SCIENCE CHINA
Earth Sciences

SPECIAL TOPIC: Integrative stratigraphy and timescale of China
•REVIEW•

January 2019 Vol.62 No.1: 25–60
https://doi.org/10.1007/s11430-017-9291-0

Cambrian integrative stratigraphy and timescale of China

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Received November 6, 2017; revised October 9, 2018; accepted October 24, 2018; published online November 29, 2018

Abstract The Cambrian Period is the first period of the Phanerozoic Eon and witnessed the explosive appearance of the metazoans, representing the beginning of the modern earth-life system characterized by animals in contrary to the Precambrian earth-life system dominated by microbial life. However, understanding Cambrian earth-life system evolution is hampered by regional and global stratigraphic correlations due to an incomplete chronostratigraphy and consequent absence of a high-resolution timescale. Here we briefly review the historical narrative of the present international chronostratigraphic framework of the Cambrian System and summarize recent advances and problems of the undefined Cambrian stage GSSPs, in particular we challenge the global correlation of the GSSP for the Cambrian base, in addition to Cambrian chemostratigraphy and geochronology. Based on the recent advances of the international Cambrian chronostratigraphy, revisions to the Cambrian chronostratigraphy of China, which are largely based on the stratigraphic record of South China, are suggested, and the Xiaotanian Stage is newly proposed for the Cambrian Stage 2 of China. We further summarize the integrative stratigraphy of South China, North China and Tarim platforms respectively with an emphasis on the facies variations of the Precambrian-Cambrian boundary successions and problems for identification of the Cambrian base in the different facies and areas of China. Moreover, we discuss stratigraphic complications that are introduced by poorly fossiliferous dolomite successions in the upper Cambrian System which are widespread in South China, North China and Tarim platforms.

Keywords Cambrian, Stratigraphy, Golden Spike, GSSP, Geochronology, South China, North China, Tarim

Citation: Zhu M Y, Yang A H, Yuan J L, Li G X, Zhang J M, Zhao F C, Ahn S Y, Miao L Y. 2019. Cambrian integrative stratigraphy and timescale of China. Science China Earth Sciences, 62: 25–60, https://doi.org/10.1007/s11430-017-9291-0

1. Introduction

As the first Period of the Phanerozoic Eon, the Cambrian is a landmark in Earth history, recording the explosive appearance of animals and marking the revolutionary transition of the earth-life system from one dominated by microbial life in the Precambrian to a modern one characterized by animals. First named in 1835 by Adam Sedgwick, the Cambrian Period was recognized as the "trilobite period" for more than one hundred years until the late 20th century, whereupon various fossils with mineralized shells and skeletons (collectively termed "small shelly fossils" (SSFs)) were discovered in pre-trilobitic strata globally, in addition to numerous fossil-*lagerstätten* from the Cambrian System with extraordinarily well-preserved soft-bodied fossils such as the Chengjiang *lagerstätte*. Systematics of these fossils revealed that almost all animal phyla with complex community structures appeared abruptly during the early Cambrian. This has been regarded as one of the most puzzling evolutionary events, coined the "Cambrian Explosion", and

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has ultimately become a symbol of the Cambrian. Ongoing investigations in recent decades have deepened our understanding of Cambrian earth history. The Cambrian is not only known as the Period which saw the explosive evolution of animals, but also episodic mass extinctions, as well as dramatic perturbations to ocean chemistry and climate (e.g. redox, nutrients and carbon and strontium isotopes). Therefore, the evolution of the Cambrian earth-life system has been one of the research frontiers in earth and life sciences.

However, understanding the evolutionary tempo, mode, and causal links between bio- and geo-events during the Cambrian has been seriously hampered due to difficulties in the regional and global stratigraphic correlation of Cambrian successions. These stratigraphic complications are mainly due to provincialism of the fossils, particularly during the early half of the Cambrian because pelagic trilobites (e.g. agnostids) and conodonts did not appear until the latter half of the Cambrian, leading to an incomplete Cambrian chronostratigraphy. Hitherto, the bases of half of the 10 Cambrian stages remain undefined. Meanwhile, sporadic but high-resolution radiometric age constraints further corroborate these stratigraphic difficulties. The present review aims to summarize the recent advances in, and main problems of, the Cambrian chronostratigraphy both on a global scale and in China in order to provide an up-to-date reference for researchers working in fields related to the Cambrian.

2. Global chronostratigraphy and timescale of the Cambrian

2.1 History review

The term ‘Cambrian’ was first used for rock sequences in North Wales of the United Kingdom by Adam Sedgwick in 1835. It partly overlapped with strata in the same area that were assigned to the Silurian, also named in 1835 by Roderick I. Murchison (Sedgwick, 1852). This problem persisted until the overlapping strata in the area were named ‘Ordovician’ by Charles Lapworth in 1879. Based on the present definition, the Cambrian System corresponds solely to the interval of the “Lower Cambrian” of Sedgwick’s original stratigraphic designation. Since its establishment, the tripartite scheme of Lower, Middle and Upper Cambrian has commonly been adopted, but these series were defined without consensus of chronostratigraphic criteria or radiometric age constraints. The situation did not improve until establishment of the International Commission on Stratigraphy (ICS) following the setup of the International Union of Geological Sciences (IUGS) in 1960. A significant advancement during the 1960s saw absolute age constraints placed upon the three Cambrian epochs or series due to the development of radiometric dating methods (Figure 1; Cowie, 1964). In order to establish the international chronostratigraphic framework, defining the base of the Cambrian became the first priority of the ICS because it is also the base of the Phanerozoic. Therefore, the International Working Group on the Precambrian-Cambrian Boundary led by J.W. Cowie was launched in 1972. From the onset, the working group accepted pre-trilobitic strata that yield rich SSF assemblages and archaeocyathids (as in Siberia) as part of the Cambrian System (Cowie and Glaessner, 1975). The working group task was completed in 1992 after approval by the IUGS of the Global Boundary Stratotype Section and Point (GSSP) for the Cambrian base, defined by the first appearance datum (FAD) of the ichnospecies *Treptichnus pedum* at the Fortune Head section, near the tip of the Burin Peninsula, southeastern Newfoundland (see detail in Brasier et al., 1994a).

While working on the Cambrian base, subdivision of the Cambrian System was also under active consideration. In 1977, Robison and his colleagues suggested that all criteria should be considered to define the number of Cambrian series and the placement of their boundary-stratotypes, and proposed several reference criteria for the series boundaries (Robison et al., 1977). The three Cambrian series were first given names which had been long used for Cambrian strata in their type areas of Great Britain in the Geological Time Scale (GTS) 1982, as proposed by Harland and his colleagues (Harland et al., 1982). Meanwhile, seven Cambrian stages were also named in the GTS 1982, and the pre-trilobite “Tommotian Stage” used in Siberia was adopted as the first stage of the Cambrian System. The Middle Cambrian Series (St Davis’s) was further divided into five sub-stages in the GTS 1989 (Harland et al., 1990; Figure 1).

After approval of the basal Cambrian GSSP in 1992, the International Subcommission on Cambrian Stratigraphy (ISCS) has been promoting the task of subdivision of the Cambrian System. Since 2000, numerous potential criteria for subdividing and defining the Cambrian series and stages have been proposed (Geyer and Shergold, 2000; Shergold and Geyer, 2003; Babcock et al., 2005). The pre-trilobitic interval of the basal Cambrian spans a long time and contains fossil fauna distinguishable from the rest of the Cambrian. As such, it was suggested that the traditional Lower Cambrian be subdivided into two series and thus the four series chronostratigraphic scheme (including a pre-trilobitic series) was proposed and named, as in Avalonia (Landing et al., 1998), Laurentia (Palmer, 1998a) and South China (Peng, 2003). However, the “three series-six stages” scheme of the Cambrian chronostratigraphy was still used in the International Stratigraphic Chart (ISC) in 2004 by the ICS (Gradstein et al., 2004). The present “four series-ten stages” framework of the Cambrian chronostratigraphy was first accepted into the ISC 2005 which was originally proposed by Peng (2004) based on the Cambrian chronostratigraphy of South China and approved by vote of the ISCS in late 2004

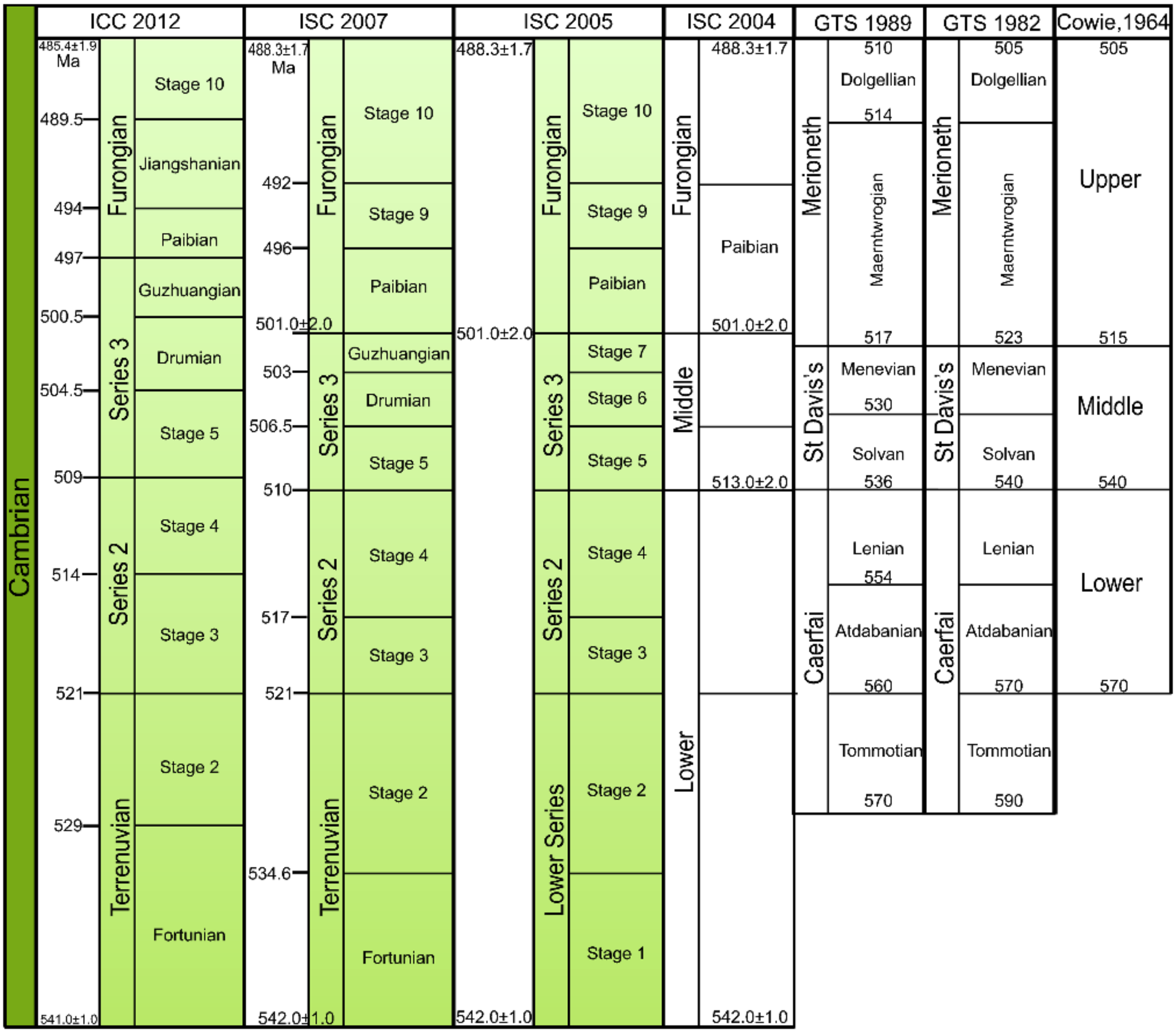

Figure 1 Brief historical summary of the International Cambrian Chronostratigraphy and Timescale. ICC, International Chronostratigraphic Chart; ISC, International Stratigraphic Chart; GTS, Geological Time Scale.

(Babcock et al., 2005). Thus far, GSSPs of the Fortunian (Terreneuvian Series), Drumian, Guzhangian, Paibian (Furongian Series) and Jiangshanian stages have been ratified; the GSSP for the base of Series 3 and Stage 5 (Miaolingian Series and Wuliuan Stage) was recently approved by the IUGS (IUGS E-Bulletin#144), and the definition of Stage 10 has been approved and GSSP candidate sections have been proposed. The remaining task for the ISCS is to subdivide the traditional Lower Cambrian, which includes choosing criteria to define stages 2, 3 and 4, and selecting GSSP candidate sections for these stages (Figure 2) (see ICC 2018; Peng et al., 2012a).

2.2 Ratified Cambrian series and stages

(i) Terreneuvian Series. The name was formally ratified for the first Cambrian series by the IUGS in September 2007. The name "Terreneuvian" is derived from "*Terre Neuve*", the modern French name for the island of Newfoundland where the GSSP of the Cambrian base is located (Landing et al., 2007).

(ii) Fortunian Stage. The first Cambrian stage. The GSSP for the stage was ratified by the IUGS in August 1992 and is defined by the FAD of the trace fossil *Treptichnus pedum* at a point 2.4 m above the base of the "Member 2" of the Chapel Island Formation in the Fortune Head section, situated near the tip of the Burin Peninsula, southeastern Newfoundland, Canada (Brasier et al., 1994a; Landing, 1994). But the stage name was formally ratified by the IUGS in September 2007. The name "Fortunian" is derived from "Fortune Head", the locality name of the GSSP section (Landing et al., 2007).

(iii) Drumian Stage. Cambrian Stage 6. The GSSP for the

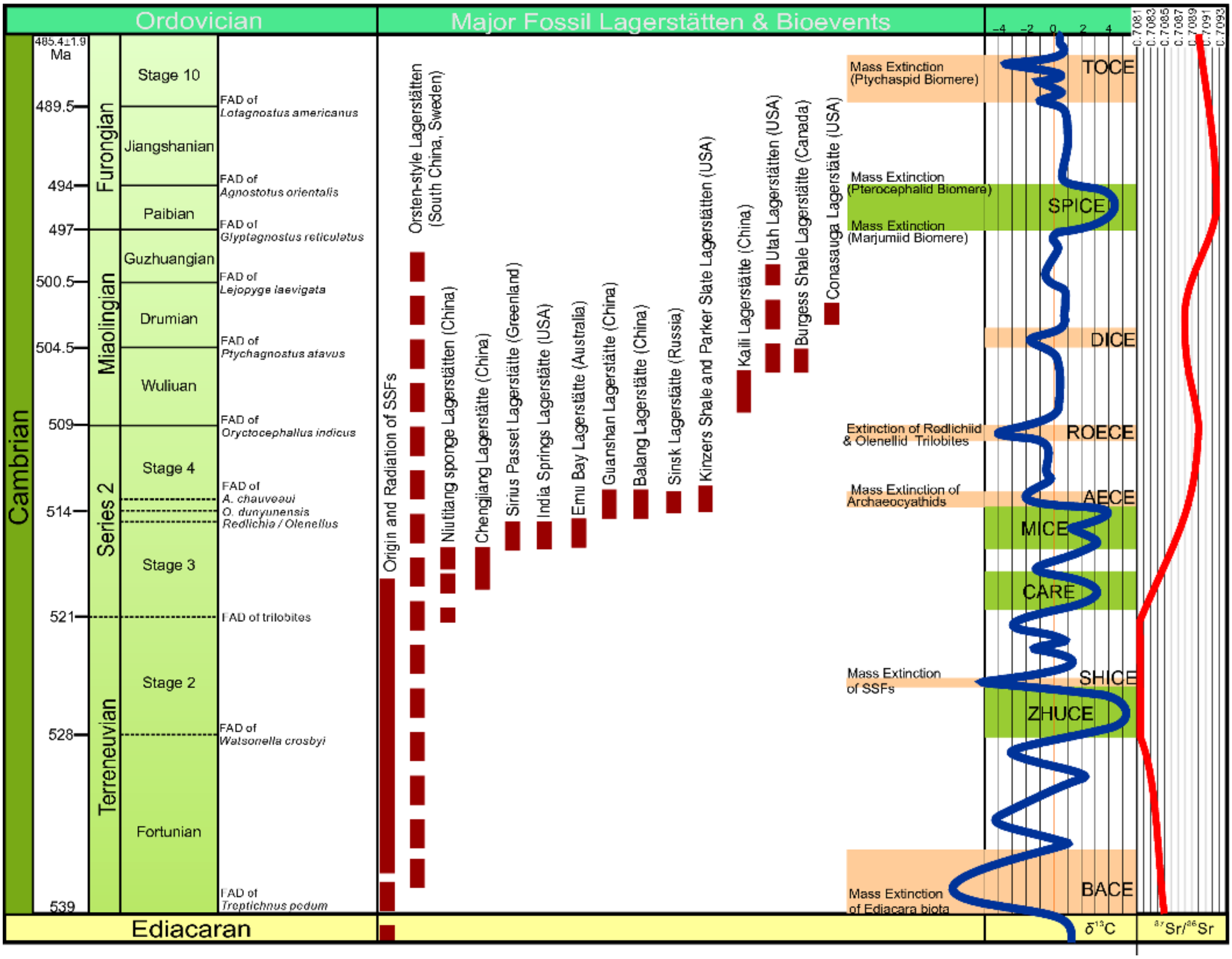

Figure 2 Cambrian chronostratigraphy, timescale and evolutionary events. The $\delta^{13}C$ profile is modified after Zhu et al. (2006) and the $^{87}Sr/^{86}Sr$ profile is adapted from Peng et al. (2012).

stage was ratified by the IUGS during late 2006 and is defined by the FAD of the agnostid trilobite *Ptychagnostus atavus* at the level of 62 m above the base of the Wheeler Formation in the Stratotype Ridge section, Drum Mountains, Utah, USA (Babcock et al., 2007). Useful secondary markers for global correlation of the base of the Drumian Stage include the DICE negative $\delta^{13}C$ excursion and the onset of a long monotonic $^{87}Sr/^{86}Sr$ isotopic shift (Babcock et al., 2007). The stage name is derived from "Drum Mountains", the locality name of the GSSP section.

