Series 3.

The boundary between Cambrian Series 2 and Cambrian Series 3 is widely recognized to define the base of Cambrian Series 2. The view that the genus Bathynotus, B. cf. B. holopygus, occurs in the Cambrian strata of the 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 Chuan-dou villages, Jianghe County, Guizhou Province for the study of the boundary between Cambrian Series 2 and
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 holaspid (251) and meraspid (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 at 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 holaspids 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...
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 typ-ical 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,
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 Dyeren 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 Kunningaspis, Chittidilla [2,17,25,29] and Nagaoaps [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. Ópik, 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 Oryctocerophas 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. anabaresis ; Lazarenko, 1958) from the Shumnoy Formation on the Sukharina River in the Igorky 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 Shumnoy 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 minusensis, Kouamikites 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 Tomagnostus fissius–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
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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