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Cambrian integrative stratigraphy, biotas, and paleogeographical evolution of the Qinghai-Tibetan Plateau and its surrounding areas

Zhixin SUN[1,2], Lang SUN[1,2], Fangchen ZHAO[1,2*], Bing PAN[1], Malik Muhammad Saud Sajid KHAN[1,2], Shehryar AHMED[1,2], Chuan YANG[1], Lanyun MIAO[1], Zongjun YIN[1], Guoxiang LI[1] & Maoyan ZHU[1,2]

[1] *State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China;*
[2] *College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*

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Abstract The Qinghai-Tibetan Plateau and its surrounding areas have a long and complex tectonic evolutionary history. Cratons and blocks, such as northern India, Lhasa, Qiangtang, Qaidam and Central Qilian, and their in-between orogenic belts constitute the main part of the Qinghai-Tibetan Plateau. During the Cambrian Period, most of these cratons and blocks were on the northwestern periphery of Gondwana, and were associated with the surrounding blocks, e.g. Arabian, Central Iran, Afghanistan, Tarim, Alxa, North China, South China and Sibumasu through the Proto-Tethys Ocean. The Cambrian stratigraphic sequences on these stable blocks are composed of mixed siliciclastic and carbonate rocks deposited in the shallow-water marine environments, and contain the trilobite assemblages of shelf facies. The Cambrian stratigraphic sequences in the Qilian tectonic belts, however, are characterized by the intermediate-basic igneous rocks and silicates formed in the Proto-Tethys Ocean, and contain the trilobite assemblages of deep-water slope facies. Combining with previous data, field observations and newly discovered fossils through funding by the Second Tibetan Plateau Scientific Expedition and Research, the general characteristics of the Cambrian strata in different tectonic units of the Qinghai-Tibetan Plateau and its surrounding areas have been summarized in this paper. Furthermore, efforts have been made to subdivide and correlate the Cambrian strata across these areas by utilizing available biostratigraphic and geochronological data. As a result, a comprehensive litho- and biostratigraphy chart has been compiled. Finally, from the biogeographic perspective, this paper also provides a brief overview of the Cambrian paleogeographical reconstruction of the major tectonic blocks, and discusses the problems associated with the evolution of the Proto-Tethys tectonic belt.

Keywords Qinghai-Tibetan Plateau, Cambrian, Stratigraphy, Paleogeography, Biota, Gondwana, Proto-Tethys Ocean

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1. Introduction

The Qinghai-Tibetan Plateau and its surrounding areas are an important part of the magnificent Tethys orogenic belt, experiencing both the initiation and cessation of several Tethys oceans (Wu et al., 2020; Zhu et al., 2022). The Cambrian strata are among the oldest sedimentary sequences in the Qinghai-Tibetan Plateau, and generally, their outcrops in these areas are characterized by severe tectonic complexities, limited availability, and challenges in their interpretation. Nevertheless, thanks to the persistent efforts of researchers over the course of more than a century, our understanding of

* Corresponding author (email: fczhao@nigpas.ac.cn)

the Cambrian strata in these areas has been steadily advanced.

The study on the Cambrian of the Qinghai-Tibetan Plateau began in the late 19th century in the Himalaya (Wynne, 1878; Redlich, 1899), and subsequently, typical Cambrian trilobite fossils were discovered in its surrounding areas during the 1930s, e.g., southwest Iran (King, 1930, 1937) and western Yunnan (Sun, 1939). With rapid development of the basic geological exploration after the Second World War, the Cambrian strata with abundant fossils have been identified in many areas, such as in Myanmar, Thailand, Pakistan, Afghanistan, Oman and Iran (Kobayashi, 1957; Stöcklin et al., 1964; Ruttner et al., 1968; Wolfart, 1970; Fuchs and Mostler, 1972; Thein, 1973; Fortey, 1994). In particular, it is worth mentioning that in the second half of the last century, China initiated the Tibetan Plateau Scientific Expedition and Research program, and significant discoveries of Cambrian fossils were achieved in the northeastern (Song, 1959; Zhu, 1960a, 1960b, 1960c; Qilian Mountain Geological Team, Chinese Academy of Sciences, 1963), eastern (Sichuan Stratigraphic Chart Compilation Group, 1978; Li et al., 1982; Zhu, 1982) and northwestern (Xiang et al., 1981) parts of the Qinghai-Tibetan Plateau. This resulted in the development of regional stratigraphy, and comprehensive correlation of Cambrian strata in China (Lu et al., 1982; Chang, 1988), providing valuable raw materials for subsequent researches. Since the beginning of this century, the understanding of the Cambrian strata in the Qinghai-Tibetan Plateau and its surrounding areas has been continuously enriched, e.g., systematic summaries of classical Cambrian sections (Myrow et al., 2006a, 2006b, 2009; Peng et al., 2009; Hughes, 2016, 2018, 2019) and discoveries of new fossil assemblages (Hughes et al., 2002, 2011; Amthor et al., 2003; Wernette et al., 2020a, 2020b, 2021; Devaere et al., 2021; Pan et al., 2023; Ahmed et al., 2023) in these areas. At the same time, the use of high-precise radio-isotopic dating methods has enabled the identification of certain Cambrian strata that lack chronostratigraphic constraints (Ji et al., 2009; Xu et al., 2022).

In general, through nearly a century of research, the Cambrian stratigraphic sequences and biotas of the Qinghai-Tibetan Plateau and its surrounding areas have been gradually revealed. However, the Cambrian stratigraphic and paleontological record in the hinterlands of the Qinghai-Tibetan Plateau, western Kunlun, western Thailand, western Myanmar, southwestern Iran, and central Afghanistan remains least understood and awaits corroboration with additional data (King, 1937; Ruttner et al., 1968; Karapetov et al., 1971; Thein, 1973; Shareq et al., 1977; Bunopas, 1992). Furthermore, in recent decades, there have been significant revisions to the global Cambrian chronostratigraphic scheme, e.g., 4 series and 10 stages have been adopted and the GSSPs (Global Boundary Stratotype Section and Point) of 6 stages and 3 series have been established (Peng et al., 2004; Babcock et al., 2005; Zhu et al., 2019; Zhao et al., 2019). In many earlier-investigated areas around the Qinghai-Tibetan Plateau, such as Qilian tectonic belts, Qaidam basin and Baoshan areas, although many fossil assemblages have been systematically described (Zhu, 1960a, 1960b, 1960c; Zhu et al., 1979; Zhou et al., 1982, 1996; Sun and Xiang, 1979; Luo, 1982, 1983), the exact biostratigraphic and paleogeographical significance of these fossil assemblages still needs to be recalibrated under the new global chronostratigraphic scheme. Most importantly, enhancing our understanding of the Cambrian stratigraphy of these areas hold significant importance in tracking the evolutionary history of the Proto-Tethys Ocean (Wu et al., 2020). With this objective in mind, this study aims to integrate previous research findings and recent advances to provide a comprehensive account of the Cambrian lithostratigraphy and fossil assemblages of the areas. We hope that this work can serve as a crucial reference for future investigations in Cambrian stratigraphy and paleontology, and provides basic information for understanding the geological evolution of the Qinghai-Tibetan Plateau and its surrounding areas.