(iv) Guzhangian Stage. Cambrian Stage 7. The GSSP for the stage was ratified by the IUGS in March 2008 and is defined by the FAD of the agnostid trilobite *Lejopyge laevigata* at the level of 121.3 m above the base of the Huaqiao Formation in the Louyixi section along the Youshui River about 4 km northwest of Luoyixi town, Guzhang County, northwestern Hunan, China (Peng et al., 2009). Secondary global markers for defining the base of the Guzhangian Stage include the appearance of either *L. calva* or *L. armata* and the base of the conodont *Laiwugnathus laiwuensis* Zone just below the base of the stage (Peng et al., 2009). The name "Guzhangian" is derived from the county name of Guzhang where the GSSP section of the stage is located.

(v) Paibian Stage (Furongian Series). Cambrian Stage 8. The GSSP for the Paibian Stage and Furongian Series was ratified by the IUGS in August 2003 and is defined by the FAD of the agnostid trilobite *Glyptagnostus reticulatus* at the level of 369 m above the base of the Huaqiao Formation in the Paibi section, Huayuan County, northwestern Hunan, China (Peng et al., 2004). The base of the Paibian Stage is close to base of the distinct SPICE positive $\delta^{13}C$ excursion, which served as a remarkable secondary global marker for the base of the stage (Peng et al., 2004). The name "Paibian" is derived from "Paibi", the village near the GSSP section.

The name “Furongian” is derived from “Furong”, the Chinese name of “*lotus*” used to be the traditional nickname name for Hunan Province where the GSSP section of the series is located (Peng et al., 2004).

(vi) Jiangshanian Stage. Cambrian Stage 9. The GSSP for the stage was ratified by the IUGS in August 2011 and is defined by the FAD of the agnostid trilobite *Agnostotes orientalis* at the level of 108.12 m above the base of the Huayansi Formation in the Duibian B section, Jiangshan City, western Zhejiang, China (Peng et al., 2012b). The base of the Jiangshanian Stage coincides with the FAD of the cosmopolitan polymerid trilobite *Irvingella angustilimbata* at the GSSP section, and is close to the termination of the SPICE positive $\delta^{13}C$ excursion, both of which can be used as secondary global markers of the base of the stage (Peng et al., 2012b). The name “Jiangshanian” is derived from the name of “Jiangshan City” where the GSSP section of the stage is located.

2.3 Newly ratified GSSP for Cambrian Stage 5 (Series 3)

The base of Cambrian Stage 5 (Series 3) corresponds to the traditional Lower/Middle Cambrian series boundary, which has traditionally been defined by a turnover event of trilobite faunas. Owing to the biogeographic control of the trilobites, particularly during the early Cambrian, there is significant discrepancy in the traditional Lower/Middle Cambrian boundary between different palaeocontinents. In the Oriental Faunal Realm (=Indo-Pacific Realm or North Realm), mainly consisting of areas of East Gondwana such as Australia, Antarctic, southern Asia and China (Lu et al., 1974; Chang, 1980; Zhang, 2006), the boundary was defined by the extinction of the redlichiid trilobites and the appearance of the ptychopariid trilobites. In the Western Faunal Realm (=Boreal-Atlantic or South Realm), consisting primarily of North America, South America, Greenland, Baltica, Eastern Europe and Siberia (Lu et al., 1974; Chang, 1980; Zhang, 2006), the boundary was defined by the extinction of the olenellid trilobites and the appearance of the paradoxid trilobites. However, as a main constituent block of North America, Laurentia has no record of the paradoxids. Intriguingly, the mixed olenellid and paradoxid trilobite faunas have been reported from regions of West Gondwana, including Morocco, Spain and southern France (Geyer and Palmer, 1995). Therefore, the biogeographic control of trilobite distribution has challenged definition of the global Lower/Middle Cambrian boundary, and thus the base of Cambrian Stage 5.

Since the 1970s, the ISCS has been trying to solve this problem (Geyer, 1990). After about 30 years of effort, several global markers have been proposed, including FADs of the species and assemblages of cosmopolitan trilobites and acritarchs (Geyer and Shergold, 2000; Geyer, 2005). Among these, the FAD of an oryctocephalid trilobite *Oryctocephalus indicus* (Reed, 1910) as a primary marker to define Cambrian Stage 5 (originally proposed by Yuan et al., 1997), was eventually approved in two separate votes conducted by the ISCS in December 2000–January 2001 and December 2004–January 2005 (Shergold and Geyer, 2001; Babcock et al., 2005). More than 20 years of investigation across most palaeocontinents demonstrated that the FAD of *O. indicus* is the best global marker for defining the base of Cambrian Stage 5 (e.g. Zhao et al., 2001a, 2012, 2014, 2017).

However, *O. indicus* has never been reported in such areas as Baltica, West Gondwana and Avalonia, and another oryctocephalid trilobite *Ovatoryctocara granulata*, which appears earlier than *O. indicus*, was here proposed as a primary marker to define the base of Stage 5 (Fletcher, 2001, 2003; Geyer, 2005). In fact, *O. granulata* is also absent in Baltica and West Gondwana (Geyer, 2015; Sundberg et al., 2016), therefore it has no advantage over *O. indicus* as a primary marker to define the base of Stage 5 (Zhao et al., 2014, 2017). To reconcile the dispute in global correlation, *O. granulata* can be taken as a secondary marker for global correlation of the base of the Stage 5, because both *O. indicus* and *O. granulata* occur in South China, Siberia and Laurentia and associated trilobites can resolve the problem for intercontinental correlations (Sundberg et al., 2016). Additionally, the FAD of *O. indicus* coincides with the extinction level of the olenellid and redlichiid trilobites (Zhao et al., 2014), and corresponds with the ROECE negative $\delta^{13}C$ excursion (Zhu et al., 2004, 2006). As such, these bio- and geo-events can serve as secondary global markers for the base of Stage 5 (Guo et al., 2010; Gozalo et al., 2013).

In July 2016, the ISCS requested proposals for a GSSP for the base of the Stage 5, using the FAD of *O. indicus* as the primary stratigraphic marker. Two GSSP proposals have been submitted to the ISCS: (1) the Claytonian Stage and Esmeraldian Series from the Split Mountain Section, Clayton Ridge, Esmeralda County, Nevada, USA, proposed by F. A. Sundberg and colleagues; and (2) the Miaolingian Series and Wuliuan Stage from the Wuliu-Zengjiayan section at Balang Village, Jianhe County, in the Miaoling Mountains, eastern Guizhou, China, proposed by Yuanlong Zhao and colleagues. In comparing these two proposals, the Wuliu-Zengjiayan section in Guizhou, China has obvious advantages: the section is more continuous and well exposed, fossils are rich throughout the entire section, there is good accessibility and the location within the National Geological Park includes security and service facilities. Before formal publication of this review, we received news that the Wuliu-Zengjiayan section secured the majority of votes in the working group of the ISCS, and the GSSP for the base of the Miaolingian Series and Wuliuan Stage has been ratified by the IUGS in June 2018 (IUGS E-Bulletin#144).

2.4 Cambrian Stage 10: the defined stage without ratified GSSP

Cambrian Stage 10 is the final stage of the Cambrian System with an upper boundary defined by the base of the Ordovician System. During the late Cambrian, conodont fauna exhibited rapid evolution from protoconodonts through paraconodonts to euconodonts; the latter of which are the most useful index fossils for global chronostratigraphic correlation in post-Cambrian Paleozoic strata. As early as 2000, Geyer and Shergold (2000) proposed use of the base of the euconodont *Cordylodus proavus* Zone to define the highest Cambrian stage. The ISCS approved this proposal by vote in December 2000–January 2001 and established a working group for the stage (Shergold and Geyer, 2001). Miller and colleagues proposed a candidate GSSP for the base of the highest Cambrian stage at the FAD of *C. andresi* in the Lawson Cove section of the Ibex area, Millard County, Utah, USA, during the Fourth Cambrian Congress in Nanjing of 2005 (Miller et al., 2005, 2006). However, the proposal to use euconodonts *C. proavus* and *C. andresi* was rejected by the ISCS in a ballot during November–December 2004 because *C. proavus* and *C. andresi* zones are too close to the base of the Ordovician, thereby making the duration of the highest stages too short when compared to the preceding two stages of the Furongian Series (Babcock et al., 2005). Instead, the majority among ISCS members favored the cosmopolitan agnostid trilobites, *Agnostotes orientalis* (Billings, 1860) and *Lotagnostus americanus* (Kobayashi, 1935), as the primary global markers to define the middle and upper stages of the Furongian and these were proposed by Peng and Babcock (2005) and approved by the ISCS in a ballot during November–December 2004 (Babcock et al., 2005). Recent detailed systematic analyses of the morphological variations and taphonomic bias, as well as stratigraphic and geographic distributions of *L. americanus* and its close species, further confirmed that *L. americanus* is a diagnostic and reliable cosmopolitan species for defining the latest Cambrian stage (Stage 10) (Peng et al., 2015).

The GSSP for the base of Stage 9 (Jiangshanian), as defined by the FAD of *A. orientalis*, had been previously ratified in 2011. At present, two candidate GSSPs for the base of Stage 10, defined by the FAD of *L. americanus*, have been proposed: (1) at 339 m above the base of the Ogon'or Formation of the Khos-Nelege section of the north-eastern Siberian Platform, Western Yakutia, Russia (Lazarenko et al., 2011); and (2) at 29.65 m above the base of the Shengjiawan Formation of the Wa'ergang section, located in Taoyuan County, western Hunan, China (Peng et al., 2013, 2014).

Although use of the conodont species *C. proavus* and *C. andresi* to define the base of Stage 10 was rejected, the FAD of another euconodont species, *Eoconodontus notchpeakensis* (Miller, 1969), that occurs earlier than *C. proavus* and *C. andresi*, was instead proposed, at a candidate GSSP 3 m above the base of the Red Tops Member of the Notch Peak Formation at the Steamboat Pass section, House Range, western Utah, USA (Landing et al., 2011; Miller et al., 2011, 2015). As emphasized by the advocates of this GSSP, the FAD of *E. notchpeakensis* is just below a prominent negative $\delta^{13}C$ excursion (HERB), which has been reported from several palaeocontinents and can be used as an auxiliary global marker, thereby suggesting that the new proposal has advantages over the use of the FAD of *L. americanus* in defining the base of Stage 10 (Landing et al., 2011; Miller et al., 2011, 2015).

Conodont biostratigraphy of the Wa'ergang section in western Hunan, China (a proposed GSSP candidate section) shows that the FAD of *L. americanus* coincides with the base of the conodont *Proconodontus posterocostatus* Zone, which is separated from the *E. notchpeakensis* Zone by the *Proconodontus muelleri* Zone (Bagnoli et al., 2017). This indicates that the FAD of *E. notchpeakensis* is much later than the FAD of *L. americanus* and still too close to the base of the Ordovician. Moreover, new chemostratigraphic data from the Wa'ergang section and global correlation demonstrates that at least three negative $\delta^{13}C$ excursions occurred in the uppermost Cambrian, of which the HERB excursion is the latest (Li et al., 2017). Importantly, the earliest $\delta^{13}C$ excursion, which represents the onset of a new $\delta^{13}C$ anomaly postdating the SPICE excursion in the early Furongian, is immediately above the FAD of *L. americanus* in the Wa'ergang section. Both bio- and chemostratigraphic information suggests that the FAD of *L. americanus*, rather than that of *E. notchpeakensis*, remains a better marker to define the base of Stage 10 and the Wa'ergang section in Hunan, China is the most competitive candidate GSSP section so far.

2.5 The undefined Cambrian stages

Stage 2, Stage 3 and Stage 4 are the remaining undefined Cambrian stages. Subdivision of the traditional Lower Cambrian is a long-standing problem in Cambrian stratigraphy (Palmer, 1998b; Geyer and Shergold, 2000; Rozanov et al., 2008a). The lower Cambrian sequences, composed predominantly of carbonate in Siberia (Russia) are well exposed and fossiliferous. A four-stage chronostratigraphic framework (Tommotian, Atdabanian, Botoman and Toyonian) has been in use since the 1960s (Rozanov et al., 1969) and has been widely co-opted in Cambrian stratigraphic terminology. The Tommotian and Atdabanian stages have even been adopted in the GTS 1982 and later versions (Figure 1). However, the Lower Cambrian stages in Siberia were established based on the traditional "unit stratotype" concept, so the definitions of these stages do not meet the "boundary stratotype (GSSP)" concept according to the international stratigraphic guide (Cowie et al., 1986; Salvador, 1994), requiring new subdivision of the lower Cambrian and definitions of the stages based on the GSSP concept.

In 2005, an International Working Group on Subdivision of the Lower Cambrian was launched. The goal of this working group is to identify the most suitable horizons for establishing stage-level and series-level GSSPs within the first and second series of the Cambrian System. In order to achieve this goal, the prior task of the working group focused on correlations of the lower Cambrian sequences between Siberia and South China, the two well-known key areas where the lower Cambrian sequences are rich in fossils and have been well investigated. Based on discussions that took place during the Sino-Russian bilateral symposia held in Nanjing (September 26–29, 2006) and Moscow (September 17–21, 2007), some agreements have been reached concerning the integrated correlations of lower Cambrian stratigraphy between Siberia and South China (Zhu et al., 2007; Rozanov et al., 2008b). Furthermore, Zhu et al. (2008) proposed a working model for subdivision of the Lower Half of the Cambrian during the 13th International Field Conference of the Cambrian Stage Subdivision Working Group held in Yakutsk, Siberia, 2008. Subsequently, the ISCS established respective working groups for Stage 2, Stage 3 and Stage 4 to promote research in identifying GSSPs for these stages (Peng and Babcock, 2011). After a decade of global efforts, numerous datasets and detailed information have been obtained, yet no consensus has been reached. Here we briefly summarize the advances and perspectives on the bases of these lower Cambrian stages.

2.5.1 Cambrian Stage 2

Defining the base of Cambrian Stage 2 demands consideration of how best to subdivide the Terreneuvian Series. The Terreneuvian is the first Cambrian series, embracing the pre-trilobitic Cambrian strata and encompassing ca. 20 million years, equivalent to one third of the entire Cambrian Period. The Terreneuvian Epoch is characterized by the rapid appearance of biomineralized animal fossils (SSFs) that achieved their greatest disparity and diversity after the first appearance of archaeocyathid sponges during the middle Terreneuvian, representing at this time the first peak stage of the Cambrian Explosion. This distinct evolutionary event was well documented globally during the late half of the last century, particularly in Siberia where the earliest archaeocyathid fauna are recorded. In Siberia, the strata containing SSFs below the earliest archaeocyathid fauna constituted the Nemakit-Daldynian Stage (Missarzhevsky, 1989), whereas the strata that hosted archaeocyathids and abundant SSFs below the first appearance of trilobites corresponded to the Tommotian Stage (Rozanov et al., 1969). The Tommotian was used as the first stage of the Cambrian from the beginning in the former USSR and worldwide since the 1980s (Harland et al., 1982). In Russia, the base of the Tommotian Stage is still used as the base of the Cambrian (Zhamoida, 2015). However, the SSF faunas have been generally regarded as Cambrian in age, as in South China where the strata containing the most abundant SSF fauna (Meishucun fauna) were largely regarded as occupying a position below the Tommotian Stage (Tommotian fauna) (Qian Y et al., 2001). Importantly, *T. pedum*, the marker fossil for defining the base of the Cambrian, occurs below strata corresponding to the Tommotian Stage in Siberia, South China and Newfoundland (Zhu, 1997; Narbonne et al., 1987; Rogov et al., 2015). So, it is certain that the base of the Tommotian Stage is above the base of the Cambrian. Since the Tommotian fauna is so characteristic, its first occurrence datum can be considered to define the base of Cambrian Stage 2.

As reef-builders, the archaeocyathid sponges shared similar life habits to other reef-building animals, favoring warm and clear water condition and therefore exhibited endemicity. Up to present, the earliest archaeocyathid fossils have only been reported from Siberia, which is thus regarded as the origination center of the archaeocyathids (Rozanov, 1992). As such, it is difficult to use the archaeocyathids for global biostratigraphic correlation. In contrast, the early mollusks were abundant and evolved rapidly during the Terreneuvian. Due to the possible long trochophore stage, these early mollusks have worldwide distribution, and therefore show great potential for global correlation (Gubanov, 1998, 2001; Gubanov et al., 1999). Among the mollusks that co-occurred with the earliest archaeocyathids is *Watsonella crosbyi*, the FAD of which has been proposed as a potential marker to define the base of Cambrian Stage 2 (Zhu et al., 2006, 2008; Li et al., 2011). This marker fossil has been proposed due to (1) its global distribution as reported in Siberia, South China, Newfoundland, western Mongolia, southern France and South Australia; and (2) its FAD coinciding with the onset of the ZHUCE, a most prominent δ^{13}C positive excursion in the basal Cambrian (Zhu et al., 2006). The proposal was supported by recent investigations of *W. crosbyi* in Siberia, southern France and South Australia (Devaere et al., 2013; Jacquet et al., 2017; Kouchinsky et al., 2017). Meanwhile, another widespread mollusk, *Aldanella attleborensis*, which first appears in a similar stratigraphic horizon to that of *W. crosbyi*, has also been proposed as a marker for the base of Cambrian Stage 2 (Parkhaev et al., 2011, 2012; Steiner et al., 2011).

In addition to the mollusks, early Cambrian acritarchs have been widely used for stratigraphic correlation (Moczydłowska, 1991; Moczydłowska and Zang, 2006; Moczydłowska and Yin, 2012). Two acritarch biozones have been established in the Terreneuvian: the lower *Asteridium tornatum-Comasphaeridium velvetum* Zone and upper *Skiagia ornate-Fimbrioglomerella membranacea* Zone. The characteristic *Skiagia ornata* in the upper zone, which has been reported from South China, South Australia, Newfoundland, southwestern Europe and Baltica, was also proposed as a potential marker for the base of Cambrian Stage 2 (Moczydłowska and Yin, 2012). However, *S. ornata* exhibits great discrepancy in stratigraphic distribution, and its earliest occurrence is usually higher than that of *W. crosbyi* and *A. attleborensis*, possibly close to the horizon of the first trilobites (Moczydłowska and Zang, 2006). As such, further work remains to solve this problem.

