

REVIEW ARTICLE

Proposal and prospects for the global Lower-Middle Cambrian boundary^{*}

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Abstract In recent years paleontologists have been working on the global stratotype section and standard point (GSSP) for the Lower-Middle Cambrian boundary in North America, China, Morocco, Spain and Russia. Continually, they suggest the potential first appearance datum (FAD) of the Middle Cambrian, such as *Oryctocephalus indicus*, *Ovatoryctoara granulata*, *Acadoparadoxides murewensis*, *Hypolenus* and *Arthrocephalus chauveaui* as being relevant to the potential stratotype section for the Lower-Middle Cambrian boundary. There are only a few trilobites distributed widely enough in the Early to Middle Cambrian connection, so virtually no trilobite(s) can act as the FAD for the global Middle Cambrian. The easily identified *Oryctocephalus indicus* is widely distributed in three realms of the global Cambrian. Its first appearance position is linked to the extinction of old species coevolution of new ones. It appears to be a comparatively good FAD of Middle Cambrian. The continuous and unbroken Wuliu section (Balang, Taijiang County, Guizhou Province, China) includes *O. indicus* and co-occurs with many benthic and nektonic trilobites. The evolution of acritarchs in the section, the changed characteristics of trace elements (REE and C isotopes) are generally consistent with the evolution of trilobites both above and below the boundary. Strata above the boundary yield the famous Kaili Biota. The Wuliu section is easily accessible from a main highway.

Keywords: Lower-Middle Cambrian boundary, GSSP, Taijiang Wuliu section, *Oryctocephalus indicus*, FAD (first appearance datum).

The International Commission on Stratigraphy is determined to finish the subdivision of all geological periods before 2009. In order to reach this goal, the International Subcommittee on Cambrian Stratigraphy has held eight field conferences for the Cambrian Stages subdivision. The suggestion of erecting Series and Stages for the subdivision of the Cambrian System in China was first put forward in detail by Peng et al.^[1~3] and has resulted in the Paibi section at Huayuan, Hunan Province becoming the Global Standard Section and Point (GSSP) for the Middle to Upper Cambrian boundary. Significant progress has been made in the study on the Lower to Middle Cambrian boundary near the village of Balang, Taijiang County, Guizhou Province, China.

1 Work and progress of the GSSP from the Lower-Middle Cambrian boundary in China

The full-time study on the Lower-Middle Cam-

brian boundary has been ongoing in China and has seen significant progress^[4~14]. While studying the Kaili Biota, Zhao and others have found a near ideal Lower-Middle Cambrian boundary section in the lower part of the Kaili Formation near Balang and proposed that the beginning of Middle Cambrian may be marked from the extinction of *Bathynotus* and the appearance of *Oryctocephalus*^[11]. Through further study in the Balang section, Yuan et al.^[9] and others regarded *Oryctocephalus indicus* as the best FAD for the Middle Cambrian. Sunderberg and McCollum^[15] also held the same view, which has been confirmed by Shergold, the chairman of the International Subcommittee on Cambrian stratigraphy and Geyer, the secretary^[16].

Some acritarchs from the Middle Cambrian, including *Crystallinium cambriense*, *Retisphaeridium howellii* occur in the *O. indicus* Zone in the Balang section which indicates that there is another acritarch

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assemblage under the *O. indicus* Zone. The assemblage and classification of acritarchs are consistent with the evolution of trilobite assemblages in general^[17, 18], which supports the utility of trilobite stratigraphic division.

In fact, the division of stratigraphic boundary based on the developing stage of the earth's crust evolution^[10], is relevant to sedimentary environment and characters of geochemistry. The evolution of trace element from below and above the boundary in Balang section^[19] has been demonstrated to be consistent with the boundary. Characteristics of trace elements, (rare earth elements and organic carbon isotopes^[20, 21]) from the Pinzhai-Danzhai section are also consistent with division of the Lower-Middle Cambrian boundary.

2 Present condition of the GSSP of the global Lower-Middle Cambrian boundary

Though we began the study on the Lower-Middle Cambrian boundary many years ago, we have been working on the GSSP for only the last 10 years.

Study on the Lower-Middle Cambrian boundary in Morocco^[22~26] and Spain^[27~33] has been well done and important progress has been made. The boundary in Spain was placed between *Hamatolenus* (*H.*) *ibericus* and *Acadoparadoxides mureoensis* zones while the boundary in Morocco lies between *Sectigena* and *Hupeolenus* zones. But, because these trilobites are regional and distributed narrowly in the section, it is difficult to use them in far reaching correlation and they cannot be used as the FAD for the Middle Cambrian.