2. Cambrian lithostratigraphic sequences of the Qinghai-Tibetan Plateau and its surrounding areas

The Cambrian strata exhibit a wide distribution across various blocks in these areas, including the Qiangtang Block, Lhasa Block, Indian Craton, Central Qilian Block, and Qaidam Block, as well as the orogenic belts between them and their surrounding stable blocks such as South China, North China and Tarim. Additionally, the Cambrian strata in Alxa, Sibumasu, Afghanistan, central Iran and Oman are also included in this study because they were likely in proximity to the aforementioned tectonic units during the Cambrian Period (Figure 1). In order to compare the Cambrian stratigraphic sequence in these areas under investigation, a detailed lithostratigraphic column of each representative area has been reconstructed. Since the Cambrian sequences in North China, South China, and Tarim blocks have been well-studied and summarized in detail (see Zhu et al., 2019, 2021; Peng et al., 2020 and literature therein), only representative sections in these three areas are used for reference (Figure 2, Profile 13; Figure 3, Profiles 14, 15 and 26).

2.1 Central Qinghai-Tibetan Plateau

In the hinterland of the Qinghai-Tibetan Plateau, although Cambrian fossils have not been found in the Lhasa and Qiangtang blocks, recent stratigraphic and isotopic evidences indicate the presence of Cambrian strata in this area.

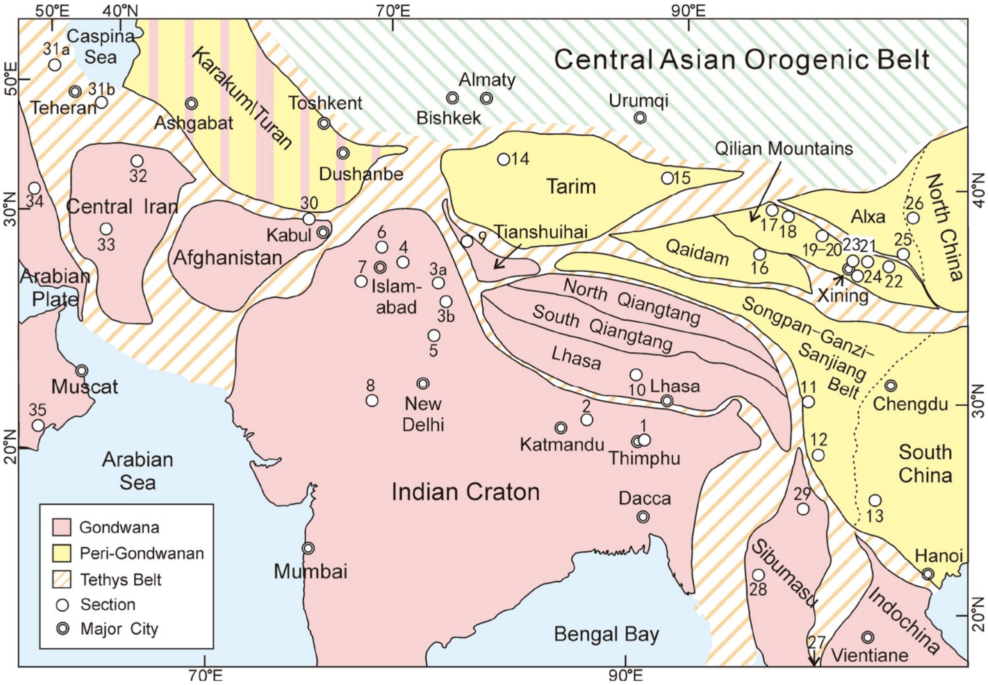

Figure 1 The schematic map showing the locations of the major Cambrian outcrops in the Qinghai-Tibetan Plateau and its surrounding areas, and the Tethys Orogenic Belt within the Gondwana (pink) and a series of cratons and terranes floating around Gondwana (yellow). There is no evidence for the position of the Karakum/Turan Block in the Cambrian. The numbers in the map correspond to the stratigraphic column numbers in Figures 2–4. Division of tectonic units refers to Wu et al. (2020).

In 2009, Ji et al. obtained a 500 Ma age on the rhyolite magmatic genetic zircons in the Zhakang section, Lhasa Block, confirming the existence of Cambrian sediments in this section. Subsequently, Li et al. (2010), Zhu et al. (2012), Hu et al. (2013) and Pan et al. (2012) further provided various evidences that this set of rocks belongs to the Cambrian. The Cambrian strata at Zhakang are more than 600 m in thickness and were named as the Zhaqian Group (Zhang et al., 2021). The lower part of this unit is dominated by metamorphic volcanic rocks, while the upper part is composed of slate and quartz sandstone. An angular unconformity separates the Zhaqian Group from the overlying Ordovician conglomerate (Ji et al., 2009; Li et al., 2010) (Figure 2, Profile 10).

In the Bomi of the southeastern Lhasa Block, Zhu and Dang (1993) established the Bomi Group, which refers to a set of metaclastic rocks (interbedded with marble and volcanic rocks), containing late Neoproterozoic-Cambrian microfossils. Later, Zhen et al. (2020) and Fang et al. (2020) considered that the Bomi Group is synonymous with the Guqin Group at Chayu (Chen et al., 1982). However, the relationship between the Guqin and Bomi groups remains elusive due to the lack of fossils and radioisotopic dates together with the complexity of the outcrops (Xie et al., 2007; Fang et al., 2020). Further, the microfossils in the Bomi Group are of relatively long stratigraphic-range taxa, so whether the Bomi Group (or Guqin Group) entirely or partially belongs to the Cambrian awaits further confirmation.

In the South Qiangtang Block, Yang et al. (2014) named a set of quartz sandstones near Rongma in Nyima County as the Rongma Formation and considered it as the Cambrian deposits based on the detrital zircon age dating. This formation is characterized by medium- and thick-bedded metamorphic quartz sandstone with thin intercalations of limestone.

2.2 Himalaya

The Cambrian strata widely outcrop in the Himalaya, such as central Bhutan, Nyalam and Pulan County in China, Ladakh and Kashmir in northwest India, and northern Pakistan (Figure 2, Profiles 1–7). This area holds a significant record for one of the most important late Cambrian orogenic events in East Gondwana, known as “The Kurgiakh Orogeny” (also referred to as the Bhimphedian movement; Srikantia et al., 1980; Cawood et al., 2007). This tectono-thermal event is manifested by the significant angular unconformity between the middle Ordovician conglomerate and the underlying Cambrian strata (upper Furongian) in the Himalaya (Bhargava et al., 2011; Myrow et al., 2016; Singh and Bhargava, 2020).

The Cambrian strata in the easternmost Himalaya have been recorded in Bhutan (Figure 2, Profile 1). In recent years,