Landing et al. (2013) argued that early Cambrian fossils are characterized by diachronous FADs and it therefore is infeasible to use the FAD of a fossil to define the base of a global chronostratigraphic unit during this time. Alternative non-biostratigraphic tools, particularly carbon isotope excursions, should be applied (Maloof et al., 2010; Landing and Geyer, 2012; Landing et al., 2013). The ZHUCE δ^{13}C positive peak, which is bracketed by the lower ranges of *W. crosbyi* and *A. attleborensis* and the *S. ornate*-*F. membranacea* Zone, has been proposed to define the base of Cambrian Stage 2. The "Laolinian Stage" has thus been suggested, with a base defined by the ZHUCE δ^{13}C positive peak at the Laolin section in Huize County, northeastern Yunnan, South China (Landing and Geyer, 2012). Other researchers have argued that, while carbon isotope chemostratigraphy is useful for correlation, defining the GSSP based on δ^{13}C values is subjective and ambiguous (Steiner et al., 2013; Steiner and Yang, 2017). In fact, the GSSP of the base of the Eocene Series and Ypresian Stage provides a paradigm for the use of carbon isotope excursions in defining these GSSPs. The GSSP for the base of the Eocene Series is defined by the onset of a prominent δ^{13}C negative excursion rather than an absolute δ^{13}C value, which has been well recorded in both marine and terrestrial sequences in the Dababiya Quarry, south of Luxor, Egypt (Aubry et al., 2007). In this context, whether a fossil FAD or a non-biostratigraphic marker (event stratigraphy, particularly a carbon isotope excursion) is more feasible to define a GSSP depends upon which one is more reliable for global correlation. It should be noted that the "Laolinian Stage" proposed by Landing and Geyer (2012) for the Cambrian Stage 2 remains an invalid name until the primary marker for defining the base of Cambrian Stage 2 is approved by the ISCS.

Based on the available data, we find that use of the FAD of *W. crosbyi* as the primary marker and the base of the ZHUCE positive δ^{13}C excursion as a secondary marker to define the base of Cambrian Stage 2 is more favorable. The potential candidate GSSPs applicable to this definition can be selected in Siberia or South China. In Siberia, the type sections of the Tommotian Stage are located in the southeastern area where a distinct unconformable surface developed at the base the Tommotian Stage (e.g. Knoll et al., 1995). However, the best sections are located in northern Siberia, where the FAD of *W. crosbyi* occurs at the base of the I'(=ZHUCE) δ^{13}C excursion below the FAD of the earliest archaeocyathid *Nochoroicyathus sunnaginicus* which is, in turn, the marker fossil for the base of the Tommotian Stage (Landing and Kouchinsky, 2016; Kouchinsky et al., 2017). In South China, the best sections are located in the Huize and Yongshan areas of northeastern Yunnan, where the FAD of *W. crosbyi* occurs near the onset of the ZHUCE δ^{13}C excursion at the base of the Dahai Member of the Zhujiaqing Formation (Zhang et al., 1997; Li et al., 2001).

2.5.2 Cambrian Stage 3

Using the first appearance of trilobites to define the base of Cambrian Stage 3 and Series 2 is a traditional concept (Babcock et al., 2005). As pointed out above, however, provincialism of the trilobites makes global correlation difficult. In particular, the widespread unconformity at the base of the Cambrian leads to the diachronous FAD of trilobites. So, defining the base of Stage 3 has been one of the most difficult stratigraphic problems (Palmer, 1998b; Geyer and Shergold, 2000; Babcock et al., 2005; Álvaro et al., 2014; Zhang et al., 2017).

To date, possible earliest trilobites include *Profallotaspis jakutensis* and *Profallotaspis tyusserica* from Siberia (Bushuev et al., 2014); *Fritzaspis generalis* and *Profallotaspis*? sp. from west Laurentia (Hollingsworth, 2007, 2011); and *Eofallotaspis tioutensis* and *Hupetina antiqua* from Morocco (Geyer, 1996). *Parabadiella huoi*/*Abadiella huoi* from South China and South Australia have been regarded as the earliest trilobites correlative to those from Siberia, Laurentia and Morocco (Zhang, 1987; Zhang et al., 2001; Yuan et al., 2011). Whether *Parabadiella* from South China is a synonym of *Abadiella* from South Australia and Morocco remains controversial (Jell, 1990; Zhang et al., 2001; Lin, 2015; Zhang et al., 2017), however these are not the earliest trilobites and appeared much late than those from Siberia, Laurentia and Morocco (e.g. Zhang et al., 2017).

Since it is difficult to use the FAD of trilobites for the base of Stage 3, are there any other potential fossil markers that can be used? Based on the available data, first appearances of several characteristic fossils are associated with the FAD of trilobites, including bradoriids, brachiopods, some mollusk species (e.g. *Pelagiella subangulata*) and other SSFs (e.g. *Microdictyon*). When comparing these potential markers, the mollusk *P. subangulata* is the most favorable species since it has been reported in Stage 3 from South China, South Australia, Siberia, and Newfoundland (Gubanov et al., 1999; Steiner and Li, 2009; Steiner et al., 2011; Betts et al., 2016). Integrated correlations indicate that the FAD of *P. subangulata* is diachronous, but usually post-dates the FAD of trilobites. Based on SSF biostratigraphy, however, Betts et al. (2016) considered that *Abadiella huoi* was the earliest trilobite and appeared simultaneous to those from Siberia, Laurentia and Morocco and the FAD of *A. huoi* could therefore be a marker for the base of Stage 3. However, the correlation of Betts et al. (2016) conflicts with the correlation based on bio- and chemostratigraphy on the global scale (Kruse et al., 2017), since their correlation assigned these bradoriids, brachiopods, archaeocyathids, *P. subangulata*, and *Microdictyon*, which are usually reported from post-trilobitic strata on other palaeocontinents, to the Terreneuvian.

Among the SSFs, the cap-shaped shelly fossil *Mobergella* is another potential marker for the base of Stage 3 as suggested by Rozanov et al. (2011) due to its worldwide distribution as reported from Greenland, Baltica, Siberia, Kazakhstan, and western Mongolia (Skovsted, 2003). Particularly in Siberia, *Mobergella radiolata* from the archearcyathid *Retecoscinus zegabarti* Zone, first occurs near the base of the Atdabanian Stage, slightly earlier than the FAD of *Profallotapsis jakutensis*. Therefore, *M. radiolata* was proposed as a marker for the base of the Atdabanian Stage (Yakutian Series) in Russia (Rozanov et al., 2011; Demindenko et al., 2012).

In addition to shelly fossils (*P. subangulata* and *M. radiolata*), the acritarch species *Skiagia ornata* and *Skiagia ciliosa* may also be useful for identification of the base of Stage 3 (Moczydłowska and Yin, 2012). However, synchroneity in the FADs of all of these non-trilobite fossils remains uncertain (Zhang et al., 2017). Due to the problems noted above, non-biostratigraphic tools should not be excluded in definition of the base of Stage 3 (Babcock et al., 2005). Landing and Geyer (2012) proposed that the δ^{13}C IV peak in the lower Atdabanian of Siberia might be a suitable marker to define Series 2 and Stage 3, despite its position above the FAD of the first trilobite horizon. Accordingly, they suggested "Lenaldanian Series" and "Zhurinskyan Stage" for Series 2 and Stage 3 based on the type section of the Atdabanian Stage in Siberia (Landing et al., 2013). The proposal requires further investigations because the global significance of the δ^{13}C IV peak in Siberia (=CARE, Zhu et al., 2006) remains uncertain due to the absence of carbonate sequences across the Terreneuvian Series and Series 2 in major palaeocontinents including Laurentia and South China.

It is clear that much work remains to be done in defining the base of Stage 3 and Series 2. Similar to the problems applicable to Stage 2, multi-stratigraphic markers (bio- and chemostratigraphy) should be considered. The sections in Siberia and Morocco may provide solutions to the problem, because (1) the earliest trilobites have been reported in both areas, and (2) continuous carbonate sequences coincident with these earliest trilobites were developed, allowing high-resolution chemostratigraphic investigation.

2.5.3 Cambrian Stage 4

To define the base of Cambrian Stage 4 requires consideration of how best to subdivide Cambrian Series 2. As is the case for the designation of other chronostratigraphic units, life evolution should be a fundamental aspect considered. Needless to say, the second Epoch of the Cambrian was the most evolutionarily profound time both in the Cambrian Period and throughout Earth history. Firstly, in addition to the appearance of trilobites, almost all metazoan body plans and phyla appeared as evidenced by fossils preserved within numerous *fossil-lagerstätten* such as the Chengjiang, South China, thus demonstrating that the Cambrian Explosion reached its peak early in Epoch 2. Subsequently however, the Cambrian evolutionary fauna experienced a major extinction event, with the extinction rate second only to that experienced in the end-Permian (Benton, 1995). The extinction interval ranged from the middle until the end of Epoch 2, consisting of two stages (1) the "Sinsk event" or the mass extinction of archaeocyathids; and (2) the "Hawke Bay" event or the mass extinction of the olenellid and redlichiid trilobites (Zhuravlev and Wood, 1996; Zhu et al., 2006). These events have not been granted as much attention as the other 'big five' extinctions in the Phanerozoic, however possible driving mechanism for these extinctions may include (1) oceanic anoxia resulted from global volcanic activity (Hough et al., 2006; Jourdan et al., 2014); and (2) large amplitude eustatic changes, including the great regression between Hongjinshao and Wulongqing Formations in eastern Yunnan and its corresponding level in South China, the Leonian regression in the Mediterranean area and the Hawke Bay regression in Baltica (Zhuravlev and Wood, 1996; Yuan and Ng, 2014; Nielsen and Schovsbo, 2015). Based on biotic evolution, the mass extinction of archaeocyathids can be used to subdivide Cambrian Epoch 2 into two stages: an early stage characterized by diversification of animals, and late stage characterized by the mass extinctions (Zhu et al., 2008).

Accompanying extinction of the archaeocyathids was a rapid turnover in trilobite faunas. In the two trilobite biostratigraphic realms, *Redlichia* and *Olenellus*, which constitute two diagnostic fossils of late Epoch 2, went extinct at the end of Epoch 2. Therefore, the FADs of *Redlichia* and *Olenellus* were first considered as potential markers for the base of Stage 4 (Babcock et al., 2005). Subsequently, the FADs of *Judomia* and *Bergeroniellus*, the trilobites near the boundary between Atdabanian and Botoman stages in Siberia, were proposed (Babcock et al., 2011; Peng et al., 2012a). However, all of these trilobites were found in shallow water facies and were thus endemic, without potential for global correlation. In order to overcome this problem, use of the FADs of pelagic eodiscid trilobites *Triangulaspis annio* and *Hebediscus attleborensis* was proposed (Korovnikov, 2012).

It is noted that oryctocephalids, another pelagic trilobite group, first appeared in mid-Epoch 2 and exhibited rapid evolution with well-established successions, thereby providing a better option for identifying the base of Stage 4

(Yuan et al., 2001, 2006, 2009; McNamara et al., 2003). As early as 2000, Peng et al. suggested using the FAD of the oryctocephalid *Arthricocephalus duyunensis* (later replaced by *Arthricocephalus chauveaui*, Peng, 2003), to define the base of the Duyunian Stage (=Stage 4) in the slope area of South China. However, the FAD of *A. chauveaui* is too high and was instead to be considered as the marker for the base of Stage 5 (Geyer, 2005). Alternatively, an early oryctocephalid species *A. jiangkouensis*, which was recently assigned to *Oryctocarella duyunensis* (Peng et al., 2017), was proposed to define the base of the Duyunian Stage (Yuan et al., 2011; Yuan and Ng, 2014).

It can be seem from the above discussion that three different trilobite levels have been suggested for the base of Stage 4. Among them, the FADs of *Redlichia*, *Olenellus*, *Judomia* and *Bergeroniellus* are the lowest ones, approximately coinciding with the mass extinction of archaeocyathids and a great regressive event; the FAD of *O. duyunensis* coincides with a global sea-level rise following this regression; and the FAD of *A. chauveaui* is the highest (Yuan et al., 2011). Robust evaluation as to the feasibility of these three levels is presently limited by the dearth of new data and further detailed investigations are required. Meanwhile, as with stages 2 and 3, other bio- and non-biostratigraphic tools should be considered. Zhu et al. (2008) suggested that the AECE δ^{13}C excursion, which coincides with the mass extinction of archaeocyathids, can be considered as a marker to identify the base of Stage 4, however high-resolution carbon isotope data during Cambrian Epoch 2 are scarce, requiring more studies on a global scale.

2.6 Deficiency of the GSSP for the Cambrian base and global correlation dilemma

Since ratification of the GSSP for the Cambrian base in 1992, as defined by the FAD of the ichonspecies *Treptichnus pedum* at the Fortune Head section, Burin Peninsula, Newfoundland, Canada (Brasier et al., 1994a; Landing, 1994), difficulties have been encountered in its global correlation (e.g. Rozanov et al., 1997; Zhu, 1997; Zhu et al., 2001, 2003; Qian et al., 2002; Peng and Babcock, 2011). Setting aside issues relating to trace fossil taxonomy, the taphonomic bias of *T. pedum* leaves identification of its first occurrence ambiguous and diachronous. Although preservation of both trace and body fossils is constrained by sedimentary facies, the fossilization potential of body fossils is controlled by decay resistance, whereas the preservation of trace fossils, which record animals moving on and burrowing within the sediments, is controlled by a greater number of factors including physical and chemical condition of the sediments and their process of deposition. Subsequent discovery of *T. pedum* 4.4 m below the GSSP further highlights this problem (Gehling et al., 2001). However, the more fatal problem is that no secondary chemostratigraphic marker and radiometric age for global correlation is available in the Fortune Head section. Due to limitations of space, further deficiencies of the Fortune Head section as a GSSP are not herein discussed.

Landing et al. (2013) also emphasized these fundamental problems with the basal Cambrian GSSP as currently defined, however they argued that "the FAD of any fossil likely underestimates its true lowest occurrence in any section", and similar problem "will apply to all FAD-based candidates in this stratigraphic interval". To overcome such problems, they revised the primary definition by de-emphasizing the significance of the *T. pedum* FAD, and redefined the GSSP horizon at the base of an assemblage zone within a succession of biotas (Landing et al., 2013; Geyer and Landing, 2016; Buatois, 2017). They state that "the position of the coterminent bases of the Cambrian System, Terreneuvian Series, and Fortunian Stage at the Fortune Head section coincides with the base of the *T. pedum* Ichnozone Assemblage, which has its base defined immediately above the highest occurrences of *H. podolica* and *P. delicates*" (Landing et al., 2013, p.145). However, the new definition for the GSSP of the Cambrian base is ambiguous: (1) the highest occurrences of *H. podolica* and *P. delicates* are right below the GSSP and above the FAD of *T. pedum* in the Fortune Head section (Narbonne et al., 1987; Gehling et al., 2001). If the FAD of *T. pedum* is not used, how is the base of the *T. pedum* Ichnozone defined? (2) *H. podolica* and *P. delicates* are body fossils with limited geographic distribution, and are usually not found in sections with co-occurring *T. pedum*. Therefore, the revised definition further complicates identification of the Cambrian base. Importantly, the redefinition remains invalid until it is approved by the ISCS, ICS and IUGS. The original concept of using the first occurrence of complex traces was derived from the outdated understanding of a two-stage radiation of the Cambrian evolutionary fauna (the appearance of Phanerozoic-aspect trace producers and subsequent origin of diverse skeletonized metazoans) (e.g. Landing, 1994). In fact, complex trace fossils have been reported in the terminal Ediacaran and occur together with the typical Ediacara fossils from the middle Dengying Formation of South China (Chen et al., 2013, 2018) and the Nama Group of Namibia (Jensen et al., 2000; Jensen and Runnegar, 2005; Macdonald et al., 2014). More recent data demonstrate successive evolution between Ediacaran and Cambrian faunas (e.g. Smith et al., 2016a; Yang B et al., 2016; Zhu et al., 2017a), suggesting that using the concept of the first occurrence of *T. pedum* or other complex trace fossils to define the Cambrian base is questionable and should be revised.

These problems with the GSSP of the Cambrian base led to the application of different definitions for the Cambrian base in different palaeocontinents and areas. One widely used marker for the Cambrian base is the BACE negative δ^{13}C excursion, which has been recorded from the Ediacaran-Cambrian boundary interval in most palaeocontinents (Magaritz et al., 1986, 1991; Zhang et al., 1997; Kimura et al., 1997; Zhu et al., 2006, 2017a; Kouchinsky et al., 2007; Li et al., 2009, 2013; Maloof et al., 2010; Smith et al., 2016a, 2016b). The age of 541 Ma adopted for the Cambria base in the ISC 2012–2018 pertains to a zircon U-Pb age at the base of the BACE δ^{13}C excursion, coinciding with the extinction of *Cloudina* from the Ara Group in Oman (Amthor et al., 2003; Bowring et al., 2007). Contrastingly, in the General Stratigraphic Scale of Russia (GSS), the base of the Tommotian Stage is still used for the Cambrian base (Khomentovsky and Karlova, 2005; Rozanov et al., 2008a; Zhamoida, 2015). In China, the Cambrian base is generally defined at the base of the Meishucunian Stage which is marked by the base of the *Anabarites trisulcatus-Protoherzina anabarica* SSF Zone (Qian et al., 1996; Zhu, 1997; Zhang and Zhu, 2000; Qian et al., 2002; Zhu et al., 2001, 2003). It is clear that the stratigraphic horizons of the Cambrian base, prescribed by different definitions, are diachronous, and consequently result in contradictory interpretations of earth-life evolutionary processes.