Siberia-Altai area is an important realm with its well-developed Cambrian. The former USSR and Russian paleontologists have worked on the Lower-Middle Cambrian boundary based on the trilobites *Bathynotus*, *Oryctocephalus*, *Ovatoryctocara* and other *Oryctocephalids*^[34~38]. *Oryctocephalus* in some areas are important fossils^[39] such as in the *Oryctocephalus frischenfeldi*-*Schistocephalus-Paradoxides primus* Zone in the lower part of the Middle Cambrian. Some specimens of *Oryctocephalus* are similar to *O. indicus*^[36, 37]. *Bathynotus* mainly occurs in *Namanoia* Zone of Toyonian Stage^[35, 38, 40, 41] or occurs in the *Edelstenaspis-Kooteniella* Zone (now known as *Anabaraspis splendens* Zone) and is associated with small ptychoparridas in the upper part of the

Toyonian Stage (late Early Cambrian). Recently Russian researchers^[42~45] have suggested that the Lower-Middle Cambrian boundary be placed between *Anabaraspis* and *Oryctocara* zones. Korovnikov^[45] opined that although *Oryctocephalus indicus* is not found in Russia *Oryctocephalus reticulatus* from *Kounamkites* Zone and located above *Oryctocara* Zone is in fact synonymous with *O. indicus*. As a result, the boundary of Lower-Middle Cambrian should lie between *Oryctocara* and *Kounamkites* zones. An acceptable international boundary-section of Lower-Middle Cambrian in Siberian Platform has not been found because of obvious differences in Cambrian biozonation. With further study it may be resolvable.

The top of the Lower Cambrian in North America was first recognized by Walcott^[46], and placed at the top of the *Olenellus* Zone, while the bottom of Middle Cambrian was not determined. Lochman and others^[47] divided the boundary of Lower-Middle Cambrian between the *Olenellus* and *Plagiura-Poliella* zones after analyzing large numbers of fossils. Recently, based on the appearance of "*Eoptychoparia piochensis*", Palmer^[48] erected the Delamarian Stage. However, "*E. piochensis*" occurs only in the state of Nevada. After many years of field work on 15 sections in Nevada, California, Utah, and Arizona, McCollum found that *Oryctocephalus* often occurs above the *Olenellus* Zone. *Oryctocephalus indicus* co-occurs in four areas. Observing that of *O. indicus* is wide-spread, Sundberg and McCollum suggested that the appearance of *O. indicus* may mark the beginning of the Middle Cambrian^[15, 49, 50], which is consistent with the observations of Yuan et al. and Zhao et al.^[15]. As a result, Sundberg, McCollum, Zhao and Yuan cooperated on the project in 1998. They recognized that the division of the Lower-Middle Cambrian boundary is essentially consistent between China and North America^[51].

The boundary of Lower-Middle Cambrian in India and Himalayas was placed between the *Redlichia* and *Oryctocephalus indicus* zones by Jell and Hughes^[52]. *Pagetia significans* and *Oryctocephalus* co-occur in the Himalayas. *Pagetia significans* from Australia associates with *Xystidura templetonensis* of Middle Cambrian^[51, 53, 54] (the lowest fossil zone of Templetonian Stage). The boundary should be in stratigraphical position below *Oryctocephalus* and above *Redlichia*.

The correlation of the Lower-Middle Cambrian

boundary in Morocco, China, North America, Russia and Australia is shown in Table 1.

Table 1. Correlation chart of the Middle-Lower Cambrian boundary in South China with those areas in Morocco, North America, Siberia and Australia

	Morocco	South China	North America	Siberia	Australia
Middle Cambrian	<i>Badulesia tenera</i> Z.	Taijiangian	Delamarian	Amganian	Templetonian
	<i>Kymataspis arenosa</i> Z.				
	?	<i>Oryctocephalus orientalis</i> Z. ▲Kailli biota <i>Oryctocephalus indicus</i> Z.	<i>Glossopleura</i> Z. <i>Albertella</i> Z. <i>Plagiura-Polielka</i> Z. (<i>Oryctocephalus indicus</i>)	<i>Kouanmites</i> Z. (<i>Oryctocephalus reynoldiformis</i> <i>Oryctocephalus reticulatus</i> (<i>indicus</i>))	<i>Dinesus-Xystridura Xystridura templetonensis</i> Z. (<i>Oryctocephalus, Pagetia significans</i>)
Lower Cambrian	<i>Ornamentaspis frequens</i> Z.	Duyunian	Dyeran	Toyonian	Ordian
	<i>Cephalopge notabilis</i> Z.				

3 Proposal of present study on the global Lower-Middle Cambrian boundary

The suggestion of *O. indicus* as the FAD for the Middle Cambrian has been recognized as an important proposal. The strengths of the proposal are: (1) it has well defined characteristics such as conico-cylindrical glabella, glabellar furrows some with rounded pits and a large body size; (2) commonly numerous in areas where it is found; (3) it is wide-spread, in addition to South China and North America it is distributed widely in the Himalayas, Australia, Korea and Siberia^[9, 13, 15, 45, 52, 54], and is not found only in west Gondwana and the Baltic area. Its appearance is consistent with the evolution of middle Cambrian trilobites. In North America or China, it follows the extinction of Lower Cambrian *Olenellus*, *Redlichia*, *Bathynotus*, which are essentially distributed globally.