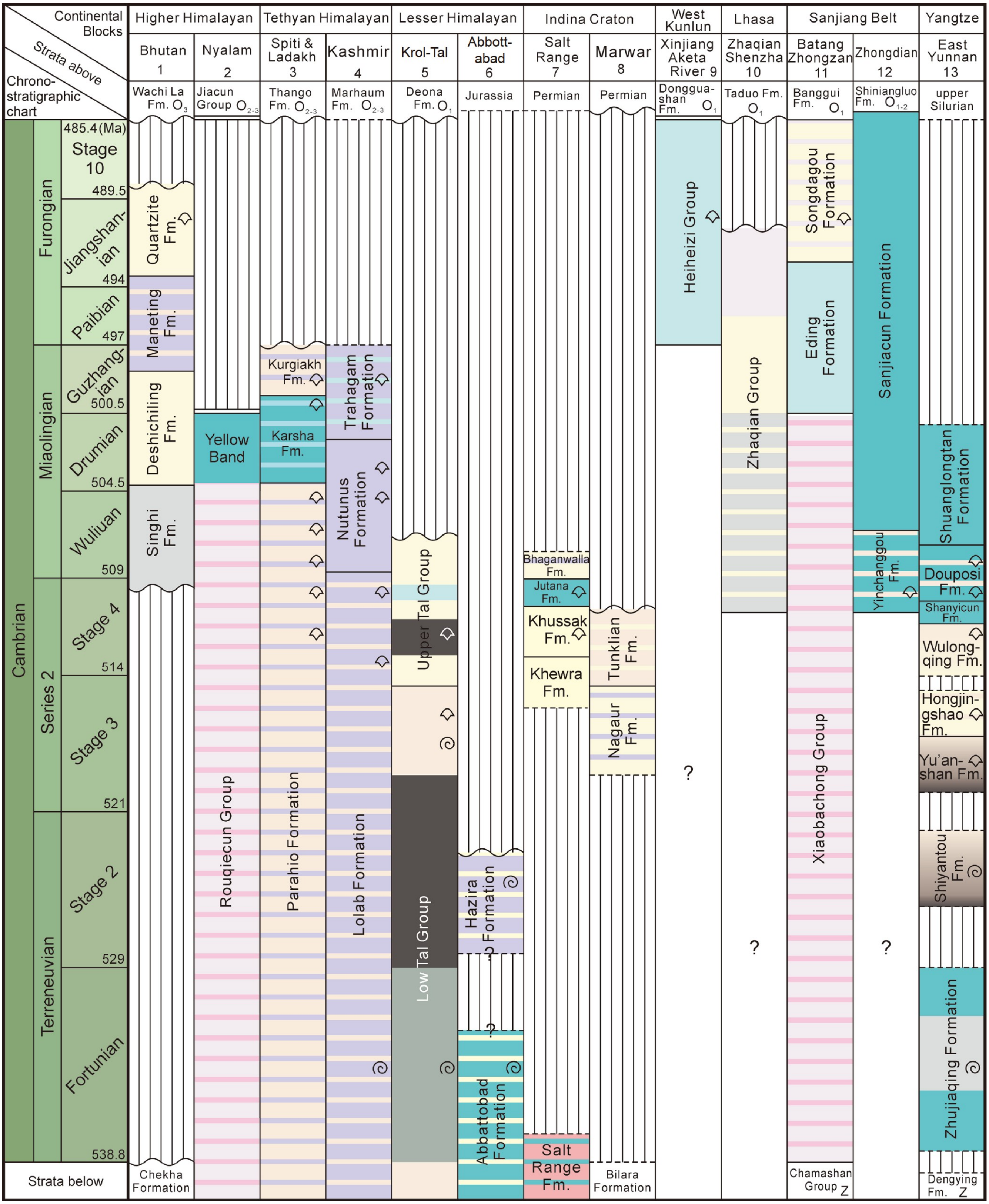

Figure 2 The correlation chart of Cambrian strata in the Qinghai-Tibetan Plateau and its surrounding areas, legends are shown in Figure 4.

much advance has been made on the Cambrian stratigraphy of Bhutan, especially the discovery of the Jiangshanian trilobites in the Quartzite Formation, which represents the first Cambrian fossil record in the Higher Himalaya (Hughes et al., 2011). The underlying Pele La Group, consisting of the Maneting, Deshichiling, and Singhi formations, has detrital zircon ages that support a Furongian age for this unit (Hughes et al., 2011; Myrow et al., 2016). However, whether the Chekha Formation below the Pele La Group belongs to the Cambrian or not remains ambiguous.

Westward into China, the Cambrian rocks are distributed in the Zhada, Pulan, Nyalam and Yadong areas on the northern slope of the Himalaya. The Cambrian rocks here are assigned to the Rouqiecun Group, which is a set of low-grade metamorphic strata without a report of the Cambrian fossils (Mu et al., 1973; Xizang Bureau of Geology and Mineral Resources, 1993, 1997; Zhao et al., 2001) (Figure 2, Profile 2). The lower part of the group is dominated by quartz schist and slate, while the upper part is composed of crystalline limestone, well-known as the 'Yellow Band' of Mount Qomolangma (or Mount Everest). The Yellow Band exhibits similarities with the Ordovician Jiacun Group of the southern Tibetan Plateau (Fang et al., 2020). Previously, this unit had been included in the lower Jiacun Group (or lateral equivalent 'Qomolangma Formation') (Mu et al., 1973; Xiang et al., 1999). Based on recent lithostratigraphic correlation with contemporaneous strata in northern India and on detrital zircon data, it seems reasonable to consider the Rouqiecun Group as being Cambrian in age (Myrow et al., 2009, 2016). In addition, a set of similar strata is referred to as the Kejia and Qiwugongba groups in Pulan (Zhao et al., 2001), which are both composed of schist, slate, and phyllite (Xizang Bureau of Geology and Mineral Resources, 1993; Xiang et al., 1999). Lithostratigraphically, the late two unit names are junior synonyms of the Rouqiecun Group.

In the west-central part of the Himalaya, the most extensively studied Cambrian rocks are preserved in Spiti, Zanskar and Kashmir, constituting of the Tethyan Himalaya zone (Figure 2, Profiles 3, 4). In Zanskar, the Cambrian rocks record the most complete sequence and are subdivided into the Parahio, Karsha and Kurgiakh formations, in ascending order. The Karsha Formation is mainly carbonate dominant, but the other two formations are mainly siliciclastic, representing a set of shallow marine sediments (Myrow et al., 2006a, 2006b; Hughes et al., 2018). The Karsha Formation is rich in agnostid trilobites and was previously suggested to be deep marine slope deposits (Garzanti et al., 1986), but recently, Myrow et al. (2006a) argued that this unit was deposited in the shallow marine shelf setting. In contrast, the Cambrian record in Kashmir is relatively fragmented, yet the lithostratigraphic associations and fossil features show notable similarities to those of the Spiti and Zanskar areas (Shah, 1982; Jell and Hughes, 1997). The Cambrian strata in the west-central Himalaya of northern India exhibit lithological and stratigraphic similarities to those found in the Nyalam and Qomolangma areas, indicating their affiliation with the Tethyan Himalaya sedimentary zone (Myrow et al., 2016). In general, the west-central part of the Himalaya is rich in Cambrian fossils, and the characteristics of assemblages further support a closely paleobiogeographic relationship with South China and Australia.

In the Lesser Himalaya of northern India, Cambrian rocks are represented in the Krol-Tal zone, south of Spiti. The Cambrian in this area is composed of mainly siliciclastic rocks of the Tal Group (Figure 2, Profile 5). Unlike the Tethys Himalaya, the fossil record of the Tal Group is limited to the early Cambrian. The basal silicic phosphorite in this unit contains early Terreneuvian shelly fossils (Hughes et al., 2005; Hughes, 2016). In the Western Lesser Himalaya of Pakistan, the early Cambrian Hazira Formation exposed near the Abbottabad district contains late Terreneuvian small shelly fossil assemblages. These fossils are mainly concentrated in a basal 2 m-thick layer of phosphatic carbonate followed upward by a 5 m-thick layer of bioclastic argillaceous dolostone (Latif, 1972, 1974; Mostler, 1980; Pan et al., 2023; Ahmed et al., 2023). The middle and upper part of the Hazira Formation consists of unfossiliferous siliciclastic rocks (shale/siltstone) nearly 100 meters in thickness. Recently, we discovered *Tannuolina zhangwentangi* from this interval, confirming the late Terreneuvian age for the Hazira Formation. *T. zhangwentangi* is an index fossil unique to the *Sinosachites flabelliformis-Tannuolina zhangwentangi* Assemblage Zone (Zone IV, Cambrian Stage 2) in South China. Until recently, the age of the underlying Abbottabad Formation (about 600 m-thick) remains disputed due to the lack of bio- and chronostratigraphic constraints. Based on the discovery of Marinoan glacial diamictite and cap carbonate at the base of underlying Kakul Formation, Khan et al. (2022) recently suggested that if not whole, most of the Abbottabad Formation belongs to the Ediacaran. This inference is further supported by our discovery of the earliest Cambrian small shelly fossils, such as *Anabarites* and *Protohertzina* from the upper part (Sirban Member) of the Abbottabad Formation, confirming that the base of the Cambrian most certainly lies in the Sirban Member of the Abbottabad Formation (Ahmed et al., 2023; Figure 2, Profile 6).