In order to address the problems posed by the basal Cambrian GSSP and resolve the dilemma in global correlation, the ISCS launched a Working Group on the Terreneuvian Series and Fortunian Stage which was approved by the ICS in 2012 with the aim of clarifying the definition of the base of the Fortunian Stage and its global correlation (see Babcock et al., 2014). The working group organized a thematic symposium during the 2nd International Stratigraphic Congress in Graz, Austria, 2015. As summarized by Zhu et al. (2015), the following potential markers for identification of the Cambrian base should be investigated in detail, including: (1) the FAD of *T. pedum*; (2) the FAD of the typical Cambrian SSFs, e.g. *Anabarites trisulcatus* and *Protoherzina anabarica*; (3) the FAD of the *Asteridium-Heliosphaeridium-Comasphaeridium* (AHC) acritarch Assemblage; and (4) the BACE negative δ^{13}C excursion, in addition to high precision radiometric ages at the corresponding horizons. The primary task is to disentangle the stratigraphic relationships between these markers. The status of recent research and problems relating to these markers are reviewed below:

(1) FAD of *T. pedum*. the FAD of *T. pedum* between palaeocontinents is diachronous. If the FAD of *T. pedum* is used to define the Cambrian base, some widely accepted Cambrian SSFs would be assigned to the Ediacaran. For example, the FAD of *T. pedum* occurs above the base of the *Anabarites trisulcatus-Protoherzina anabarica* Zone near the top of the Lower Phosphorite Bed in the Meishucun section, eastern Yunnan, South China (Zhu, 1997) and a similar case is made in Siberia (Rogov et al., 2015). In Namibia, use of the FAD of *T. pedum* for defining the Cambrian base would place some widely accepted Ediacaran fossils into the Cambrian, because *T. pedum* and similar treptichnid traces occur together with the typical Ediacara fossils (Jensen et al., 2000; Jensen and Runnegar, 2005). In Greenland and Sweden, *T. pedum* first occurs above an uncomformity (Jensen, 1997; Jensen et al., 2016).

(2) FAD of *Anabarites trisulcatus* or *Protoherzina anabarica*. The rapid first appearance of mineralized shells and skeletons (SSFs) is a symbolic event marking the Cambrian Explosion of animals. Among these SSFs, the calcareous tube *Anabarites trisulcatus* and phosphatic protoconodont *Protoherzina anabarica* are characteristic and occur worldwide, thus their first appearance can be used to define the Cambrian base. However, mixed Cambrian (*Anabarites*) and Ediacaran (*Cloudina* or cloudinids) skeletal assemblages have been recently reported from South China, Kazakhstan and Siberia (Zhuravlev et al., 2012; Yang B et al., 2016; Zhu et al., 2017a). Integrated stratigraphic investigations indicated that *Cloudina* or cloudinids extended up to the BACE δ^{13}C excursion, and *Anabarites* first appeared in the interval below the BACE excursion, suggesting a successive evolutionary process of skeletal animals across the Ediacaran-Cambrian transition (Zhu et al., 2017a), thus reinforcing uncertainties in the use of the FADs of these skeletal fossils in definition of the Cambrian base.

(3) FAD of the AHC acritarch Assemblage. Four early Cambrian acritarch assemblages have long been established and widely used for stratigraphic correlation (Moczydłowska, 1991). In particular, the first assemblage (*Asteridium tornatum-Comasphaeridium velvetum* Zone or *Asteridium-Heliosphaeridium-Comasphaeridium* (AHC) Assemblage) has been reported from the East European Platform, South China, Tarim, Lesser-Himalaya, South Australia, Spain and Avalonia (Ahn and Zhu, 2017 and references therein), and have commonly been used to identify basal Cambrian strata in which skeletal fossils are absent. The new data from South China indicate that the AHC assemblage occurs in the horizon corresponding to the nadir of the BACE excursion and slightly below the base of *A. trisulcatus-P. anabarica* SSF Zone (Ahn and Zhu, 2017), supporting the AHC assemblage as a useful marker for the Cambrian base. However, further investigations are required to test the temporal relationships between the first occurrences of the AHC assemblage, the shelly fossils *A. trisulcatus* and *P. anabarica*, and BACE excursion.

(4) BACE negative δ^{13}C excursion. The BACE excursion has long been used as an alternative marker to define the Cambrian base, particularly in sequences devoid of fossils (Zhu et al., 2006). In the comprehensive review of the GTS 2012, both Ediacaran and Cambrian charts used the BACE excursion as a marker for the base of the Cambrian Period, but different levels of the excursion have been chosen

(Narbonne et al., 2012; Peng et al., 2012a). The main question often posited concerns which level in the δ^{13}C excursion is most practicable to define the boundary: (1) at the onset of the BACE excursion whereupon δ^{13}C values start to decrease (Zhu et al., 2006; Peng et al., 2012a) or (2) at the nadir of the BACE excursion where δ^{13}C reaches values of −6‰ or even lower (Narbonne et al., 2012)?

At present, all available biostratigraphic markers appear to be problematic in their ability to define the Cambrian base. Comparatively then, the BACE excursion is the best solution and thus should be the primary marker (Zhu et al., 2017b). The suggested base of the Cambrian can be redefined as the onset of decreasing δ^{13}C values from the terminal Ediacaran positive carbon isotope plateau (EPIP) to the BACE excursion (Figure 2).

2.7 Cambrian chemostratigraphy

With technological advances in isotopic analysis and increasing popularity, carbon, oxygen and strontium isotope chemostratigraphy has attracted intensive use in stratigraphic correlations. Particularly, high-resolution carbon isotope chemostratigraphy has been used through the majority of periods in earth history (Saltzman and Thomas, 2012) and even as the primary tool in definition of the base of the Eocene Epoch (Paleogene Period) (Aubry et al., 2007). Although unreliable in the Precambrian, oxygen isotopes have additionally played a significant role in Phanerozoic stratigraphy and paleotemperature reconstruction of seawater, achieving millennial-scale resolution in the Cenozoic (Grossman, 2012). The resolution of strontium isotopic data is lower relative to C and O isotope chemostratigraphy but the distinct evolutionary pattern exhibited by Sr isotopes in the Precambrian and Cambrian has made them an important and widely applied tool in Precambrian and Cambrian stratigraphy (McArthur et al., 2012).

During the Cambrian, the global carbon isotope curve exhibits dramatic perturbations that are closely linked with evolutionary events, and thus can be used in Cambrian chemostratigraphy. Zhu et al. (2006) compiled the first complete Cambrian δ^{13}C profile based on global data, and named ten δ^{13}C anomalies, which have been widely adopted in subsequent Cambrian chemostratigraphic studies. Another Cambrian δ^{13}C profile, compiled by Saltzman and Thomas (2012) and based on data from western Laurentia and Morocco, exhibits no significant difference from that presented by Zhu et al. (2006). Although the past decade has witnessed the accumulation of data, only minor revisions to the δ^{13}C profile originally presented by Zhu et al. (2006) are required (Figure 2). Here we briefly summarize major features of the Cambrian δ^{13}C evolution:

(1) Terreneuvian. The most valuable Terreneuvian δ^{13}C chemostratigraphic data were obtained from sections in Siberia (e.g. Brasier et al., 1994b; Kouchinsky et al., 2007), Morocco (Maloof et al., 2010), western Mongolia (Smith et al., 2016b) and South China (Zhang et al., 1997; Li et al., 2009). However, these δ^{13}C chemostratigraphic profiles exhibit significant discrepancies between areas and their correlations are problematic. Nevertheless, a general evolutionary pattern can be distinguished. The prominent BACE negative excursion at the base of the Fortunian and the ZHUCE positive excursion corresponding to lower Stage 2 are global events, thus can be used as chronostratigraphic markers. In the interval between the BACE and ZHUCE excursions, however, more than four fluctuations in the δ^{13}C curve have been reported from some sections in Siberia and western Mongolia. These frequent δ^{13}C variations are not correlatable in other continents and may either record global changes in seawater, or alternatively, result from changes in local conditions, and thus require further investigation.

It is interesting to note that the ZHUCE excursion is commonly characterized by one δ^{13}C peak with values >+4‰ in the majority of sections from Siberia and South China. However, in the Sukharikha section of northwestern Siberia, two δ^{13}C peaks (5p and 6p) with values >+4‰ have been reported (Kouchinsky et al., 2007) and a similar phenomenon is also reported from sections in Morocco (Maloof et al., 2010). In contrast to the record in Siberia, however, a prominent negative excursion, with δ^{13}C values <−4‰ is recorded in Morocco between peaks 5p and 6p. The negative excursion between 5p and 6p is comparable in magnitude to the SHICE negative excursion above the ZHUCE excursion. Based on available data, it is difficult to prove that peak 5p from Morocco and the Sukharikha section of Siberia is equivalent to the ZHUCE. Moreover, possible equivalent excursions to 5p and 6p have recently been reported from western Mongolia (Smith et al., 2016b), however in this instance, 6p may correspond with strata of Stage 3 based on biostratigraphic correlation, while 5p represents the ZHUCE corroborated by the presence of *Watsonella crosbyi* from the strata below 5p (Landing and Kruse, 2017).

(2) Series 2. The δ^{13}C data in Series 2 can be subdivided into two stages, which closely correspond to two stages of animal evolution. The lower stage is characterized by two positive excursions (CARE and MICE) with minor negative fluctuations in between, which together correspond to the peak of the Cambrian explosion; whereas the upper stage is characterized by two negative excursions (AECE and ROECE), which coincide with the mass extinctions of the archaeocyathids and redlichiid/olenellid trilobites respectively (Zhu et al., 2006).

(3) Miaolingian. Carbon isotope data remained stable with an average value of 0‰ and minor negative excursions near the bases of the Drumian and Guzhangian stages. However, the DICE excursion near the base of the Drumian has been reported worldwide (Montañez et al., 2000; Zhu et al., 2004;

Howley and Jiang, 2010; Pagès and Schmid, 2016), whilst the prominent excursion near the base of the Guzhangian reported from west Laurentia (Saltzman, 2005) has not been recorded in the GSSP section in Hunan, South China (Peng et al., 2009).

(4) Furongian. The SPICE positive excursion is well constrained by biostratigraphy and has been documented from all palaeocontinents in various settings (Gerhardt and Gill, 2016 and references therein) and is thus widely used for chronostratigraphic correlation. The SPICE excursion is coincident with the mass extinction of trilobites and has been linked to the widespread development of oceanic anoxia (Gill et al., 2011). In turn, subsequent, rapid oxygenation may have triggered the onset of the Great Ordovician Diversification (Saltzman et al., 2011).

A distinct $\delta^{13}C$ negative excursion in the uppermost Cambrian was first reported from Black Mountain, western Queensland, Australia (Ripperdan et al., 1992) and has subsequently been documented from western Laurentia and Argentina (Ripperdan and Miller, 1995; Buggisch et al., 2003). The negative excursion occurs at the conodont *Eoconodontus* Zone, close to the base of the Ordovician, and was named the TOCE with an explicit definition (Top of Cambrian Excursion) (Zhu et al., 2006). The TOCE excursion exhibits large spatial variations in $\delta^{13}C$ values (4–1.5‰) (Miller et al., 2011; Li et al., 2017). It should be noted that the TOCE excursion has commonly been mixed with the HERB and SNICE excursions in the literature. The name 'HERB' first appeared in a GSA abstract without definition (Ripperdan, 2002) and the name 'SNICE' was coined by Sial et al. (2008). As such, HERB is an invalid synonym and SNICE a junior synonym, of TOCE.

The $^{87}Sr/^{86}Sr$ ratio of ocean water is homogenous due to the long mean residence time of Sr in the oceans (≈10^6 years) relative to the oceanic mixing time (≈10^3 years). Variation in the ratio of $^{87}Sr/^{86}Sr$ is controlled by Sr supply, with $^{87}Sr/^{86}Sr$ derived from mantle sources being lighter than that supplied by continental weathering and thus, the evolution of $^{87}Sr/^{86}Sr$ ratios can be a reliable tool for stratigraphy. The $^{87}Sr/^{86}Sr$ ratios in Precambrian oceans were low, reflecting a dominantly mantle-derived source. An increase in the proportion of continental crust available for weathering during construction of the supercontinents (Rodinia and Gondwana), in addition to the super-greenhouse conditions which persisted during the Cambrian, resulted in a gradual increase in the ratio of $^{87}Sr/^{86}Sr$ during the Neoproterozoic and Cambrian, reaching peak values of 0.70925 in the latest Cambrian (Halverson et al., 2007; Shields, 2007; McArthur et al., 2012). The implication of Sr chemostratigraphy in the Cambrian Period have been summarized by McArthur et al. (2012) and Peng et al. (2012a) and only the most significant changes to the $^{87}Sr/^{86}Sr$ curve that can be used for Cambrian stratigraphic correlation are emphasized herein (Figure 2).

(1) At the base of the Cambrian, $^{87}Sr/^{86}Sr$ ratios are equivalent to those recorded from the terminal Ediacaran (ca. 0.70845) but decline gradually during the Fortunian and reach a nadir at the base of Stage 2 (0.70805). Stage 2 is characterized by low values of $^{87}Sr/^{86}Sr$.

(2) A gradual increase in $^{87}Sr/^{86}Sr$ values occurs at the base of Stage 3 to a maximum value of 0.70894. A slight decrease in the ratio of $^{87}Sr/^{86}Sr$ starts at the Wuliuan Stage.

(3) An increasing trend in $^{87}Sr/^{86}Sr$ begins in the Guzhangian Stage and reaches a peak value of 0.70925, coincident with the late SPICE interval of the Paibian Stage. Subsequently, $^{87}Sr/^{86}Sr$ ratios decline again and reach a value of 0.70900 at the base of the Ordovician.

2.8 Cambrian geochronology

Peng et al. (2012) provided absolute ages for all Cambrian stage boundaries based on available geochronological data and proportional estimations of biozone duration. Since then, advances in Cambrian geochronology have largely focused on the basal Cambrian. Here we briefly review and discuss the age of the base of the Cambrian.

The current age of 541 Ma presented in the International Chronostratigraphic Chart (ICC 2018) is a zircon U-Pb CA-ID-TIMS age (541.00±0.29 Ma) from an ash bed within the dolostone of the A4C Member of the Ara Group, Oman (Amthor et al., 2003; Bowring et al., 2007; Schmitz, 2012). The ash bed is at the base of a $\delta^{13}C$ negative excursion and above the last appearance level of *Cloudina* and *Namacalathus*.

Another reference age for the base of the Cambrian is a zircon U-Pb ID-TIMS age of 540.61±0.67 Ma from an ash bed in the upper Spitskopf Member of the Nama Group, southern Namibia (Grotzinger et al., 1995; Schmitz, 2012). The ash layer is from just below the interval bearing the distinct soft-bodied Ediacara-type fossils (Grotzinger et al., 1995) within the late Ediacaran positive carbon isotope plateau (EPIP) and below the BACE negative excursion (Wood et al., 2015; Zhu et al., 2017a). In our opinion, therefore, the age of 540.61±0.67 Ma from the Nama Group of Namibia supersedes the 541.00±0.29 Ma age from the Ara Group of Oman as the maximum age to constrain the base of the Cambrian. The BACE excursion from the Ara Group of Oman appears to be incomplete due to the prevalence of evaporate facies in this sequence and thus a possible hiatus cannot be excluded. In addition, the precise stratigraphic horizon from which the ash bed with the age of 541.00±0.29 Ma was recovered remains uncertain because of the poor fossil record of the Ara Group. Moreover, recent investigations have indicated that the range of *Cloudina* can, in some cases extended into the BACE excursion (Yang B et al., 2016).

Recent U-Pb CA-ID-TIMS ages from a number of ash beds in the Spitskopf Member of the Nama Group (Namibia) indicate that the interval yielding typical Ediacara-type fossils in this section is younger than 540.61±0.67 Ma (Linnemann et al., 2017). Similarly, new zircon U-Pb ID-TIMS ages from ash beds in the Ediacaran-Cambrian boundary interval of eastern Yunnan, South China constrain the onset of the BACE excursion to ca. 540.7–539.6 Ma (Zhu et al., 2015, 2017b). All new data presented above collectively imply that the age for the base of the Cambrian is close to or younger than ~539.6 Ma and we therefore suggest that the currently used age of 541 Ma for the base of the Cambrian be revised to 539 Ma based upon updated geochronological constraints (Figure 2).

3. Cambrian chronostratigraphy and timescale of China

3.1 Historical review

Study of Cambrian stratigraphy and paleontology in China has a rich history of nearly 140 years, beginning with the pioneering work of European's in the late 19th and early 20th centuries (Richthofen, 1877; Dames, 1883; Bergeron, 1899; Monke, 1903; Walcott, 1905, 1906; Lantenois, 1907; Blackwelder, 1907; Deprat, 1912; Mansuy, 1907, 1912). However, the basic lithostratigraphic framework in both North and South China were established by Chinese pioneers in geology during the early 20th century (e.g. Lee and Chao, 1924; Sun, 1924, 1935; Ting and Wang, 1937; Wang, 1938, 1945; Lu, 1941, 1945). Due to extensive geological mapping and basic survey of mineral resources carried out in China during the 1950s, a tremendous amount of data pertaining to Cambrian stratigraphy from all major areas of China was obtained during this period. Lu Y.H., an outstanding Chinese pioneer and trilobite expert, provided the first summary of Cambrian stratigraphy in China during the first All China Conference on Stratigraphy held in 1959 (Beijing). There, he proposed a Cambrian chronostratigraphic framework for China that consisted of 3 series and 8 stages, namely Lower Cambrian Chiungchussu, Tsanglangpu and Lungwangmiao stages, Middle Cambrian Hsuchuang and Changhsia stages, and Upper Cambrian Kushan, Changshan and Fengshan stages (Lu, 1962). Including the subsequently established Maochuang Stage, all of these stage names were derived from the corresponding lithostratigraphic units (names of the formations) (Lu, 1962). A similar Cambrian chronostratigraphic framework for China (3 series and 9 stages) was additionally proposed by Sun Y.Z. (Sun, 1961) at almost the same time. Since Sun Y. Z.'s proposal was formally published earlier than that of Lu Y.H., it was regarded as the first Cambrian chronostratigraphic framework of China (All China Commission of Stratigraphy, 2002). The "Mantou", "Danshi" and "Wengshui" stages in Sun Y. Z.'s proposal have, however, rarely been accepted and the subdivision originally proposed by Lu Y. H. has become the basic Cambrian chronostratigraphic framework of China in both practice and scientific literatures (Figure 3).