Recently, *Ovatoryctocara granulata* was proposed as the FAD of the Middle Cambrian^[55] and it is recognized that it can be correlated to Redlichids, Olenellids and Paradoxidids from all realms^[55]. In fact, *O. granulata* also occurs in South China, Greenland, Newfoundland and Siberia. But only a few specimens are found in South China and Newfoundland. What is more, *O. granulata* occurs in

the upper part of the *Redlichia guizhouensis* Zone and associates with *Bathynotus*. If *O. granulata* is as the FAD of Middle Cambrian, the bio-sequence will cause confusion in the two realms from Southeast Asia and North America. Moreover, in addition to arguments over its classification, its distribution is more restricted, and it is not found in North America.

Although Fletcher^[56] has put forward *Arthricocephalus chauveaui* as the FAD for the Middle Cambrian, its distribution is restricted and is found only in Greenland and South China. In spite of *A. chauveaui* wide-spread areal distribution in Cambrian sections in South China, its temporal range is very long and occurs in the same strata with *Palaeolenus*^[57]. As a result, it is difficult to accept this species as the FAD for the Middle Cambrian.

Oryctocephalids are widely spread. They evolved rapidly and demonstrate wide environmental adaptability. Therefore they should be the best FAD for boundary division of the Middle Cambrian. Oryctocephalids, especially major taxa^[58~61], occurring close to the Lower-Middle Cambrian boundary, are not thoroughly studied, e. g. *Oryctocephalus*. The evolutionary sequence of oryctocephalids on a global scale is still not established. This in turn influences

the erection and correlation of the GSSP of the Lower-Middle Cambrian. In the next several years, we shall progress in these evolutionary studies which will help to correlate basal Middle Cambrian strata from all over the world to recognize the FAD for Middle Cambrian. Study will focus especially on *O. indicus*. Fortunately, the oryctocephalid *Tonkinella*^[32] has been found recently for the first time in Middle Cambrian strata from North Spain. This suggests to us that it is quite possible that recognition of world wide evolution within the oryctocephalids will mandate selection of an oryctocephalid as the FAD for the Middle Cambrian.

4 Advantages of the candidate stratotype section from the Lower-Middle Cambrian at Wuliu near Balang Village, Taijiang County, Guizhou Province

The Wuliu section is a near ideal candidate stratotype section for the Lower-Middle Cambrian boundary. Though there are many proposals for division of the Lower-Middle Cambrian, *O. indicus* as the FAD of Middle Cambrian and the candidate section at Wuliu have many advantages. These advantages include:

(1) *O. indicus* first appears 52.80 m above the base of the Wuliu section. The species has only 2 pairs of marginal spines on the pygidium; it may be the most primitive species of the genus and is in the lowest stratigraphic position. A strong case can be made that it is the real FAD of the Middle Cambrian^[57].

(2) Confirmation of GSSP of Lower-Middle Cambrian in Balang, Taijiang is completely consistent with the extinction pattern of Cambrian trilobites. First occurrence of *O. indicus*, as the FAD of Middle Cambrian, is only 0.8 m above the last occurrence of *Redlichia* (which is the major genus of the Lower Cambrian from the Asia-Pacific realm) and only 1.2 m above the last occurrence of *Bathynotus*^[62]. It is also the turning point of the apparent extinction event of Lower Cambrian trilobites^[14, 57, 63].

(3) The evolution of any period of acritarchs is completely in accordance with that of trilobites^[13, 17, 18].

(4) The changed characters of trace elements (REE and the C isotopes) are consistent with the oc-

currence of the FAD from trilobites in general^[19, 20, 21].

(5) The Wuliu section is an important Cambrian section^[64]. The famous Kaili Biota of the Middle Cambrian is above the Lower-Middle Cambrian boundary in Balang, Taijiang. The presence of a famous biota is usually a good supplement to the erection of a boundary stratotype section. Recently, the International Commission on Stratigraphy accepted Edicara as a new name for the system originally known as Sinian in China, or known as Vendarian in Russia, because the system contains the famous Edicara Fauna.

(6) The Kaili Formation in Wuliu is 214 m thick, and it consists mainly of exposed undeformed silty and calcareous mudstone and shale.

(7) The area of Balang, Taijiang belongs to a transition belt, which contains trilobites both benthic and nektonic which is helpful in world wide correlation. There are many oryctocephalids, more than 11 genera^[57, 63], close to the Middle-Lower Cambrian boundary in Balang, which helps to correlate the strata globally as well as the boundary horizon. Under the strata containing *O. indicus* at Wuliu, there are rare occurring *Ovatoryctocara granulata* and *O. sp.* associated with *Redlichia* and *Bathynotus*, located just on the upper part of the whole *Redlichia* strata. Though the conditions of *O. granulata* as the FAD for the Middle Cambrian is not as good as *O. indicus*, both of them may be advantageous in correlating strata from all over the world and in helping to establish the stratotype section for the Lower-Middle Cambrian boundary.

(8) The Wuliu section has very easy access, for it is only 5 km down a well graded road from National Highway 302.

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