To the south of the Himalaya, the Cambrian strata are preserved in the Salt Range of Pakistan in Indian Craton. Compared to other parts of India, the Salt Range holds the distinction of having the oldest exploration history of Cambrian rocks and fossils (Redlich, 1899; King, 1941; Figure 2, Profile 7). The Cambrian strata in the Salt Range overlie the terminal-Ediacaran salt-bearing rocks of the Salt Range Formation, and include only part of the Cambrian Series 2. Here the sequence is only about 300 m-thick and comprises a mixed suite of shallow-water siliciclastic and carbonate rocks. Some of these rocks exhibit well-preserved, salt pseudomorphs and mud cracks on bedding surfaces. In general, body fossils are rare in this sequence, and the presence of rich trace fossils indicates a shallower littoral sedimentary sequence compared to those further north in the Himalaya (Hughes et al., 2019). Further southeastward, in the Rajasthan of the Indian peninsula, the occurrence of trace fossils combined with detrital zircons data confirm the presence of Cambrian rocks in the upper Bilara Group (Prasad et al., 2010; Kumar and Pandey, 2010; Xu et al., 2022; Figure 2, Profile 8).

2.3 West Kunlun

The Cambrian rocks in the West Kunlun orogenic belt are distributed on the Tianshuihai Block, south of the Kangxiwa suture zone (Figure 2, Profile 9). In this area, the strata yielding Cambrian fossils are known as the Heiheizi Group, which comprises a set of thick carbonate rocks and outcrops along the southern bank of the Akta River. The occurrence of the trilobite *Pagodia*? *kunlunensis* (Zhang, 1981) suggests that the age of the Heiheizi Group at least ranges up to the late Cambrian time. In the Tianshuihai area, Wen et al. (2000) proposed that the siliciclastic rocks of the uppermost Tianshuihai Group, which was previously thought to be the late Mesoproterozoic, may also belong to the Cambrian. Later, Li et al. (2013) named a set of siliciclastic rocks, which unconformably underlies the Ordovician strata and has a lighter metamorphism than the underlying Neoproterozoic strata, as the Tianshuihu Formation, and considered it to be the Cambrian as well but without precise age constrain. In addition, early Cambrian magmatic activities have been reported from various localities on the Tianshuihai block, suggesting a possible connection with the Gondwana (Zhu et al., 2016; Gu and Wu, 2017).

2.4 Songpan-Ganzi-Sanjiang Belt

In the eastern part of the Qinghai-Tibetan Plateau, the Cambrian strata are preserved in the vicinity of Batang and Yanyuan in Sichuan Province, and Zhongdian and Ninglang in Yunnan Province (Figure 2, Profiles 11, 12). The area is located to the east of the Jinshajiang Fault Zone and was part of the western margin of the Yangtze Block during the Cambrian (Wu et al., 2020). The Cambrian strata near Batang are relatively thick, and include the Xiaobachong Group, Eding and Songdagou formations, in ascending order (Sichuan Stratigraphic Chart Compilation Group, 1978; Li et al., 1982). The Xiaobachong Group and Songdagou Formation consist of metaclastic rocks, while the Eding Formation is a carbonate-dominant sequence. The Eding and Songdagou formations contain late Cambrian brachiopod and trilobite fossils (Li et al., 1982; Zhu, 1982), but there is a lack of chronostratigraphic constraints on the underlying Xiaobachong Group. While the Cambrian in the Zhongdian area is mainly composed of the dolostone-dominated strata. The lower siliciclastic part is named as the Yinchanggou Formation, and the upper part is called the Sanjiacun Group (Leng, 1983). The lowermost Yinchanggou Formation contains a trilobite assemblage with a stratigraphic range from the Cambrian Stage 4 to Wuliuan Stage (Leng, 1983; Hughes et al., 2002). The Cambrian around the Ninglang area is a succession of siliciclastic rocks that currently lacks formal subdivision (Li et al., 1982). However, the trilobite assemblages within this succession can be correlated with that in the Wulongqing Formation of eastern Yunnan Province in the southwestern Yangtze shelf.

2.5 Qilian Mountains

The Qilian Mountains can be divided into the Central Qilian Block, the northern and southern Qilian tectonic belts. During the Cambrian, this area experienced strong volcanic activities. The Cambrian in the area is mainly composed of complex lithologic assemblages of basic volcanics, siliceous and siliciclastic rocks together with fossil-bearing limestones. These rocks are mainly distributed in the North Qilian tectonic belt, with sporadic occurrences in the other two areas (Figure 3, Profiles 17–24).

2.5.1 *Northern Qilian tectonic belt*

The Northern Qilian tectonic belt was a part of the Proto-Tethys Ocean and was strongly influenced by regional orogenic activities (Song et al., 2019). The Cambrian strata in this area consist dominantly of marine volcanic rocks interbedded with mixed siliceous, siliciclastic, and carbonate rocks. The marine volcanic strata are extensively distributed from west to east in this tectonic belt, including Chuancigou and Tianbaohe in Qilian County, Suyougou and Dayimalong in Minle County, Daliang in Menyuan County and Heicigou in Tianzhu County (Zhu, 1960a; Qilian Mountain Geological Team, Chinese Academy of Sciences, 1963; Gansu Stratigraphic Chart Compilation Group, 1980; Qinghai Stratigraphic Chart Compilation Group, 1980; Yu, 1994; Zhou et al., 1996; Lin et al., 1995). However, in the western part of this tectonic belt, specifically Yumen and Jingtieshan areas, the Cambrian rocks are mainly characterized by sedimentary rocks. The chronostratigraphic constraints on these predominantly marine volcanic rock sequences mainly come from the trilobite-bearing limestone interbeds. The trilobites in these sequences have been roughly divided into two stratigraphic assemblages: the lower assemblage is from the late Drumian to the Guzhangian in age, and reported trilobite specimens were mainly collected from Heicigou of Tianzhu County (Zhu, 1960a; Zhou et al., 1996), Tianbaohe of Qilian County and Dayimalong of Minle County (Zhu et al., 1979); the upper assemblage is of the Paibian in age, and trilobite fossils were mainly recovered from Daliang in Menyuan County (Zhou et al., 1996; Zhu et al., 2021) and Suyougou in