Based on investigations of the pre-trilobitic strata in eastern Yunnan, southeastern China, Qian (1977) named the Meishucunian Stage as the first Cambrian stage of China. Since then, formal subdivision of the Cambrian chronostratigraphy of China has been completed. The resulting chronostratigraphic framework consists of 3 series and 10 stages, namely Lower Cambrian Meishucunian, Chiungchussuan, Tsanglangpuan and Lungwangmiaoan stages, Middle Cambrian Maochuangian, Hsuchuangian and Changhsian stages, and Upper Cambrian Kushanian, Changshanian and Fengshanian stages. This framework was ratified by the All China Commission of Stratigraphy during the second All China Conference on Stratigraphy in 1979 (Beijing) and recommended to the international geological community during the 26th International Geological Congress (IGC) in Paris in 1980 (Figure 3; Xiang et al., 1980; Zhang et al., 1980a). The Cambrian chronostratigraphy and classic summaries and reviews on the studies of the Cambrian stratigraphy of China prior to the 1980s (Chang, 1980; Xiang et al., 1981; Lu et al., 1982) have made great contributions to the investigation of Cambrian stratigraphy and mineral resources in China during the last two decades of the 20th century.

According to the "International Stratigraphic Guide" (Salvador, 1994; Remané et al., 1996) however, the Cambrian chronostratigraphy of China had two shortcomings: (1) all stage names were derived from the names of lithostratigraphic units, and (2) there were no formal definitions for all stages. In order to overcome the issue of nomenclature, Chinese Cambrian researchers led by Prof. Lu Y.H. suggested that the stage names be retained but that the lithostratigraphic units from which stage names had originated be renamed or, in some cases, prior names be reinstated (Lu et al., 1994). Following this suggestion, Luo et al. (1994) revised the Lower Cambrian lithostratigraphic framework in eastern Yunnan, upon which the Lower Cambrian stages of China had been based. The Chiungchussu Formation (Fm) was renamed as Heilingpu Fm, the two members of the Tsanglangpu Fm were replaced by two Formations (Hongjingshao Fm and Wulongqing Fm), and the Lungwangmiao Fm was renamed the Shanyicun Fm. Chen et al. (1996) further upgraded the status of two members of the Chiungchussu Fm to two Formations, namely the Shiyantou Fm and Yu'anshan Fm. As the Middle and Upper Cambrian stages had already been established in North China, Zhang et al. (1994) suggested that the earlier lithostratigraphic units (Mantou and Chaomidian Fms) originally named by Blackwelder (1907), replace the Maochuang, Hsuchuang, Changshan and Fengshan Fms. After resolving the issue of

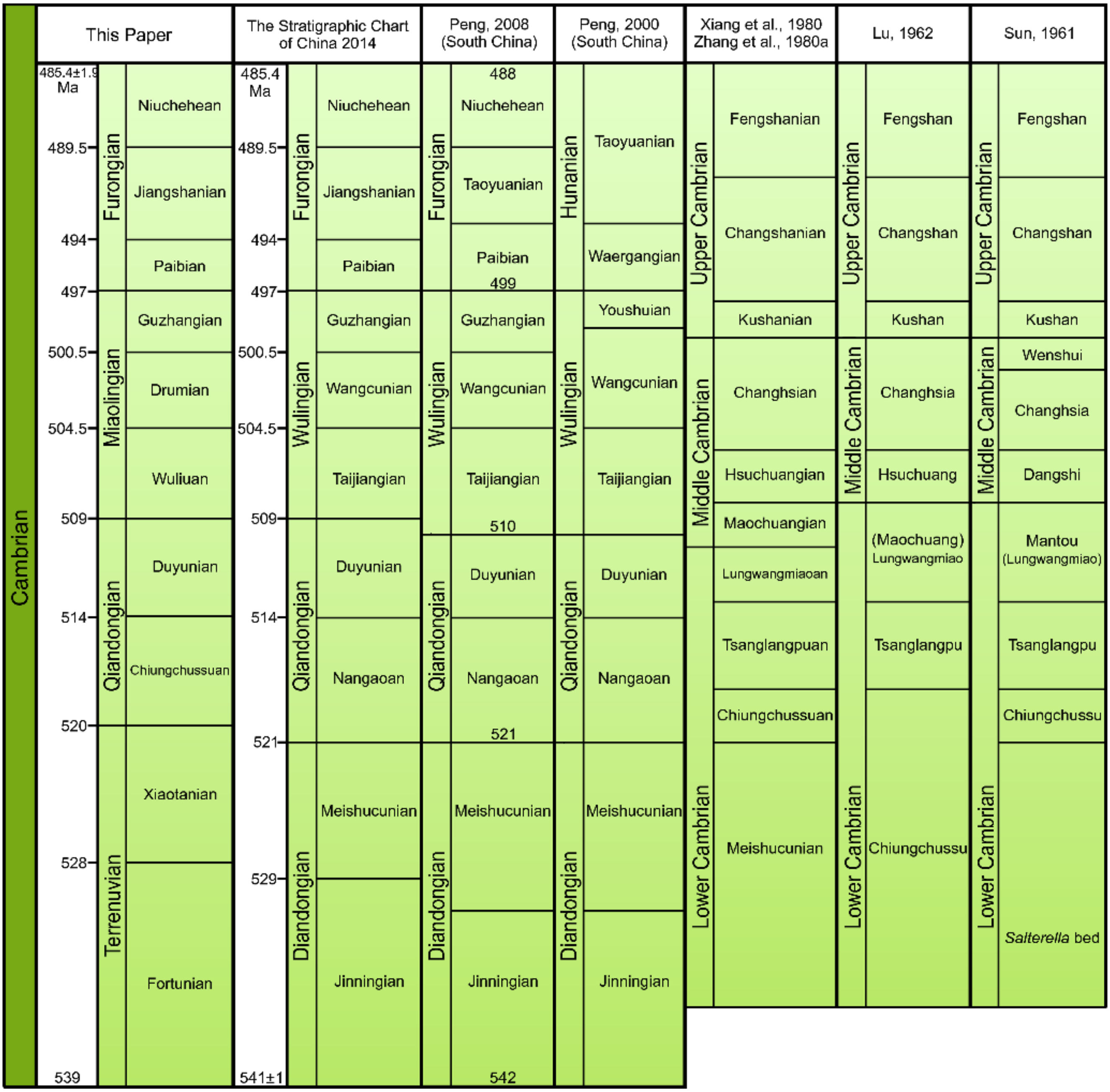

Figure 3 Brief historical summary of the Cambrian Chronostratigraphy and timescale of China.

nomenclature, the stage bases and their stratotype sections were eventually defined (see Xiang et al., 1999; All China Commission of Stratigraphy, 2002).

The traditional Cambrian chronostratigraphy of China was principally established based on the biostratigraphy of shallow marine facies. Due to the provincialism and endemic distribution of the associated index fossils, this designation has encountered difficulties in intrabasinal and international correlation. To address this correlation problem, around the time of the third All China Conference on Stratigraphy in 2000 (Nanjing), Peng and colleagues proposed a new Cambrian chronostratigraphic framework of South China. This updated framework consisted of 4 series and 9 stages and was primarily based on trilobite biostratigraphy from deeper water, slope facies of eastern Guizhou and western Hunan, with the exception of pre-trilobitic Cambrian strata that are still based on the biostratigraphy of small shelly fossils (SSFs) from shallow water facies of eastern Yunnan (Figure 3; Peng et al., 1998, 2000a, 2000b; Peng, 2000, 2003). The great potential for global correlation has been substantiated through detailed biostratigraphy of agnostid trilobites in the slope facies of South China, and GSSPs of the Guzhangian, Paibian and Jiangshanian stages have been defined in South China in past years (Peng et al., 2004, 2009, 2012b). Accordingly, Peng provided a revised version of the Cambrian chronostratigraphy of South China (Peng, 2008, 2009a, 2009b).

Since 2000, in fact, both the traditional Cambrian chronostratigraphic framework of China and that constructed for South China have been used. Although this has caused some confusion in practice, the Cambrian chronostratigraphic framework of South China was eventually accepted as the standard for China as a whole and ratified by the All China Commission of Stratigraphy during the fourth All China Conference on Stratigraphy in 2013 (Beijing) (Figure 3; Wang et al., 2014; Zhang et al., 2014; also see The Stratigraphic Chart of China 2014). Here we briefly summarize the stages in the up-to-date stratigraphic chart of China in descending order.

(i) Niuchehean Stage. Named by Peng (2008) and based on the stratotype section at the Wa'ergang village in Taoyuan County, Hunan. The base of the Niuchehean Stage is defined by the FAD of an agnostid trilobite *Lotagnostus americanus* at the level of 29.65 m above the base of the Shenjiawan Fm in the Wa'ergang section (Peng et al., 2014).

(ii) Jiangshanian, Paibian and Guzhangian stages. Equivalent to the International Chronostratigraphic Chart (ICC) as detailed above.

(iii) Wangcunian Stage. Named by Peng et al. (1998) and based on the stratotype section at the Wangcun village in Yunshun County, Hunan. The base of the Wangcunian Stage is defined by the FAD of an agnostid trilobite *Ptychagnostus atavus* at the base of the Huaqiao Fm in the Wangcun section (Peng and Robison, 2000; Peng et al., 2009a).

(iv) Taijiangian Stage. Named by Peng et al. (1998). The stratotype section is the Wuliu-Zengjiayan section located at Balang village in Jianghe County, Guizhou. The base of the Taijiangian Stage is defined by the FAD of an oryctocephalid trilobite *Oryctocephalus indicus* at 52.8 m above the base of the Kaili Fm in the Wuliu-Zengjiayan section (Zhao et al., 2001, 2012).

(v) Duyunian Stage. Named by Peng (2000). The stratotype section is the Nangao section in Danzhai County, Guizhou. The base of the Duyunian Stage is defined by the FAD of a trilobite *Arthricocephalus chauveaui* at 25 m above the base of Bed 10 of the Nangao section (Zhang et al., 1979; Peng, 2003).

(vi) Nangaoan Stage. Named by Peng (2000). The stratotype section is the Xiaoshai section in Yuqing County, Guizhou. The base of the Nagaoan Stage is defined by the FAD of trilobites, which is equivalent to the FAD of *Tsunyidiscus* sp. within Bed 5 of the Xiaoshai section (Zhang et al., 1979).

(vii) Meishucunian Stage. Named by Qian (1977) without formal definition of its base. The name is derived from the Meishucun Fm (Chiang et al., 1964). The stratotype section is located at Xiaowaitoushan, Meishucun village, Jinning County, Yunnan. The Meishucunian Stage was originally defined by the FAD of SSFs (Luo et al., 1982, 1984), however it was temporally redefined to the base of the *Paragloborilus-Siphogonuchites* Zone in order to meet the requirements for the GSSP of the base of the Cambrian due to the fact that the Xiaowaitoushan section was one of the candidate GSSP sections for the base of the Cambrian during the 1980s and early 1990s (Luo et al., 1994). In the Stratigraphic Chart of China 2002, the Meishucunian Stage was redefined to the FAD of the *Anabarites trisulcatus-Protohertzina anabacica* Assemblage Zone at the base of the Zhongyicun Member of the Xiaowaitoushan section (All China Commission of Stratigraphy, 2002). This definition has been widely used to define the base of the Cambrian in China. However, Peng (2008) insisted on using the definition of Luo et al. (1994) and proposed instead to use the FAD of *Paragloborilus subglobosus* to define the base of the Meishucunian Stage, which is at the base of Bed 7 of the Xiaowaitoushan section. The definition of Peng (2008) was accepted in the Stratigraphic Chart of China 2014.

(viii) Jinningian Stage. Named by Peng (2000). The stratotype section is located at Xiaowaitoushan section, Meishucun village, Jinning County, Yunnan. The base of the Jinningian Stage is defined by the FAD of *T. pedum*, which is located within the upper part of Bed 4 (top of the lower phosphorite) in the Xiaowaitoushan section, corresponding to the middle *A. trisulcatus-P. anabarica* Zone (Zhu, 1997; Zhu et al., 2001). However, Peng (2008) considered the FAD of *T. pedum* at the Xiaowaitoushan section to be higher than the FAD of *T. pedum* at the GSSP section (Fortune Head, Newfoundland) based on the age of 533 Ma from Bed 5 of the Xiaowaitoushan section. Therefore, the base of the Jinningian Stage remains uncertain in the Xiaowaitoushan section (Peng, 2008).

3.2 Revision of the Cambrian chronostratigraphy of China

Based on the international stratigraphic guide and recent advances in the Cambrian stratigraphy of China, we provide a revised version of the Cambrian chronostratigraphy of China (Figure 3). The revision is based on the following principles: (1) series- and stage-level units in the Stratigraphic Chart of China should be the same as those in the International Chronostratigraphic Chart (ICC) (Wang and Peng, 2017); (2) the Chinese series and stages can be used if the corresponding series and stages in the ICC remain undefined; and (3) the Chinese series and stages should be defined, where possible, by proposed global criteria, and stratotype sections and points for the bases of these series and stages should be appointed.

Following the principles above, the Jinningian, Taijiangian and Wangcunian stages, which have the same definition as the international Fortunian, Wuliuan and Drumian stages respectively, should be abandoned in the Cambrian chronostratigraphy of China. Accordingly, the Diandongian and Wulingian series should be replaced by the Terreneuvian and Miaolingian series. The Niuchehean Stage however, is retained because it has the same definition as Stage 10 in the ICC with the stratotype section and point as its base. Since the subdivision of the lower half of the Cambrian remains problematic, the bases of international stages 2, 3 and 4 have not been defined. In order to avoid confusion, these stages in the Cambrian chronostratigraphy of China must be revised with explicit definitions and appointed stratotype sections and points for their bases (Figure 3).

(i) Duyunian Stage. The Cambrian Stage 4 of China was originally defined by the FAD of *Arthricocephalus chauveaui*. As discussed above, there are three potential markers to define the base of the Stage 4. Among these markers, the FAD of *A. chauveaui* is the stratigraphically highest one. Because the FAD of *Oryctocarella duyunensis*, which occurs earlier than the FAD of *A. chauveaui*, is close to the level of the mass extinction of archaeocyathids (or the Sinsk Event and AECE δ^{13}C negative excursion), Yuan et al. (2011) regarded the FAD of *O. duyunensis* (Peng et al., 2017) as a more appropriate marker to define the base of Stage 4. However, prior to taxonomic revision of *Arthricocephalus* and *Oryctocarella* by Peng et al. (2017), *O. duyunensis* from the lower Balang Formation in the slope facies of South China was assigned to *A. chauveaui* and various other species. In fact, the reliable *A. chauveaui* actually occurs in the upper Balang Formation (Peng et al., 2017). It should be pointed out that the specimen of *A. chauveaui* used by Peng (2003) to define the stratotype section and point for the base of the Duyunian Stage is a specimen of *O. duyunensis* (Peng et al., 2003, Figure 2B; Peng et al., 2017). This specimen is, in fact, not from the Nangao section in Danzhai, the stratotype section of the Duyunian Stage, but rather from the lower Balang Formation in the Huanglianba section of Songtao (Zhao et al., 2001b, pl.1, Figure 6). Therefore, we revise the definition of the Duyunian Stage and accept the suggestion of Yuan et al. (2011) to use the FAD of *O. duyunensis* to define its base, which is compatible with its original definition (Peng, 2003). As Yuan et al. (2011) did not appoint the stratotype section and point for the FAD of *O. duyunensis*, whether the earliest *A. chauveaui* from the Nangao section in Danzhai is *O. duyunensis* remains uncertain, hence detailed work on more sections is required to choose the stratotype section and point for the base of the Duyunian Stage. At present, the Huanglianba section of Songtao, Guizhou can be appointed as a temporary stratotype section for the Duyunian Stage, with its base at 37.6 m above the base of the Balang Formation (Zhao et al., 2001b).

In the ICC, a U-Pb age of 514 Ma from an ash bed at the top of the lower Comley Sandstone Formation, western England is used for the base of Stage 4. Since this age horizon corresponds to the trilobite *Callavia* Zone, which is below the FAD of *A. chauveaui* in Avalonia (Shergold and Geyer, 2003; Harvey et al., 2011), it represents a maximum age for Stage 4. Assuming that the FAD of *O. duyunensis* is approximately equivalent to the *Callavia* Zone, the age of 514 Ma is more suitable for the base of the Duyunian Stage.

(ii) Chiungchussuan/Nangaoan Stage. The Nangaoan Stage, originally assigned to Stage 3 in slope facies of South China (Peng, 2000), is now adopted in the Stratigraphic Chart of China 2014. The Xiaoshai section in Yuqing County, Guizhou, which was assigned as the stratotype section of the Nangaoan Stage, was not located in the slope facies but instead corresponds to the transitional belt between platform and slope facies. The first trilobite in the slope area of South China is the eodiscid *Hubeidiscus orientalis*, which appeared later than the FAD of *Tsunyidiscus niutitangensis* in shallow water facies based on integrated stratigraphic analyses (Yang et al., 2003; Zhu et al., 2003; Yang et al., 2005). The first trilobite *Tsunyidiscus* sp. from the Xiaoshai section (Zhang et al., 1979) appeared later than the FAD of *Parabodiella huoi*, the latter being the earliest trilobite in China (Zhang, 1987; Zhang et al., 2001; Yuan et al., 2011; Zhang et al., 2017). The traditional and widely used Chiungchussuan Stage is defined by the FAD of *P. huoi* at 8.8 m above the base of the Yu'anshan Formation in the Badaowangou section near Meishucun, Jinning County, Yunnan (Luo et al., 1994; Zhu et al., 2001). As the first trilobite in the slope facies appeared later than the FAD of *P. huoi*, we insist that the Chiungchussuan Stage be used as the Cambrian Stage 3 of China. Although *P. huoi* represents the first trilobite in China, it is not regarded as the earliest trilobite in the stratigraphic record globally (e.g. Zhang et al., 2017), therefore, the age for the base of the Chiungchussuan Stage should be younger than 521 Ma, as designated for Cambrian Stage 3 in the ICC. Hence, 520 Ma is here suggested for the base of the Chiungchussuan Stage.

(iii) Xiaotanian (new)/Meishucunian Stage. The Meishucunian Stage is adopted for Cambrian Stage 2 in the Stratigraphic Chart of China (2014). As discussed above, the Meishucunian Stage has classically been used for the basal Cambrian phosphorites that are widespread in South China and contain abundant SSFs (Qian, 1977; All China Commission of Stratigraphy, 2002). The revised definition of the Meishucunian Stage, adopted in the Stratigraphic Chart of China 2014, has resulted in some confusion in practice. The FAD of the mollusk *Watsonella crosbyi* or *Aldanella attleborensis* was considered as the potential marker for the base of Cambrian Stage 2 in the ICC. In accordance with this proposed definition and in order to avoid confusion, we propose use of a new stage, the Xiaotanian Stage, to replace the Meishucunian Stage as Cambrian Stage 2 in China because both original and revised definitions for the Meishucunian Stage do not meet international criteria. The Xiaotanian Stage is defined by the FAD of *W. crosbyi* at the base of the Dahai Member (Zhujiaqing Formation) in the stratotype Xiaotan section, Yongshan County, northeastern Yunnan (Li et al., 2001).