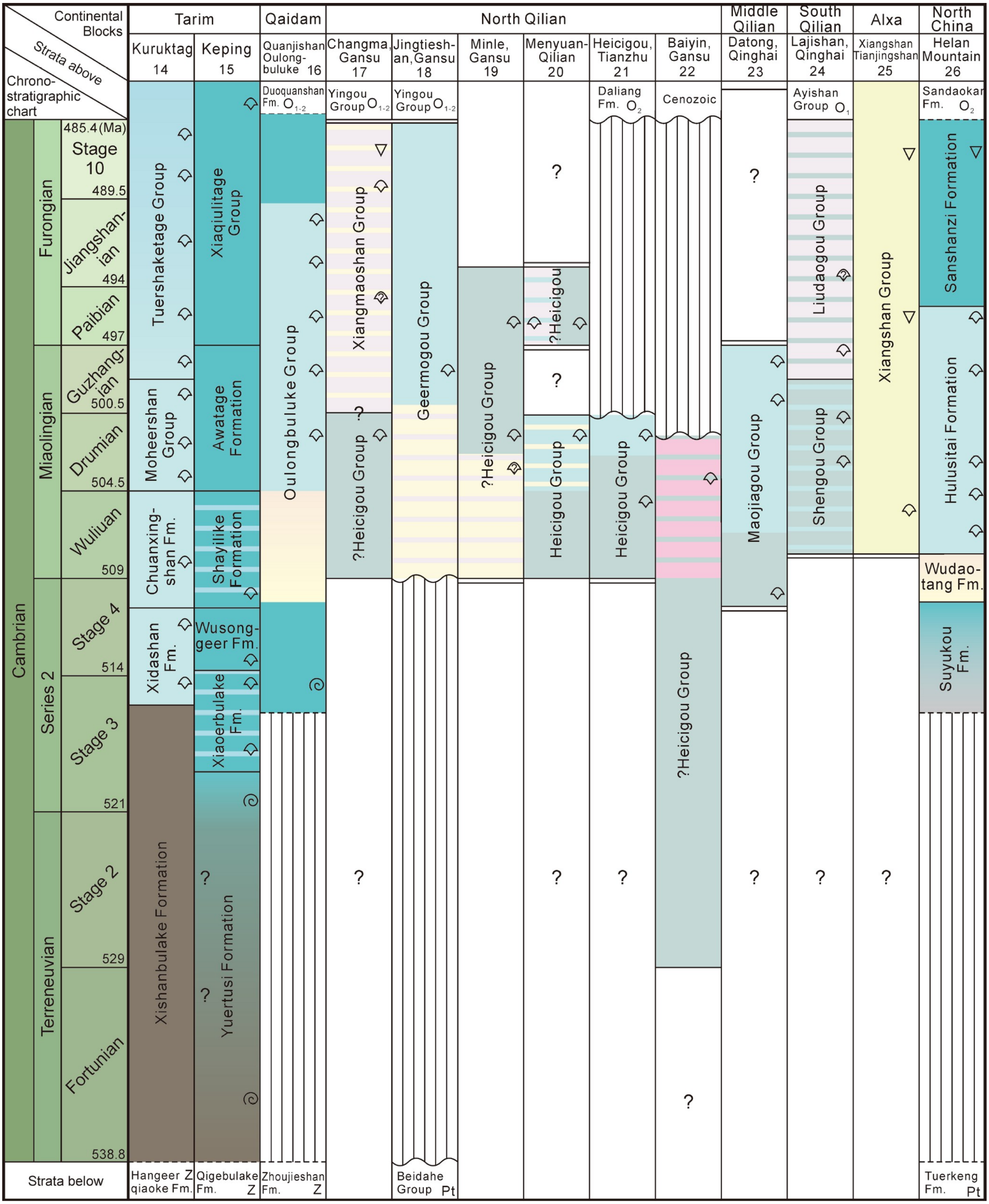

Figure 3 The correlation chart of Cambrian strata in the Qinghai-Tibetan Plateau and its surrounding areas with legends shown in Figure 4.

Minle County (Zhu et al., 1979; Qinghai Stratigraphic Chart Compilation Group, 1980). Notably, the Suyougou trilobite assemblage is unique, and exhibits characteristics of the trilobite association in the slope-basinal facies (Zhou et al., 1996). In addition, Zhou et al. (1996) also reported the Wuliuan trilobite assemblage around Heicigou, which represents the oldest Cambrian fossils in this area. Li and Zhou (1974) published a list of Cambrian trilobites collected in the vicinity of the Baiyin area, which potentially belongs to the late Wuliuan. However, additional work is required to support above inference. On the other hand, Lin et al. (1995) found gravels with the late Cambrian trilobites in the Ordovician conglomerate at Qiqing in Sunan County. Similarly, Wang et al. (2007) also reported late Cambrian trilobites and conodonts from the limestone mass within the diamictites in Changma area. These findings further suggest the presence of Cambrian sedimentary rocks younger than the Paibian Stage in the North Qilian tectonic belt.

Generally, this suite of marine volcanic rocks in the area was called the 'Hecigou Group (Formation)', but the definition is apparently inaccurate. In the type section at Hecigou, Tianzhu County, the 'Heicigou Group' consists mainly of both felsic and mafic marine volcanic rocks and pyroclastic rocks (Xiang et al., 1981; Zhou et al., 1996). In contrast, near Chuancigou, Qilian County, the 'Heicigou Group' not only contains volcanic rocks but also a thick succession (500 m-thick) of metamorphic rocks (quartz schist and marble) (Qinghai Provincial Regional Stratigraphic Compilation Group, 1980; Qinghai Bureau of Geology and Mineral Resources, 1997). Whereas, at the upstream reach of the Dayekou river, Minle County, there is a set of complex sequences of metamorphic siliciclastic rocks more than 700 meters thick, containing trilobites from the late Drumian to the Guzhangian (Zhu et al., 1979; Zhou et al., 1996). Taken together, these findings indicate that Cambrian strata in these areas differ significantly from the stratotype section of the 'Heicigou Group', hence necessitating the establishment of new lithostratigraphic units and emendation of the Heicigou Group in future studies.

In the vicinity of Changma at the western North Qilian tectonic belt (Figure 3, Section 17), a set of Cambrian low-metamorphic siliciclastic rocks was named as the Xiangmaoshan Group by the Stratigraphic Chart Compilation Group of Gansu Province (1980), which overlies volcanic rocks of the 'Heicigou Group'. According to the Gansu Stratigraphic Chart Compilation Group (1980) and the Qilian Mountain Geological Team, Chinese Academy of Sciences (1963), the Xiangmaoshan Group in this area is considered to be part of the late Cambrian based on the occurrence of trilobites. However, due to the scarcity of any formal descriptions and illustrations of these trilobite specimens, it is currently difficult to constrain the exact age of this unit. Additionally, Wang et al. (2007) pointed out that the so-called Xiangmaoshan Group around Changma is actually a part of mélange sequence and the fossils attributed to this unit were recovered from the limestone olistostromes. Thus the tectonic history of this unit warrants re-examination.

In Geermogou, north of the Jingtieshan iron ore mine, there is a set of Cambrian strata called the Geermogou Group, which is mainly composed of siliciclastic rocks in the lower part, limestone in the upper part, and unconformably overlies the Precambrian metamorphic rocks (Gansu Stratigraphic Chart Compilation Group, 1980; Xiang et al., 1981) (Figure 3, Section 18). Trilobite fossils from the limestone interval indicate that the strata are roughly correlated with the Guzhangian (Zhou et al., 1982; Lin et al., 1995). It is worth noting that there is a Cambrian ophiolite belt containing Cambrian trilobite fossils at Qiqing, Sunan County and at Yushigou, Qilian County, not far from Geermogou (Xiao et al., 1978; Song et al., 2019). As the only confirmed Cambrian strata covering the metamorphic basement in the entire Qilian Mountains, are the Geermogou Group directly correlated with the set of trilobite-bearing ophiolites, or are they in an up-down relationship? This issue is very important for understanding the stratigraphic sequence and tectonic evolution in the whole area, and deserves further exploration.