It should be emphasized that the "Laolinian Stage"—proposed by Landing and Geyer (2012) for Cambrian Stage 2 in the ICC does not have priority of nomenclature over the Xiaotanian Stage. This is because the Xiaotanian Stage has a different definition from the "Laolinian Stage", the latter instead being defined by the ZHUCE $\delta^{13}C$ positive peak at the Laolin section in Huize County, northeastern Yunnan.

4. Subdivision and correlation of Cambrian stratigraphy in major regions of China

4.1 South China

The Cambrian strata of South China are well developed and exposed in the Yangtze Platform, Jiangnan slope and basin. The Cambrian sequences in the different sedimentary settings exhibit dramatic discrepancies in lithology, thickness and fossils assemblages, thus resulting in difficulty in stratigraphic correlation of the sequences in different facies. As illustrated in Figure 4, recent advances in the Cambrian stratigraphy of South China have mainly been made in the studies of the lower half of the Cambrian on the Yangtze Platform and the upper half of Cambrian in the Jiangnan slope area. On the Yangtze Platform, SSF and archaeocyathid biozones have been revised and improved; while in the Jiangnan slope area, high-resolution trilobite biostratigraphy has been established, leading to ratifications of the GSSPs of the Wuliuan, Guzhangian, Paibian and Jiangshanian stages in the area over the past 15 years. Additional advances include conodont biostratigraphy and chemostratigraphy.

4.1.1 Biostratigraphy of South China

(i) Trilobites in shallow water facies. As noted above, *Parabadiella huoi* represents the earliest trilobite in South China and China as a whole. Fossils associated with *P. huoi* include the earliest hyolithimorph hyoliths, bradoriids and brachiopods. Whether *Parabadiella* from South China is a synonym of *Abadiella* from South Australia and Morocco remains controversial (Jell, 1990; Zhang et al., 2001; Lin, 2015; Zhang et al., 2017). In order to avoid confusion in correlation; we therefore revise the *Parabadiella* Zone to the *Parabadiella huoi* Range Zone. The *Wutingaspis-Eoredlichia* Interval Zone consists of two subzones: the lower *Tsunyidiscus niutitangensis* Subzone and upper *Yunnanocephalus* Subzone (Steiner et al., 2001). The *Palaeolenus* and *Megapalaeolenus* zones in the upper Chiungchussuan Stage have been revised as the *Palaeolenus lantenoisi* Zone and *Palaeolenus fengyangensis* Zone, because *Megapalaeolenus* has been regarded as a junior synonym of *Palaeolenus* (Lin and Peng, 2009).

Trilobite zonation in the traditional Tsanglangpuan and Lungwangmiaoan stages was based on biostratigraphy in their stratotype area of eastern Yunnan, but use of these trilobite zones has been inconsistent. In the interval between the *Drepanuroides* Zone and *Palaeolenus lantenoisi* Zone, the widely used *Metarelichoides-Chengkouia* Zone and *Paokannia-Szechuanolenus* Zone from the upper Mingxinsi Formation in Guizhou (Zhou and Yuan, 1980) (later revised to the *Paokannia-Ushbaspis* Zone, Yuan and Zhao, 1999), have never been reported in the stratotype area of the Tsanglangpuan Stage of eastern Yunnan (Luo et al., 1994). They were thus not accepted in the traditional stratigraphic chart of China (Zhang and Zhu, 2000; All China Commission of Stratigraphy, 2002). The absence of these zones in the stratotype area is due to the corresponding interval here being composed of a poorly fossiliferous, course-grained siliciclastic sequence. Thus, the *Ushbaspis* Zone and *Szechuanolenus-Paokannia* Zone were used in the Stratigraphic Chart of China 2014. However, the trilobites within the *Ushbaspis* and *Szechuanolenus-Paokannia* zones are, in some sections, commonly mixed, so the *Szechuanolenus-Paokannia-Ushbaspis* Assemblage Zone was suggested instead (Yuan et al., 2011).

In the shallow water facies, the base of the Duyunian Stage approximately corresponds to the base of the *Palaeolenus fengyangensis* Zone. In the interval above the *P. fengyangensis* Zone, only the *Redlichia murakamii-Hoffetella* Zone was listed in the traditional stratigraphic chart of China (All China Commission of Stratigraphy, 2002) because the interval in the stratotype area of the Lungwangmiaoan Stage is composed of the poorly fossiliferous dolostone of the Shanyicun Formation (Luo et al., 1994). In fact, in the corresponding interval between the widely distributed massive dolostone (e.g. Loushanguan, Xixianchi and Sanyoudong groups) and the *Redlichia murakamii-Hoffetella* Zone, trilobites are abundant from the Wingshudong and Gaotai Formations in central Guizhou, and the Shilongdong Formation in western Hubei. Trilobite zonation has even been established in the Douposi and Shuanlongtang Formations of eastern Yunnan. Among these trilobite zones, both the *Redlichia guizhouensis* Zone and *Paragraulos kunmingensis-Chittidilla plana* Zone contain *Redlichia*, and thus belong to the Duyunian Stage (Yuan and Ng, 2014). Contrastingly, the *Kaotaia magna* Zone from the Gaotai Formation and *Kutsingocephalus* Zone or *Sinoptychaparia* Zone from the upper Douposi Formation contain *Pegati*, but are devoid of *Redlichia* (Zhou et al., 1980). Lu et al. (1982) combined these trilobite zones to form the *Kaotaia-Kutsingocephalus* Zone.

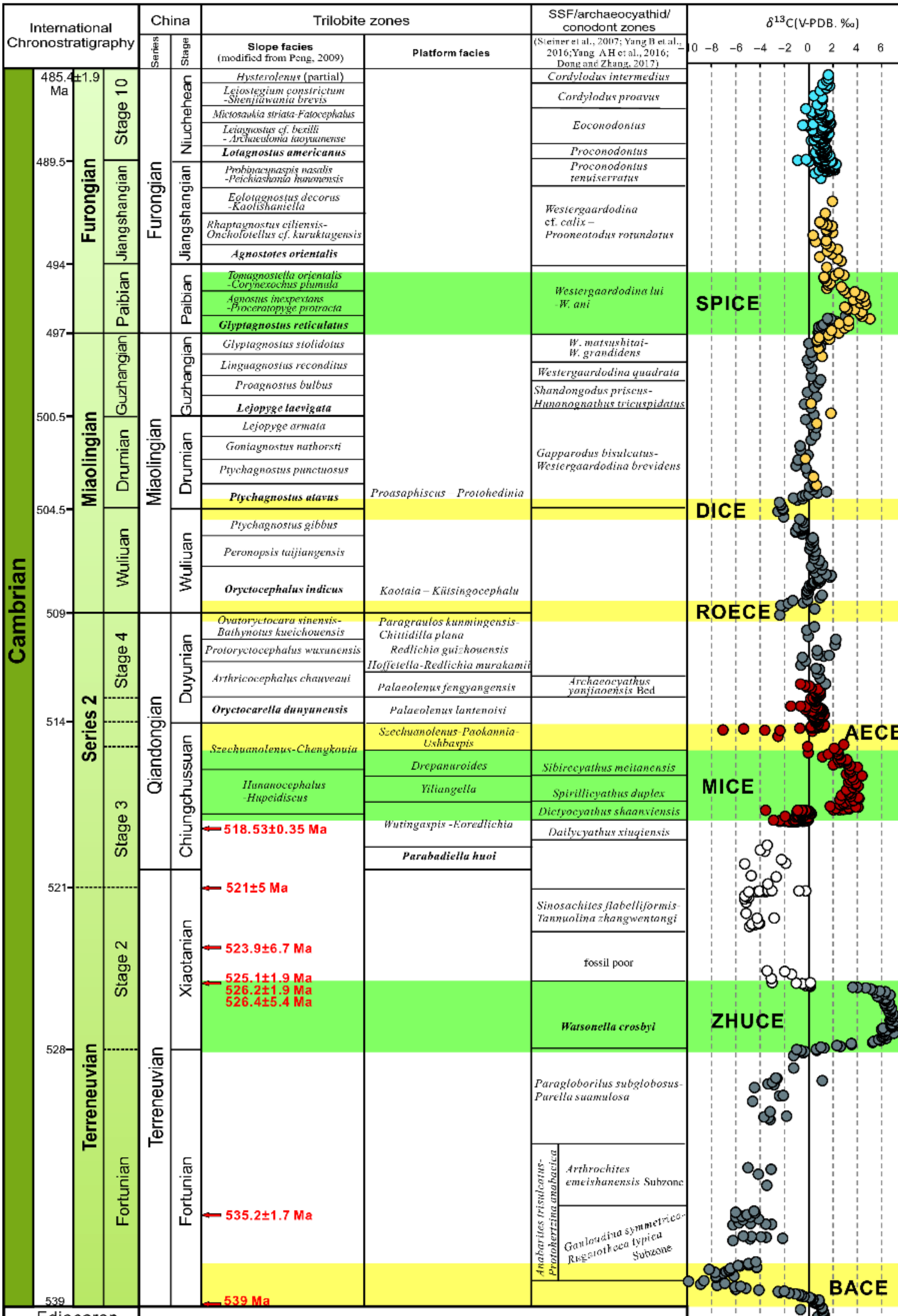

Figure 4 Cambrian chronostratigraphy and timescale of South China. $\delta^{13}C$ data are from Saltzman et al. (2000), Zhu et al. (2004), Li et al. (2017) and unpublished data of authors.

In the deeper water area, *Kaotaia* was reported to co-occur with *Oryctocephalus indicus* (Yuan et al., 2002; Luo et al., 2009), therefore the *Kaotaia-Kutsingocephalus* Zone should correspond with the Wuliuan Stage. In the interval above the *Kaotaia-Kutsingocephalus* Zone, the *Protohedinia* Zone was recognized in the Shuanlongtang Formation (Luo et al., 1994). *Protohedinia* is a common trilobite in carbonates corresponding to the interval above Gaotai and Douposi Formations (Zhang and Zhu, 2000), thus we suggest use of a new *Proasaphiscus-Protohedinia* Zone for this interval in the shallow water area of the Yangtze Platform. The *Proasaphiscus-Protohedinia* Zone contains *Manchuriella*, and approximately corresponds to the lower Drumian Stage (Zhang et al., 1980b).

(ii) Trilobites in the slope area. The trilobites, particularly the agnostid trilobites are abundant and diverse in the deeper facies preserved in stratigraphy of western Hunan and eastern Guizhou. In this area, 28 trilobite zones have been recognized in the interval from the Duyunian Stage to the top of the Cambrian (Figure 4; Peng, 2009a). In the Chiungchussuan (=Nangaoan) Stage, Peng (2000, 2009a) listed 4 trilobite zones largely based on collections from the Jiumenchong and Bianmachong Formations in eastern Guizhou (Zhou and Yuan, 1980; Zhou et al., 1980; Lin, 2008). However, with the exception of *Hupeidiscus* from the limestone at the top of the Jiumenchong Formation, all other trilobites were reported from the transitional belt between the platform and slope facies in the Yuqing-Shiqian-Jiankou-Cenggong area. In the slope area in the east, along the Danzhai-Taijiang-Cenggong-Jiangkou-Songtao-Huanyuan-Guzhang-Zhangjiajie transect, only *Hupeidiscus* has been reported from the limestone at the top of the Jiumenchong Formation and equivalent interval. If trilobites are employed in the transitional belt to establish biozones, the *Szechuanolenus-Chengkouia* Zone can be used due to the fact that both genera are common in the Bianmachong Formation in eastern Guizhou. In western Hunan, *Hunanocephalus* occurs in lower Cambrian black shale; however its correlation with the trilobites in eastern Guizhou remains uncertain. Lin (2008) named the *Hunanocephalus-Hupeidiscus* Zone and regarded it as a zone below the *Szechuanolenus-Chengkouia* Zone.

The black limestone member yielding *Hupeidiscus* at the top of the Jiumenchong Formation is widely distributed in the slope facies of South China and thus can be used as a marker bed for correlation (Yang et al., 2005). Abundant sponges, bivalved arthropods and tubular fossils, which are characteristic components of the Chiungchussuan Stage, have been discovered in black shales below the *Hupeidiscus* bed (Yang et al., 2003; Yang et al., 2010). Additionally, a Ni-Mo polymetallic sulfide bed from the basal Jiumenchong Formation is widely recognizable, not only in the slope area but also in the shallow water area at the base of the Chiungchussuan Stage. The Ni-Mo polymetallic sulfide bed with a Re-Os isotopic age of 521±5 Ma (Xu et al., 2011) represents a distinct palaeoceanographic event and thus can be used a reference marker for defining the base of the Chiungchussuan Stage (Zhu et al., 2003). The bio- and event-stratigraphic data indicate that the *Hupeidiscus* horizon in the slope area is higher than the base of the Chiungchussuan Stage and equivalent to the top Niutitang Formation and Mingxinsi Formation in shallow water facies of Guizhou and the top Yu'anshan Formation and lower Hongjinshao Formation in eastern Yunnan (Figure 4).

(iii) SSF. Four SSF zones have been established in the pre-trilobitic Cambrian (Terreneuvian) sequences of the Yangtze Platform, South China over the past two decades (Figure 4; Qian, 1999; Qian Y et al., 2001; Steiner et al., 2007). Among them, the *Anabarites trisulcatus-Protohertzina anabarica* Zone can be subdivided into two subzones, namely the lower *Ganloudina symmetrica-Rugatotheca typica* Range Subzone and the upper *Arthrochites emeishanensis* Subzone. The *G. symmetrica-R. typica* Subzone is newly recognized in the cherty dolostone interval between the dolostone of the Dengying Formation and the phosphorus-rich beds of the basal Cambrian (e.g. the basal Daibu, Maidiping and Kuanchuangpu Formations). This subzone represents a transitional assemblage from the typical Ediacaran to Cambrian skeletal fossils (Yang B et al., 2016) and appears at the base of the BACE excursion.

SSF zones have also been recognized in the lower Chiungchussuan Stage, including the *Pelagiella subangulata* Range Zone in the shallow water facies area and the *Rhombocorniculum cancellatum* Zone and *Ninella tarimensis-Cambroclavus fangxiangensis* Zone in the relatively deeper water facies area (Steiner et al., 2007). Moreover, a *Kaiyangites-Calcihexactina* assemblage was reported from the basal Cambrian in the slope area (Qian, 1999; Steiner et al., 2007).

(iv) Archaeocyathids. Archaeocyathids mainly occur in the Qiangdongian of the western Yangtze Platform. The earliest archaeocyathids were reported from the Mingxinsi Formation, which is equivalent to the middle *Wutingaspis-Eoredlichia* Zone; while there latest occurrence is from the Tianheban Formation in the Yangtze Gorges area, western Hubei. Recently, the archaeocyathids of South China in four zones and one bed have been summarized by Yang A H et al. (2016) based on systematic revisions and occurrence data from well-studied sections. Yang A H et al. (2016) outline the relationships between archaeocyathid and trilobite zones with implications for global correlation (Figure 4).

(v) Conodonts. Investigation of conodont biostratigraphy in South China have focused on exposed limestone sequences in the slope area, largely from western Hunan. In total, 13 conodont biozones have been recognized from the basal Huaqiao Formation to the basal Ordovician, among which 11 zones belong to the Cambrian (Dong et al., 2004). Recent investigations have validated these conodont biozones and their correlations with trilobite zones have also been clarified (Figure 4; Bagnoli et al., 2017; Dong and Zhang, 2017).

4.1.2 Chemostratigraphy of South China

Cambrian chemostratigraphic studies of South China commenced in the early 1990s, when Brasier et al. (1990) employed $\delta^{13}C$ chemostratigraphy for global correlation of the Precambrian-Cambrian boundary. With continuing accumulation of $\delta^{13}C$ data in the past three decades, $\delta^{13}C$ chemostratigraphy has played a significant role in subdivision and correlation of Cambrian strata in South China. Here we present a composite Cambrian $\delta^{13}C$ chemostratigraphic profile of South China (Figure 4). The data pertaining to the lower Cambrian are from the Xiaotan section in Yongshan County, northeastern Yunnan. No data are available in the interval from the upper Xiaotanian Stage to the basal Chiungchussuan Stage due to an absence of carbonate lithologies. The data of the middle-upper Chiungchussuan Stage are from archaeocyathid-bearing carbonates in central Guizhou, while the data from the Duyunian to the top of the Cambrian are from the continuous carbonate sequence which is characterized in slope facies of western Hunan (Saltzman et al., 2000; Zhu et al., 2004; Li et al., 2017). The Cambrian $\delta^{13}C$ chemostratigraphic profile of South China exhibits global $\delta^{13}C$ evolutionary patterns with records of major excursions and thus can be used as a practical tool for stratigraphic subdivision and correlation, particularly for the those strata devoid of fossils. For example, the $\delta^{13}C$ profile from the middle and upper Cambrian in northern Guizhou published by Zuo et al. (2008) shows clearly the AECE, ROECE and SPICE excursions. The SPICE excursion in the Loushanguan Formation provides key evidence for correlation of this unfossiliferous dolostone sequence, which is widespread in the shallow water area of the Yangtze Platform.

4.1.3 Geochronology of South China

Cambrian geochronological investigations have been primarily concentrated in lower Cambrian strata, particularly in eastern Yunnan and the slope area. Two distinct ash layers in the classic Meishucun section have been dated: the ash from Bed 5 in the middle Zhongyicun Member has a SIMS U-Pb age of 535.2±1.7 Ma (Zhu et al., 2009); while the ash from Bed 9 at the base of the Shiyantou Formation has a SIMS U-Pb age of 525.1±1.9 Ma (Compston et al., 2008). The ash at the base of the Shiyantou Formation in Chengjiang County has also been dated with a SIMS U-Pb age of 523.9±6.7 Ma (Okada et al., 2014). Recently, an ID-TIMS U-Pb age of 518.53±0.35 Ma was obtained from the Maotianshan Shale Member of the Yu'anshan Formation, in which the soft-bodied Chengjiang fossils occur, in Chengjiang County (Yang et al., 2018). These ages are from strata with well-established biostratigraphy, thus providing age constraints on the stratigraphic boundaries in addition to evolutionary and geological events. More precise zircon ID-TIMS U-Pb ages have been obtained from the Ediacaran-Cambrian transitional interval (unpublished data from authors). Among these, a new age of 539 Ma near the base of the BACE excursion will provide a direct date for revising the age of the Ediacaran-Cambrian boundary (Zhu et al., 2017b).

Except the ages from eastern Yunnan, a SIMS U-Pb age of 526.2±1.9 Ma was reported from an ash bed at the base of the Jiulaoding Formation at the Meidiping section in Emei, central Sichuan (Compston et al., 2008) and a SIMS U-Pb age of 526.4±5.4 Ma was reported from the basal Shuijintuo Formation at the Yanjiahe section in the Yangtze Gorges area, western Hubei (Okada et al., 2014). These ages are consistent with the age for the base of the Shiyantou Formation in Yunnan. In addition, Jiang et al. (2009) reported a SHRIMP U-Pb age of 532.3±0.7 Ma from the basal Niutitang Formation at the Zhongnan section in Songlin, northern Guizhou. Whether the age is compatible with the age of Bed 5 in the Meishucun section, Yunnan remains uncertain because there is an obvious uncomformity at the base of the Niutitang Formation at the Zhongnan section and SSFs are absent.

A number of zircon SHRIMP U-Pb ages have also been reported from the Ediacaran-Cambrian transitional sequences in the marginal and slope facies, including 542.1±5 Ma and 536.3±5.5 Ma from the base and top respectively of the chert interval of the basal Niutitang Formation in the Gangziping section, Zhangjiajie, western Hunan (Chen et al., 2009); 542.6 ±3.7 and 522.3±3.7 Ma from the upper Liuchapo Formation and basal Niutitang Formation respectively at the Bahuang section (Chen et al., 2009, 2014), 536±5 Ma from the top of the Liuchapo Formation at the Pingyin section (Zhou et al., 2013), and 522.7±4.9 Ma from the basal Niutitang Formation at the Taoyin section in Jiangkou County, northeastern Guizhou (Wang X Q et al., 2012). Although these ages lack biostratigraphic control, they are very significant in lithostratigraphic correlation. First, the chert interval within the Ediacaran-Cambrian transitional sequences (Liuchapo Formation and corresponding strata) from the marginal and slope areas of the Yangtze Platform is diachronous, and the Ediacaran-Cambrian boundary is located within the chert interval; secondly, the base of the Niutitang Formation is similarly diachronous, and should be older than 522 Ma. This conclusion is supported by the Re-Os isotopic age of 521±5 Ma from the Ni-Mo polymetallic sulfide bed above the base of the Niutitang Formation (Xu et al., 2011).

4.2 North China

The fossiliferous Cambrian strata in North China are mainly composed of shallow water sedimentary sequences. The traditional Middle and Upper Cambrian Chronostratigraphy of China was established based on classic trilobite biostratigraphy of the Cambrian strata in North China (Lu, 1962; Xiang et al., 1981; Lu et al., 1982). However, the new Cambrian Chronostratigraphy of China is based largely on trilobite biostratigraphy from the deeper water slope facies in South China and as such, precise chronostratigraphic correlation between North China and South China is problematic (Peng, 2009). Recent advances in the Cambrian stratigraphy of North China include biostratigraphy (e.g. trilobites and conodonts) and δ^{13}C chemostratigraphy, which together improve the Cambrian chronostratigraphic framework in North China (Figure 5).

4.2.1 Biostratigraphy of North China

(i) Trilobites. The traditional Changshanian consists of 4 trilobite zones, however a *Prochuangia-Paracoosia* Zone beneath the *Chuangia* Zone has been additionally suggested by Peng (2009b). The base of the Paibian Stage is located in the middle of the *Prochuangia-Paracoosia* Zone and corresponds to the basal interval of the SPICE (Ng et al., 2014a). The previous *Drepanura premesnili* Zone and *Diceratocephalus armatus* Zone (Zhu et al., 2007) were revised and replaced by the *Neodrepanura premesnili* Zone by Yuan et al. (2012). Recently, trilobite biostratigraphy of the Changhsia and Hsuchuang Formations has been improved based on detailed taxonomic investigations of large fossil collections (Figure 5; Yuan et al., 2012; Yuan and Li, 2014) but application of these zones throughout North China demands further investigation.

In the Maochuang Formation and equivalent interval, the position of the *Yaojiayuella ocellata* Zone or *Probowmaniella jiawangensis* Zone has been traditionally regarded as one zone below the *Shantungaspis aclis* Zone. However, the distribution of trilobites in the Laoyinshan section of the Huainan area, northern Anhui indicates that the *Y. ocellata* Zone and *P. jiawangensis* Zone are not stratigraphically equivalent. Indeed, the *Y. ocellata* Zone in the Zhongtiaoshan area of Shanxi is equivalent to the *Weijiaspis* Zone in the Huainan area of northern Anhui and thus appears below the *P. jiawangensis* Zone, the latter containing the eodiscid *Pagetia* that first occurs in the Wuliuan Stage in South China. Therefore, the base of the Wuliuan Stage and Miaolingian Series of North China is close the base of *P. jiawangensis* Zone (Yuan and Li, 1999).

The earliest trilobite in North China is *Estaingia*, commonly referred to as *Hsuapsis* (a junior synonym of *Estaingia*), from the basal Cambrian Xinji Formation that is distributed along the southern marginal area of the North China Platform. *Estaingia* is abundant in the Xinji Formation and includes several species and indeterminate species, thus the *Estaingia* Zone is suggested (Zhang et al., 1995).

(ii) Conodonts. Since the early 1980s, 11 conodont biozones have been recognized from the late Drumian to the uppermost Cambrian in North China. These conodont biozones are consistent with those of South China and worldwide and can thus be used for global correlation (An et al., 1983; Chen and Gong, 1986; Bagnoli et al., 2014; Dong and Zhang, 2017).

(iii) SSFs. Abundant SSFs, usually associated with *Estaingia*, have been reported from the basal Cambrian of North China (He et al., 1984; Qian, 1999). A mollusk *Stenotheca drepanoida-Pelagiella madianensis* Assemblage Zone has been established (Feng et al., 1994). Some SSFs from the assemblage and *Estaingia* are also founded in equivalent strata of South Australia and can be correlated with the upper Chiungchussuan Stage of South China (Yun et al., 2016, and references therein).

In addition, the earliest graptolites (e.g. *Dendrograptus*, *Callograptus* and *Dictyonema*) in North China have been recorded from the *Changshania* Zone in Xiaoxian, northern Anhui (Li, 1984). The first cephalopods (*Plectronoceras*) in North China appear in the *Tsinania-Ptychaspis* Zone, while the first diversification of the cephalopods characterized by the ellesmeroceriids occurs in the uppermost Cambrian and thus the *Sinoeremoceras* Zone or *Acaroceras-Eburoceras* Zone has been established (Chen et al., 1979). All of these fossils can be used for stratigraphic correlation.

4.2.2 Chemostratigraphy of North China

Cambrian δ^{13}C chemostratigraphic studies in North China were first carried out for the Cambrian-Ordovician boundary in the 1990s (Chen et al., 1995; Zhang et al., 1999). The Cambrian δ^{13}C profile in North China is, however, largely incomplete (Zhu et al., 2004) and the most recent studies have focused on particular δ^{13}C excursions, such as the SPICE (Ng et al., 2014a, 2014b). The available data indicate that the ROECE, DICE and SPICE are present in North China, suggesting that the Cambrian δ^{13}C data show similar evolutionary patterns representative of the global oceans at this time and would thus be of potential significance for stratigraphic correlation.

4.3 Tarim

Cambrian rocks mainly outcrop in the Wushi-Keping area in the northern margin of the Tarim basin and the Quruqtagh area in the northwestern margin of the Tarim basin. The Cambrian strata in the Quruqtagh area are the most complete and well-exposed and the research history of these strata can be traced back to the 1920s–1930s when a joint China-Sweden expedition carried out systematic investigations of Cambrian stratigraphy and paleontology in this area (Norin, 1937; Troedsson, 1937). The Cambrian sequences in the northern Quruqtagh area are composed of grey and well-

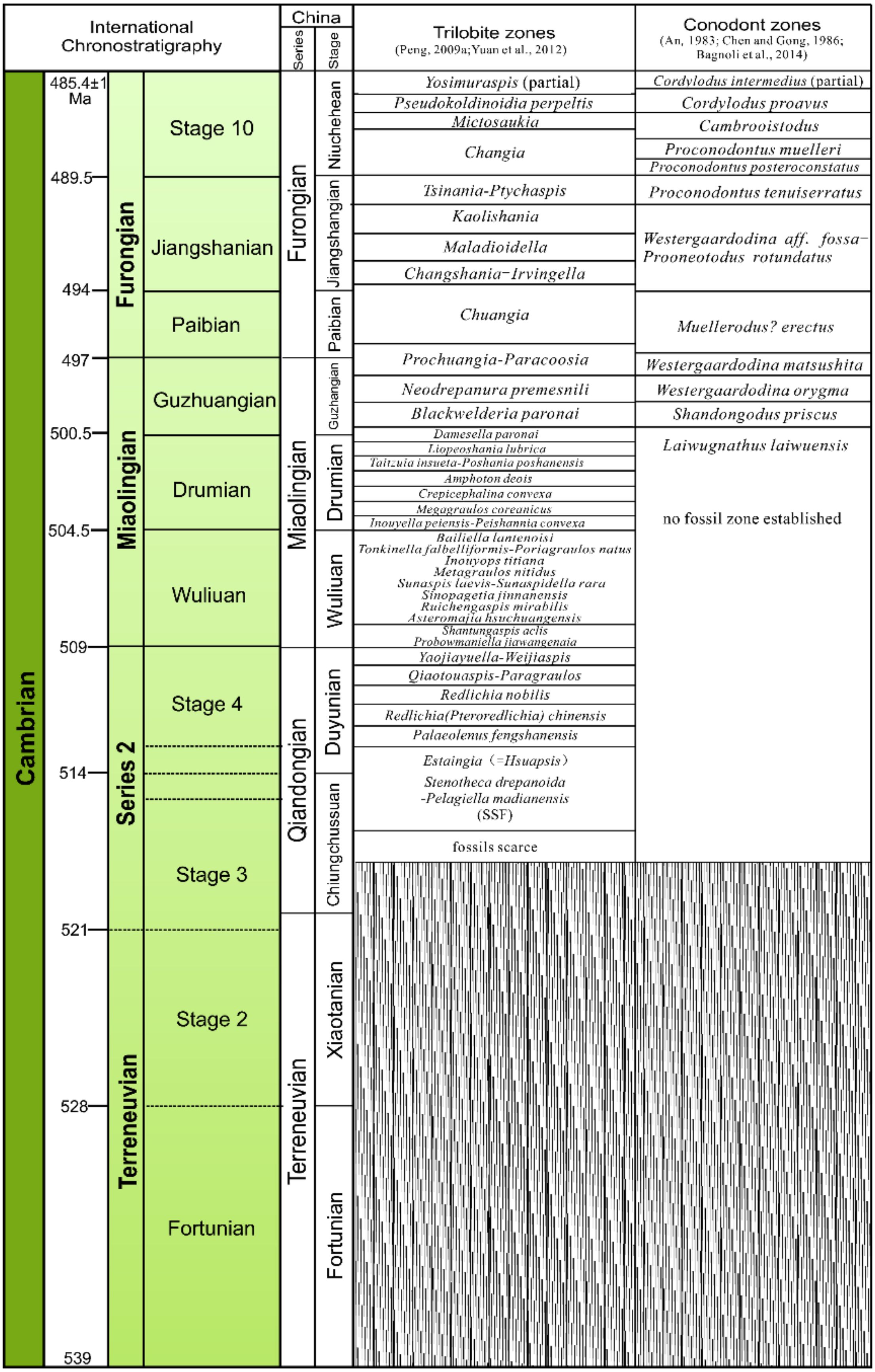

Figure 5 Cambrian chronostratigraphy and timescale of North China.

bedded limestone with frequent tempestites or turbidites, representing deposition in a deeper water slope setting. In the southern Quruqtagh area, the Cambrian sequences are characterized by bedded cherts, black limestone, carbonaceous mudstone and dolostone that may represent deposition in a restricted intra-shelf basin or deeper water basin. The Cambrian sequences in the Wushi-Keping area are characterized by shallow water carbonates with phosphorites at the base. Aside from the Cambrian strata of the Wushi-Keping and Quruqtagh areas, sporadic Cambrian outcrops are distributed in the southern Haerlik Mountain (southern Tianshan Mountain), where Cambrian rocks are composed of deeper water carbonate and turbidites deposited in a slope setting at the northern margin of the Tarim Platform (Zhou, 2001; Feng et al., 2006). In comparison to South and North China, investigations on the Cambrian of Tarim remain relatively preliminary (Figure 6) however, significant progresses has been achieved in the past two decades thanks to intensive exploration for oil and gas in the area.

4.3.1 Biostratigraphy of Tarim

(i) Wushi-Keping area (shallow water facies). Cambrian strata in the Wushi-Keping area consist of, in ascending order, the Yuertus, Xiaoerbulake, Wusongger and Shayilike Formations, and Awatage and Qiulitage groups.

(ii) Trilobites. According to the review by Lin et al. (in Zhou, 2001), the *Tsunyidiscus* Zone, *Ushbaspis* Zone and *Kepingaspis-Tianshanocephalus* Zone can be recognized in the Xiaoerbulake Formation, and the *Paokannia* Zone was recognized in the upper Wusongger Formation. These trilobite zones can be correlated with the trilobites in the Chiungchussuan Stage of South China. Among them, the *Tsunyidiscus* Zone corresponds to the upper *Wutinggaspis-Eoredlichia* Zone and lower *Yiliangella* Zone. The *Kunmingaspis-Chitidilla* Zone from the basal Shayilike Formation corresponds to the upper Duyunian Stage. Poorly fossiliferous dolostones of the Awatage and Qiulitage groups dominate the middle and upper Cambrian sequence in the area and thus no trilobite zonation is recognized.

(iii) SSFs. SSFs were reported from the basal Cambrian Yuertus Formation (Qian and Xiao, 1984; Yue and Gao, 1992; Qian, 1999). The Yuertus Formation is composed of three members: (1) basal black phosphatic cherts with thin interbeds of dolostone or lenticular dolostone; (2) middle black carbonaceous shale with interbeds of dolostone; and (3) upper dolostone with thin interbeds of shale. The *Anabarites-Protohertzina* Assemblage from the basal Yuertus Formation represents typical SSFs of the basal Fortunian Stage. The *Lapworthella-Ninella-Cambroclavus* assemblage reported from the upper Yuertus Formation shares some SSF components with the *Ninella tarimensis-Cambroclavus fangxiangensis* Zone from the Chiungchussuan Stage of the southern Shaanxi area in the northern Yangtze Platform of South China (Steiner et al., 2007).

Moreover, the characteristic basal Cambrian AHC assemblage of acritarchs has been reported from the basal Yuertus Formation (Yao et al., 2005; Dong et al., 2009). Sparse conodonts (e.g. *Proconoduntus cambrica*) have also been discovered and the *Monocostodus sevierensis* Zone was recognized in dolostones of the Qiulitage Group (Zhou et al., 1991; Zhang and Gao, 1992).

(iv) Quruqtagh area (deeper water facies). The Cambrian strata in this area consist of, in ascending order, the Xishanbulake, Xidashan, Chuanxinshan, Moheershan, Tuershaketage and Jinlonggou (south) or Baiyungang (north) Formations.

(v) Trilobites. Trilobites are abundant in Cambrian strata of the Quruqtagh area, and exhibit similar zonation to that of the slope area of South China, as summarized and reviewed by Lin et al. (in Zhou, 2001) and Peng (2009b) and thus provide a principle tool for chronostratigraphic correlation (Figure 6)

(vi) Conodonts. As in South and North China, the earliest conodonts in the Quruqtagh area also occur in the Gushanian Stage. Though only 4 conodont biozones have been recognized in the area (Figure 6; Zhong and Hao, 1990), the diversification of conodonts in the uppermost Cambrian (Jinlonggou or Baiyungang Formations) provides the greatest aid to chronostratigraphic correlation. Since Cambrian sequences in the Quruqtagh area are composed predominantly of deeper water limestone, further, detailed conodont biostratigraphic investigations will improve high-resolution chronostratigraphic subdivision and correlation of the Cambrian in this area.

Other biostratigraphic data in the Quruqtagh area include: (1) the basal Cambrian AHC assemblage of acritarchs and *Kaiyangites* from the Xishanbulake Formation; (2) rich shelly fossils (e.g. mollusk *Pelagiella*, brachiopod *Lingulella* and sponge spicules) associated with the earliest trilobite *Ushbaspis* in the Xidashan Formation (Gao et al., 1984; Zhong and Hao, 1990); and (3) abundant archaeocyathids from the Xidashan Formation in the northern Quruqtagh area (Zhang, 1983).