2.5.2 *Central Qilian Block*

Tectonically, the Central Qilian Block is a sandwiched block between the Northern Qilian and Southern Qilian tectonic belts. The Cambrian strata in this area are named as the Maojiagou Group, which outcrops in Datong and Huzhu counties of Qinghai Province. Here, the lower part of this unit is mainly composed of mafic volcanic rocks, while the upper part was dominated by trilobite-rich carbonate rocks (Lu, 1964; Qilian Mountain Geological Team, Chinese Academy of Sciences, 1963; Qinghai Stratigraphic Chart Compilation Group, 1980; Xiang et al., 1981) (Figure 3, Profile 23). Except for the trilobite *Chittidilla* (*Diandongaspis*) sp. typical of the Cambrian Series 2 from the lower interbedded limestone (Qinghai Bureau of Geology and Mineral Resources, 1997), other trilobite taxa found in the Maojiagou Group predominantly indicate an age from the late Drumian to the late Guzhangian. These trilobite assemblages include abundant agnostids (Zhu, 1960b, 1965; Zhou et al., 1996), representing a fauna associated with deeper water settings (Zhou et al., 1996). Both the overlying and underlying strata of the Maojiagou Group are characterized by thick-bedded dolostone. Previously, these dolomitic strata were both considered to have a conformable contact with the Maojiagou Group, but later investigations indicate being in fault contact (Wang and Chen, 1981; Zhou et al., 1996), making it impossible to define the stratigraphic boundaries of the Maojiagou Group.

2.5.3 *Southern Qilian tectonic belt*

The Cambrian rocks in the Southern Qilian tectonic belt are well-known in the Laji Mountain area, and composed of mixed suites of basic-volcanic, siliciclastic and carbonate rocks (Figure 3, Profile 24). Here the Cambrian strata have been divided into the Nidanshan Group in the lower part and the Liudaogou Group in the upper part (Qinghai Stratigraphic Chart Compilation Group, 1980; Zhou et al., 1996; Lin et al., 1995; Xiang et al., 1999). The limestone beds in the Nidanshan and Liudaogou groups contain rich trilobite assemblages of the middle and late Cambrian, which are similar in appearance to those from the slope facies of South China (Zhu et al., 1979; Zhou et al., 1996; Lin et al., 2013, 2015). Recent studies suggest that the Lower Paleozoic strata in Laji Mountain represent a set of complex ophiolitic melange (Fu et al., 2021). If the Cambrian strata in Laji Mountain are indeed mixed deposits from different sources, its established stratigraphic framework needs to be reevaluated.

2.6 Qaidam Block

The Cambrian strata named as the Olongbuluke Group (Formation) of the Qaidam Block are distributed in Olongbuluke, Quanjishan, Shihuigou and its environs (Zhu, 1960c; Qinghai Stratigraphic Chart Compilation Group, 1980; Qinghai Bureau of Geology and Mineral Resources, 1997). These strata are characterized by sedimentary sequences deposited in the stable carbonate platform facies, and they markedly differ from those in the Qilian Mountains (Zhu, 1960c; Mu et al., 1963; Qilian Mountain Geological Team, Chinese Academy of Sciences, 1963; Qinghai Stratigraphic Chart Compilation Group, 1980) (Figure 3, Profile 16). Similarity of the Cambrian sequence between the Qaidam Block and the North China Craton is quite obvious. First, the base of the Cambrian strata both has an unconformable contact with the underlying Ediacaran strata. Secondly, the basal phosphatic conglomerate beds in the Qilian Mountains bear a close resemblance to the basal Cambrian strata of North China (e.g. Xinji, Houjiashan and Suyukou formations). Above the lower dolostone is a 120 m-thick succession of purplish red shale and sandstone, corresponding to the Mantou Formation in North China. Subsequently, the overlying strata consist of oolitic limestone and bear Drumian-Jiangshanian trilobite fossils (Zhu, 1960a; Zhu et al., 1979; Lai et al., 1984), which are also similar with those from the Hulusitai Formation in the Helan Mountain area of North China. Similarly, the uppermost Cambrian rocks consist of unfossiliferous dolostone in thickness of tens of meters, and can be correlated with the Sanshanzi Formation of North China. Not only does the Cambrian exhibit similarities with North China, but also the Ediacaran of the Qaidam Block demonstrates comparable characteristics (Pang et al., 2021). These lithostratigraphic resemblances further support the paleogeographical connection of Qaidam and its surrounding areas with the North China Craton. However, a more comprehensive investigation and detailed subdivision are necessary for the Olongbuluke Group (Formation).

2.7 Alxa Block

The reliable Cambrian rocks in the Alxa Block are only recognized at Xiangshan and Tianjingshan in Zhongwei City, Ningxia, and are characterized by the flysch deposits, which were collectively referred to the Xiangshan Group (Figure 2, Profile 25). The unit is further subdivided into four unnamed subgroups by the Ningxia Bureau of Geology and Mineral Resources (1990). Although the strata containing mid-Cambrian trilobites within the unit are considered as the exotic rocks, the Xiangshan Group may still contain Cambrian deposits younger than the Wuliuan based on the recent discovery of conodont fossils (Ningxia Bureau of Geology and Mineral Resources, 1990; Li, 1997; Zhou and Xiao, 2010).

The Dahuangshan Group in the areas of Shandan, Yongchang and Wuwei of Gansu Province may belong to the Cambrian (Gansu Stratigraphic Chart Compilation Group, 1980; Gansu Bureau of Geology and Mineral Resources, 1997). Similar to the Xiangshan Group, the Dahuangshan Group is also composed of the deep-marine turbidities deposits, but their age remains ambiguous (Zhou and Xiao, 2010).

2.8 Sibumasu Block

The Sibumasu block is located in the southeast of the Qinghai-Tibetan Plateau, and is closely related to the South Qiangtang Block. The Changning-Menglian Fault to the west of the Sibumasu block shares similar characteristics with the Longmucuo-Shuanghu Fault (Metcalfe, 2013; Wu et al., 2020). In this tectonic unit, the Cambrian strata occur in Baoshan area of Yunnan Province, Shan Plateau of Myanmar, western Thailand and the southern Malay Peninsula (Figure 4, Profiles 27–29). The Cambrian sequence in Baoshan area is complete and composed of a set of mildly metamorphosed siliciclastic rocks with abundant fossils. The lowermost Gongyanghe Group in the area is a set of thickly flyschs, containing only sponges and microfossils, and its age cannot be determined accurately. This unit is succeeded ascendingly by the Hetaoping, Liushui and Baoshan formations, all of which consist mainly of siliciclastic rocks interbedded with carbonates. These three units can be correlated with the strata of the Guzhangian to the uppermost Cambrian based on reported trilobite fossils (Luo, 1985a, 1985b; Yunnan Bureau of Geology and Mineral Resources, 1990).

Recently, Aung and Cocks (2017) and Wernette et al. (2021) systematically summarized the Cambrian stratigraphy and trilobite fossil assemblages in the Shan Plateau, Myanmar. In comparison with Baoshan area, the Cambrian sequence in the Shan Plateau consists of the coarse siliciclastics, and the fossils in the sequence all belong to the

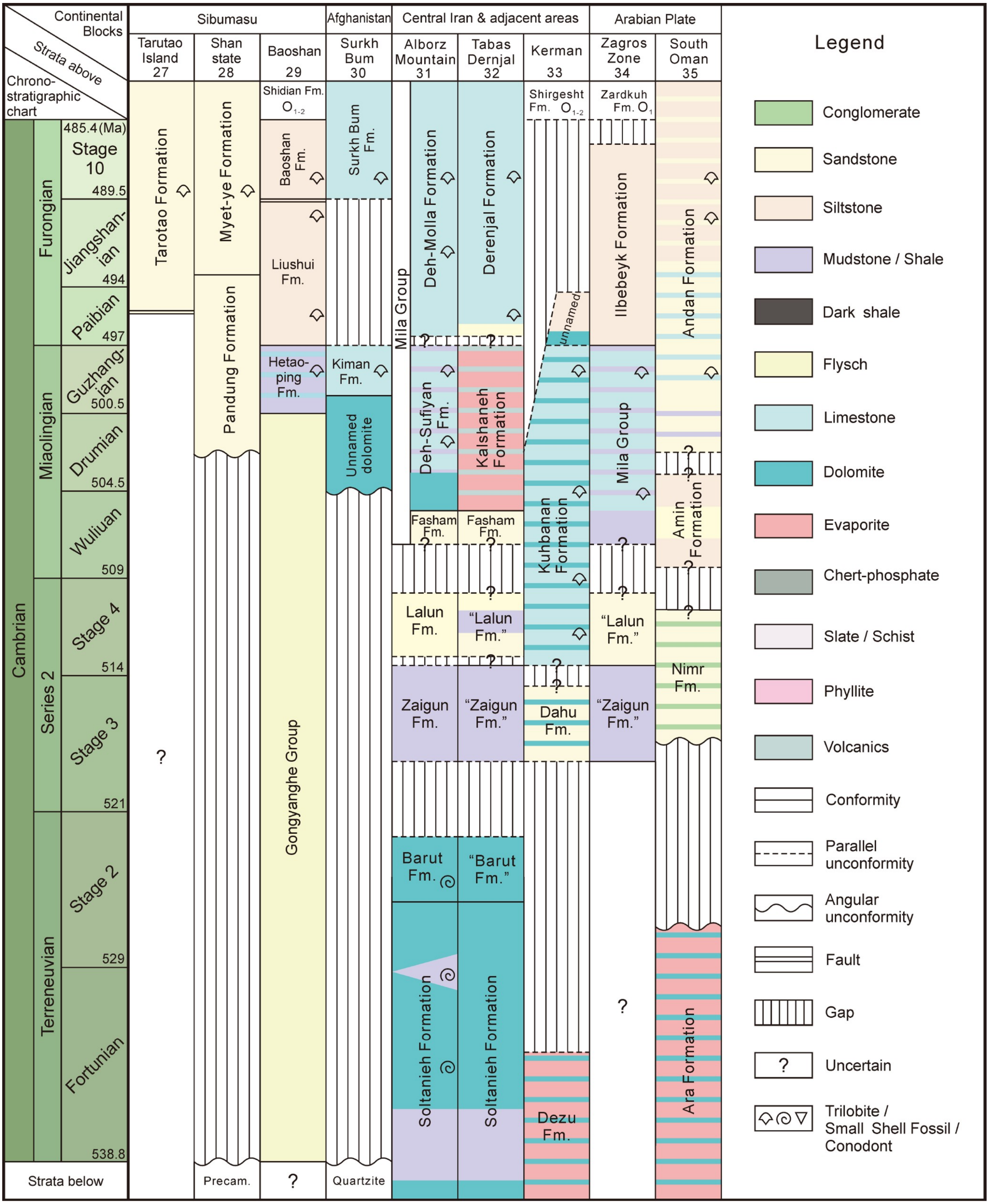

Figure 4 The correlation chart of Cambrian strata in the Qinghai-Tibetan Plateau and its surrounding areas.

upper Furongian.

In western Thailand, the Cambrian strata are known as the Chao Nen Formation, which is dominated by quartz sandstone and shale. The middle Chao Nen Formation contains late Cambrian trilobites, while the upper Chao Nen Formation has more limestone interbeds and was considered to belong to the Ordovician (Bunopas, 1981,, 1983 , 1992).

The Tarutao Island in Thailand and the adjacent Langkawi Island in Malaysia represent the southernmost distribution of the Cambrian strata in the Sibumasu (Wernette et al., 2020a, 2020b, 2023). The trilobites in the area had attracted the attention of relevant scholars earlier (Kobayashi, 1957; Shergold et al., 1988). Similar to western Myanmar and Thailand, the Tarutao Group on Tarutao Island consists mainly of siliciclastic rocks, representing late Furongian to lowermost Ordovician deposits (Teraoka et al., 1982; Bunopas et al., 1983; Wongwanich et al., 2002; Wernette et al., 2023). Similarly, the Machinchang Group on Langkawi Island is also suggested to be late Cambrian in age (Lee, 1983).

In general, the Cambrian sequences from the different areas in the Sibumasu Block are relatively similar. Except for the flysch formation of the Gongyanghe Group in Baoshan area, which may be earlier than the Guzhangian, the Cambrian sequences in other areas mainly belong to the Furongian, and all of them contain similar trilobite assemblages. It is important to note that extensive evidence has shown that the Sibumasu Block was part of Gondwana during the Cambrian (Metcalfe, 2013; Burrett et al., 2016; Morley, 2018; Wernette et al., 2021). However, unlike the core regions of the Qinghai-Tibetan Plateau, the Cambrian sequences in the Sibumasu Block do not exhibit a distinct unconformity with overlying Ordovician strata.

2.9 Afghanistan

The relatively well-studied area for the Cambrian in Afghanistan is the Surkh Bum in the Herat tectonic belt (Figure 4, Profile 30). The lower part of the Cambrian strata in this area is an unnamed dolostone succession without fossils, and the upper part, known as the Kirman Formation, consists of fossil-rich limestone. The trilobite assemblage of the Kirman Formation indicates it can be correlated with the Guzhangian (Wolfart, 1974a; Wolfart and Wittekindt, 1980). The Surkh Bum Formation overlies the Kirman Formation with paraconformity. The biostratigraphy data of trilobite and brachiopod fossils indicates that the lowermost part of the Surkh Bum Formation possibly belongs to the uppermost Cambrian (Wolfart, 1970). The Cambrian trilobite assemblages in the area include some endemic types, and there are also some species exhibiting close affinities with that from eastern Gondwana (Wolfart, 1974a).

2.10 Iran

The Cambrian strata in Iran mainly occur in three major tectonic units, namely the Alborz Mountains, Central Iran Block and Zagros Mountains Zone, and are characterized by the typical shallow-water platform sediments (Figure 4, Profiles 31–34).