4.3.2 Chemostratigraphy of Tarim

A general Cambrian δ^{13}C profile was reported for the Wushi-Keping area as early as the middle 1990s (Du et al., 1994; Wang and Yang, 1994). The profile, with distinct records of the BACE, AECE and ROECE excursions was subsequently corroborated by more detailed data collection (Jing et al., 2008; Wang et al., 2011; Guo et al., 2017), providing an important tool for subdivision and correlation of the Cambrian in this area. It should be noted that the SPICE excursion that has been recorded in both shallow and deep water facies worldwide has never been reported in the Wushi-Keping area, which suggests that a depositional hiatus may exist at

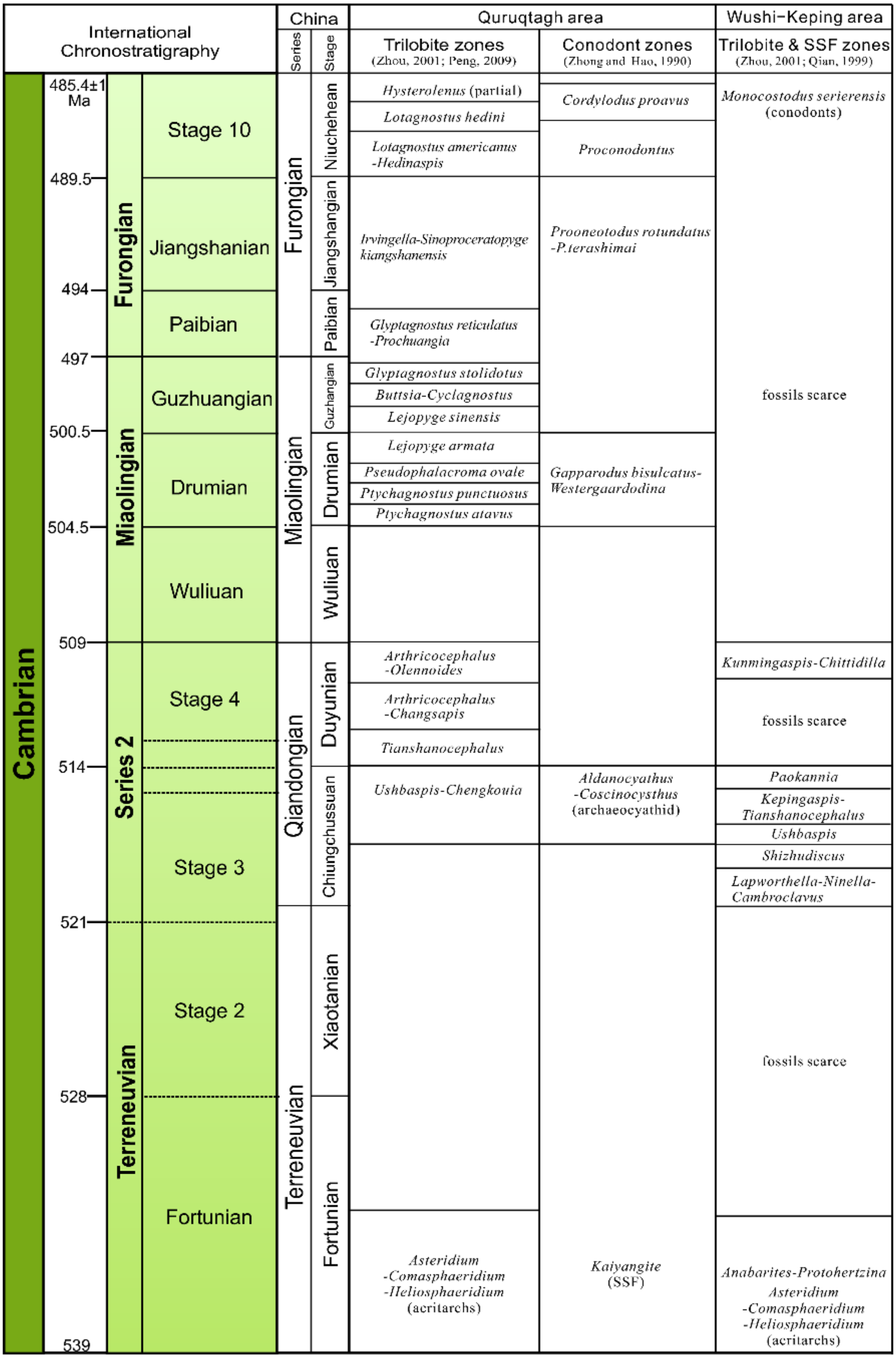

Figure 6 Cambrian chronostratigraphy and timescale of Tarim.

the base of the Furongian in the area, thus requiring further investigation. So far, almost no Cambrian $\delta^{13}C$ data have been published for the Quruqtagh area. Recent preliminary data indicate that the SPICE excursion seems to be recorded but the $\delta^{13}C$ values are relatively low; while the ROECE excursion seems to be entirely absent (Liu et al., 2016). Therefore, more attention to Cambrian $\delta^{13}C$ chemostratigraphy of the Quruqtagh area is required in future investigations.

5. Identification of the base of the Cambrian in China

5.1 The base of the Cambrian in South China

In the majority of areas of the Yangtze Platform, the basal Cambrian sequence is characterized by cherty and phosphatized rocks of various thicknesses (centimeters to hundreds of meters). These rocks have been partitioned into various lithostratigraphic units, including the Zhujiaqing Formation of eastern Yunnan, Gechongwu Formation of western Guizhou, Maidiping Formation of western Sichuan, Yanjiahe Formation in the Yangtze Gorges area of western Hubei, and Kuangchuanpu Formation of southern Shaanxi etc. In general, this unique sequence is separated from dolostone of the underlying Dengying Formation by a sharp, unconformable surface. Usually, the basal Cambrian cherty and phosphatized interval contains SFFs and the AHC acritarch assemblage (e.g. Qian, 1999; Steiner et al., 2007; Ahn and Zhu, 2017). Due to the fact that the BACE negative excursion is the best marker for the base of the Cambrian (as discussed above), the base of the Cambrian in most areas of South China is coincident with the unconformity at the top of the Dengying Formation and it is thus easy to recognize in the field. This is exemplified by the Yanjiahe section at the southern limb of the Huangling Anticline in western Hubei, which was regarded as one of the best Precambrian-Cambrian boundary sections of South China (Ishikawa et al., 2008, 2013; Jiang et al., 2012; Wang D et al., 2012). However, in eastern Yunnan and western Sichuan, the BACE excursion is located within the top of the Dengying Formation (e.g. Brasier et al., 1990; Zhang et al., 1997; Li et al., 2009, 2013). Therefore, identification of the base of the Cambrian in specific sections requires detailed chemostratigraphic investigation.

In the deep water slope and basinal facies of South China, however, the Precambrian-Cambrian boundary interval is characterized by a transitional sequence composed of bedded cherts and black shale. Due to the absence of fossils and carbonates, the use of biostratigraphic and carbonate $\delta^{13}C$ chemostratigraphic tools are not suitable for identification of the base of the Cambrian in this area. Traditional designation of the Cambrian base at the boundary between the cherts and black shale units have proved to be incorrect by more recent investigations due to variability in the chert interval between facies in these areas (e.g. Liuchapo, Laobao and Piyuancun Formations). In the upper slope, the chert interval is underlain by thick-bedded dolostone, while in the lower slope and basin area it underlain by black shale. Meanwhile, the chert interval contains both terminal Ediacaran fossils (e.g. *Palaeopascichnus*; Dong et al., 2008; Dong et al., 2012; Wang J G et al., 2012) and Cambrian fossils (e.g. sponge spicules and *Kaiyangites*; Yin et al., 1982). Collectively, these data suggest that the chert interval is a diachronous unit and the base of the Cambrian is located within the chert unit. This suggestion is supported by the geochronological data summarized above. Further efforts to identify the Cambrian base in slope and basinal areas of South China have utilized organic carbon $\delta^{13}C$ chemostratigraphy and a possible BACE excursion has been recognized (e.g. Guo et al., 2013), providing additional support for defining the base of the Cambrian in these area.

5.2 The diachronous base of the Cambrian in North China

The base of the Cambrian in North China is indisputably characterized by a well-known unconformity. The major issues that remain unsolved in North China are: (1) whether the base of the Cambrian is a diachronous surface and how old the lowest Cambrian strata are, and (2) which of the numerous unconformable surfaces represents the base of the Cambrian?

In the southern and southwestern margins of North China, a characteristic phosphorite bed, widely recognizable at the base of the basal Cambrian Houjiashan and Xinji Formations, is usually regarded as the marker bed for the base of the Cambrian. The trilobite *Estaingia* and associated SSFs from the lower Houjiashan and Xinji Formations suggest that the lowest Cambrian strata in the area are no older than the *Yilaingella* Zone of the Chiungchussuan Stage (Zhang et al., 1995; Qian, 1999; Yun et al., 2016). The lowest Cambrian strata become gradually younger from the platform margin to the platform interior. In Shandong, Hebei and western Liaoning area, the basal Cambrian carbonate (Chanping or Fujunshan Formation) contains *Palaeolenus fengyangensis* and *Redlichia* and does not contain the phosphorite bed at the base, corresponding to the Duyunian Stage (Zhang and Zhu, 1979).

It should be noted that there is a black shale interval (Yutaishan or Dongpo Formation) below the Houjiashan and Xinji Formations. The Yutaishan Formation is underlain by the Fengtai diamictite, distributed in the Madian area of Huoqiu, Henan, and the Bagongshan area of Huainan, Anhui. In contrast, the Dongpo Formation is underlain by the Luoquan diamictite and distributed in the area along Zhu-madian-Linbao of Henan and Luonan of southern Shaanxi. Whether the black shale interval belongs to the Cambrian remains controversial. Our recent data confirm that the upper Yutaishan Formation is of Cambrian age because it yields typical inarticulate brachiopods. However, the black shale of the lower Yutaishan Formation exhibits a continuous transition from the underlying Fengtai diamictite. Similar, the Dongpo Formation and underlying Luoquan diamictite also constitute a continuous depositional sequence. Since no reliable age constraint exists for the Fengtai and Luoquan diamictites, the ages of the lower Yutaishan Formation and Dongpo Formation remain uncertain. The contact between the Dongpo Formation and overlain Xinji Formation is unconformable, thus the Dongpo Formation is regarded as Precambrian in age. Obviously, further investigation of the black shale and underlying diamictite is warranted.

In the Huaibei area of northern Anhui, the Jinshanzhai and Gouhou Formations, underlying the trilobite-bearing Houjiashan Formation, are usually considered to be Cambrian in age despite a lack of fossil evidence (Xing et al., 1984, 1985; Qian M P et al., 2001). Recent investigation suggests that they are early Neoproterozoic in age based on organic-walled microfossils (e.g. *Trachyhystrichosphaera*, *Valeria* and *Dictyosphaera*) from the Gouhou Formation (Xiao et al., 2014; Tang et al., 2015). However, most recently, a zircon U-Pb age of 518.4±2.9 Ma has confirmed a Cambrian age for the Gouhzou Formation (He et al., 2017). As there is no obvious hiatus between the Gouhou Formation and the underlying Jinshanzhai Formation, and the basal conglomerate is recorded at the base of the Jinshanzhai Formation, we consider the unconformity at the base of the Jinshanzhai Formation in this area to represent the base of the Cambrian but this requires confirmation by further investigations.

Similar to the Huaibei area of northern Anhui, the Cambrian age of the Getun and Dalinzi Formations underlying the trilobite-bearing Jianchang Formation in the Dalian area of Liaodong Peninsula, remains unresolved. The Dalinzi Formation is composed of colorful siliciclastic rocks with common halite pseudomorphs and mud cracks, similar to the Gouhou Formation in the Huaibei area, suggesting that they may be correlatable. Similarly, the Getun Formation is composed of organic-rich, fine-grained siliciclastic rocks with carbonate interbeds and is comparable to the Yutaishan Formation in the Huainan and Heqiu areas. Moreover, there is no obvious sedimentary gap between the Getun Formation and the overlying Dalinzi Formation but there is a sharp contact with the underlying Xinmingcun Formation. Therefore, the Getun and Dalinzi Formations are possibly Cambrian in age.

Additionally, in the Tonghua area of southern Jilin, the Heigouzi and Qinggouzi Formations underlying the trilobite-bearing Jianchang Formation have also been regarded as Cambrian in age (Yue et al., 1990; Qian, 1999; Duan et al., 2005). The Cambrian age of the Heigouzi Formation is supported by the presence of hyoliths and other SFFs at its base, however a Cambrian age for the Qinggouzi Formation lacks any palaeontological or radiometric basis. In summary, the base of the Cambrian in North China is marked by an unconformity and the lowest Cambrian units are diachronous with a basal age no younger than 518 Ma.

5.3 The base of the Cambrian in Tarim

In the shallow water area of Tarim (the Wushi-Keping area), the contact between the basal Cambrian Yuertus Formation and the underlying Ediacaran Qigebulake Formation is unconformable. Thus, the base of the Cambrian is easy to identify. In the deeper water Quruqtagh area, however, it is difficult to identify the precise position of the base of the Cambrian because the basal Cambrian fossil-bearing Xishanbulake Formation is composed of cherts and no chemostratigraphic data are available. The sequence underlying the Xishanbulake Formation is the Hankalchough diamictite and its associated carbonate bed (1–6 m). No sedimentary gap is recognizable between the carbonate bed and overlying Xishanbulake cherts. Since no age constraint is available for the Hankalchough diamictite, the base of the Cambrian is temporally placed at the base of the Xishanbulake Formation.

6. Subdivision and correlation of the dolostone sequence of the upper Cambrian in China

A thick, massive or thick-bedded dolostone sequence is widely developed in the upper portion of the Cambrian System in the shallow water facies areas of South China and North China, as well as Tarim. Associated strata include the Loushanguan, Erdaoshui, Xixiangchi Groups and Sanyoudong Formation of the Yangtze Platform, the Sanshanzi Formation in the Huainan area of Anhui and its adjacent area of Henan in North China, and the Awatage and Qiulitage Groups in the Wushi-Keping area of Tarim. The dolostone sequence is a diachronous unit with age ranging from the Miaolingian to the lower Ordovician based on the fossils that occur in the strata below and above the sequence. As this dolostone unit is poorly fossiliferous, further subdivision and correlation of the sequence is problematic. At present, the most practical means of resolving this problem is to apply conodont biostratigraphy and $\delta^{13}C$ chemostratigraphy. For example, the SPICE excursion and conodont biozones have been documented from the Loushanguan Group in northern Guizhou (Zuo et al., 2008; Fan et al., 2013). However, in the Awatage and Qiulitage Groups of Tarim, published data do not record the SPICE excursion and conodont fossils are very poor, thus the presence of gaps in sedimentation cannot be excluded in the area, and further careful sedimentary analyses are required.

7. Summary

Through generations of unremitting effort, studies on Cambrian stratigraphy have made remarkable contributions to the establishment of the international Cambrian chronostratigraphy and played a significant role in research on Cambrian geology and exploration of mineral resources in China. At present, the designation of GSSPs for stages in the upper half of the Cambrian is nearly complete. Among them, the GSSPs of the Miaolingian and Furongian Series and 4 stages (Wuliuan, Guzhangian, Paibian and Jiangshanian) are located in South China. The GSSP for Stage 10 may also be defined by a section in South China. However, it is crucial to recognize the difficulties inherent in the definition and subdivision of stages in the lower half of the Cambrian. It is clear that it may prove impossible/unfeasible to use a single criterion or stratigraphic marker to define the GSSPs of these lower Cambrian stages, and multiple criteria or stratigraphic markers should be applied. Recognition of the present state of research and the characteristics of lower Cambrian sequences in South China will permit further contributions to be made to the establishment of the international Cambrian chronostratigraphy. Firstly, the well-developed Ediacaran-Cambrian transitional sequence in eastern Yunnan may potentially be ideal for defining the GSSP of Stage 2 because this sequence hosts a continuous SFF succession and chemostratigraphic record and, particularly, contains multiple ash layers that provide the opportunity for high-resolution radiometric dating. Secondly, the pelagic trilobites, oryctocephalids, are well documented and show rapid evolution in the deep water slope sequence of upper Series 2 in areas of southeastern Guizhou, southwestern Hunan and southern Anhui and provide potential for defining the GSSP of Stage 4. Therefore, detailed stratigraphic studies of these sequences in South China should be a priority in the coming years. Available geochronological data indicate that the lower two Cambrian series (~30 Ma) span a greater time interval than the upper two Cambrian series (~23.6 Ma), and thus additional stages within the lower two Cambrian series should be established if possible.

In the past decade, Cambrian stratigraphic studies in China have made significant advances, as reviewed above (Figures 4–6). However, numerous stratigraphic questions remain unresolved. The primary unanswered questions and problems are as follows.

(1) Stratigraphic correlations between sequences in the shallow water platform facies and deep water slope and basinal facies, including: (a) A precise biostratigraphic correlation of trilobite zones between the shallow and deep water facies. (b) The application of more integrated stratigraphic approaches to resolve subdivision and correlation of lower Cambrian sequences in South China. This has so far been challenged by poorly fossiliferous sediments and a dearth of carbonate in the deep water facies of South China, which are instead characterized by black cherts and shale. (c) Subdivision and correlation of the poorly-fossiliferous dolostone sequence of the middle-upper Cambrian in shallow water facies of the Yangtze Platform, North China and Tarim. The potential solution to this problem may use a combination of conodont biostratigraphy and $\delta^{13}C$ chemostratigraphy.

(2) Identification of the base of the Cambrian. In view of the deficiency of the GSSP of the Cambrian base, it is difficult to use the FAD of the trace fossil *T. pedum* to define the Cambrian base. Here we propose use of the BACE $\delta^{13}C$ negative excursion to define the he Cambrian base. Accordingly, the base of the Cambrian in shallow water facies of the Yangtze Platform is coincident with the unconformity at the top of the Dengying Formation or located within the dolostone unit at the top of the Dengying Formation. It is, however, difficult to recognize the BACE in the deep water sequences in South China and Tarim due to the absence of carbonate. The base of the Cambrian in North China is coincident with a major uncomformity but the age of the oldest Cambrian strata in marginal areas of North China remains controversial and requires clarification.

(3) Cambrian rocks are widely distributed in other areas of China (outwith South China, North China and Tarim) and include exposures in the Tibetan Plateau, Qaidan basin, northern Tianshan, Qinling orogenic belt and western Yunnan. Due to limitations of space, these Cambrian rocks are not discussed in this review, however the Cambrian rocks in these areas remain poorly investigated and therefore deserve greater attention in future investigations.

Acknowledgements *We thank Jiayu Rong and Shuzhong Shen for their encouragement and support for this review, Shanchi Peng, Yuanlong Zhao and an anonymous reviewer for their critical comments and suggestions, and Frederick Bowyer for language improvement. The review benefited from discussions and collaborations with numerous colleagues all over China and abroad in the past two decades. The study was supported by the National Natural Science Foundation of China (Grant Nos. 41672029, 41661134048) and the Strategic Priority Research Program (B) of the Chinese Academy of Sciences (Grant Nos. XDB18000000, XDB10010101).*

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(Responsible editor: Shuzhong SHEN)