The Cambrian rocks of the northern Alborz Mountains have been extensively studied (Stöcklin et al., 1964; Kushan, 1973; Hamdi, 1989; Peng et al., 1999). In the western Alborz Mountains, several mixed siliciclastic-carbonate intervals of the Soltanieh Formation contain relatively rich Terreneuvian small shelly fossils and trace fossils, so this area is well known for its extensive research on the Terreneuvian chronostratigraphy (e.g. Hamdi et al., 1989; Kimura et al., 1997; Devaere et al., 2021; Etemad-Saeed et al., 2021). The carbonate rocks of the Terreneuvian Slotanieh Formation are overlain by a thick succession (> 1000 m-thick) of shale and coarse siliciclastic rocks, which is subdivided into several lithostratigraphic units, including the Barut, Zaigun and Lalun formations in ascending order. No other body fossils have been found in these units except for small shelly fossils in the lowest Barut Formation (Devaere et al., 2021). The presence of trace fossils, such as *Cruziana*, together with the over all characteristics of sedimentary sequences, suggests that these units may belong to the deposits during the Terreneuvian-Cambrian Epoch 2 (Geyer et al., 2014; Bayet-Goll and Daraei, 2020, 2021). The siliciclastic sequence is unconformably overlain by the middle Cambrian, carbonate-dominant (limestone) rocks of the Mila Formation (Geyer et al., 2014; Bayet-Goll et al., 2021). The Mila Formation was recently upgraded to a group-level unit, i.e. the Mila Group, which was further subdivided ascendingly into the Fasham, Deh-Sufiyan, and Deh-Molla formations (Geyer et al., 2014). Trilobite fossils are abundant through the Mila Group except at the base. The trilobite assemblages from the Mila Group are broadly comparable with those from the Wuliuan to the Cambrian-Ordovician boundary interval in other parts of the world (Kushan, 1973; Wittke, 1984; Peng et al., 1999).

The Cambrian rocks of the Central Iran Block occur in the Tabas and Kerman areas (Ruttner et al., 1968; Wolfart, 1974b, 1983). The Cambrian strata of Dernjal Mountain near Tabas are roughly similar to those of Alborz Mountain. However, a notable distinction is the presence of the Kalshaneh Formation in this area, which corresponds to the lower part of the Mila Group. The Kalshaneh Formation is nearly a kilometer-thick sequence consisting of dolostone, limestone, shale and basic volcanic rock (Ruttner et al., 1968). Paleontological research in this area is relatively limited, and late Cambrian trilobites are recovered only from few horizons in the limestone of the Derenjal Formation, which is equivalent to the upper middle part of the Mila Group (Ruttner et al., 1968). In the Kerman area, the lower part of the Cambrian strata comprises two distinct formations, namely the Desu (Dezu) Formation, being predominantly of evaporite and dolostone, and the Dahu Formation, being characterized by the presence of sandstone and shale. Although no fossils have been found in these successions, lithostratigraphic comparison indicates that the Dahu Formation can be tentatively correlated with Series 2 of the neighboring area (Wolfart, 1974b). The Dahu Formation is overlain by the Kuhbanan Formation, which is characterized by limestone, dolostone and siliciclastic sequence (Wolfart, 1983). Trilobite fossils indicate that the Kuhbanan Formation may be correlated with the Stage 4—Guzhangian Stage (Wolfart, 1974b; Ameri, 2015). Above the Kuhbanan Formation, it is a succession of dolostones and quartz sandstones with the age remaining undetermined (Wolfart, 1974b; Ameri, 2015).

The Cambrian succession of the Zagros Mountain Zone is similar to that of the Kerman area (Central Iran Block) in both lithological and faunal aspects (King, 1930, 1937). Although the early and middle Cambrian strata here were traditionally assigned names corresponding to lithostratigraphic units of the Alborz Mountains, as the Zaigun, Lalun formations and the Mila Group in ascending order (Setudehnia, 1975), this lithostratigraphic framework requires further elaboration in the future (Geyer et al., 2014). The limestone of the Mila Group in the area yields trilobites corresponding to Stage 4 to the Guzhangian. Above the Mila Group, it is a siliciclastic succession of several hundred meters thick named as the Ilebayk Formation, which age is considered to be the Furongian based on its acritarch fossils (Ghavidel-syooki and Vecoli, 2008).

2.11 Oman

The Cambrian strata in southern Oman are characterized by Sabha-type deposits in the lower part and coastal siliciclastic deposits in the upper part with scarce fossils (Figure 4, Profile 35; Gorin et al., 1982; Hughes Clarke, 1988; Millson et al., 1996). The Ara Formation/Group, being the top lithostratigraphic unit of the Huqf Group/Supergroup, is characterized by the multiple parasequences of dolostones and evaporates. Paleontological, chemostratigraphical and geochronological data indicate that the Precambrian-Cambrian boundary lies within this succession (Amthor et al., 2003; Bowring et al., 2007). Unconformably overlying the Ara Formation/Group is a thick (>1000 m-thick) siliciclastic-dominant sequence of the Haima Group, which, in ascending order, includes the Nimr, Amin and Andan formations. In the Huqf area, the Andam Formation contains abundant trilobites and trace fossils, which indicate that the Andam Formation can be correlated with the Guzhangian to the uppermost Cambrian (Fortey, 1994; Millson et al., 1996). In the northern Oman mountains, the carbonates of the Ediacaran Buah Formation are overlain by mixed siliciclastic-volcaniclastic rocks of the Fara Formation (Tschopp, 1967). The chronostratigraphic data suggests that the Fara Formation may be of the lowmost Cambrian (Brasier et al., 2000; Bowring et al., 2007). However, it should be noted that the Fara Formation is unconformably overlain by Permian strata, and most of the Cambrian strata are absent in northern Oman.

3. The Cambrian biotas and biostratigraphy in the Qinghai-Tibetan Plateau and its surrounding areas

The research areas have experienced distinct tectonic and paleogeographical evolution that differs from those documented in South China, North China, and Tarim, which are renowned for diverse Cambrian fossil assemblages. During the Cambrian, most stable tectonic blocks in the areas represented shallow water platforms at the margin or on the periphery of Gondwana, and usually lacked complete Cambrian successions. The Cambrian fossil biotas in these areas are limited with few globally distributed index fossils. Therefore, the biostratigraphic and chronostratigraphic framework of the Cambrian strata of the Qinghai-Tibetan Plateau and its surrounding areas remain at very low resolution.

At present, most Cambrian fossil biotas are reported from the Himalayan areas, such as Bhutan, northwestern India and northern Pakistan, and include the representative fossils from the lower Terreneuvian to the Guzhangian (Jell and Hughes, 1997; Peng et al., 2009; Hughes, 2016; Singh and Bhargava, 2020; Figure 5). Some trilobite biozones in the areas can be directly correlated with those of South China or even with the global biostratigraphic framework, such as *Paokannia magna*, *Drepanopyge gopeni*, *Redlichia noetlingi*, *Oryctocephalus indicus*, *Lejopyge acantha*, and *Proagnostus bulbus* zones in ascending order (Peng et al., 2009; Hughes, 2016). Recently, we discovered abundant small shelly fossils in the Western Himalaya of northern Pakistan. Although detailed work on these small shelly fossils are in progress, the small shelly fossil assemblages exhibit similar evolutionary successions of the basal Cambrian small shelly fossils in South China, providing reliable biostratigraphic evidence for redefining the Neoproterozoic-Cambrian boundary as well as subdivision and global correlation of the Terreneuvian strata in Western Himalaya (Pan et al., 2023; Ahmed et al., 2023). In addition, there is a combination of *Bailiella lantenoisi* and *Tonkinella breviceps* in the Cambrian strata of Kashmir (Jell and Hughes, 1997), which is very similar to that of the uppermost Wuliuan in North China, providing an important tool for biostratigraphic correlation between two areas. It should be noted that another trilobite from the upper Wuliuan in Kashmir has been classified as the *Iranolesia butes* (=*Proasaphiscus butes*), which usually occurs in North China. However, it remains ambiguous whether the specimens from the Himalaya can be identified as *Iranoleesia butes* from North China (Yuan et al., 2012).

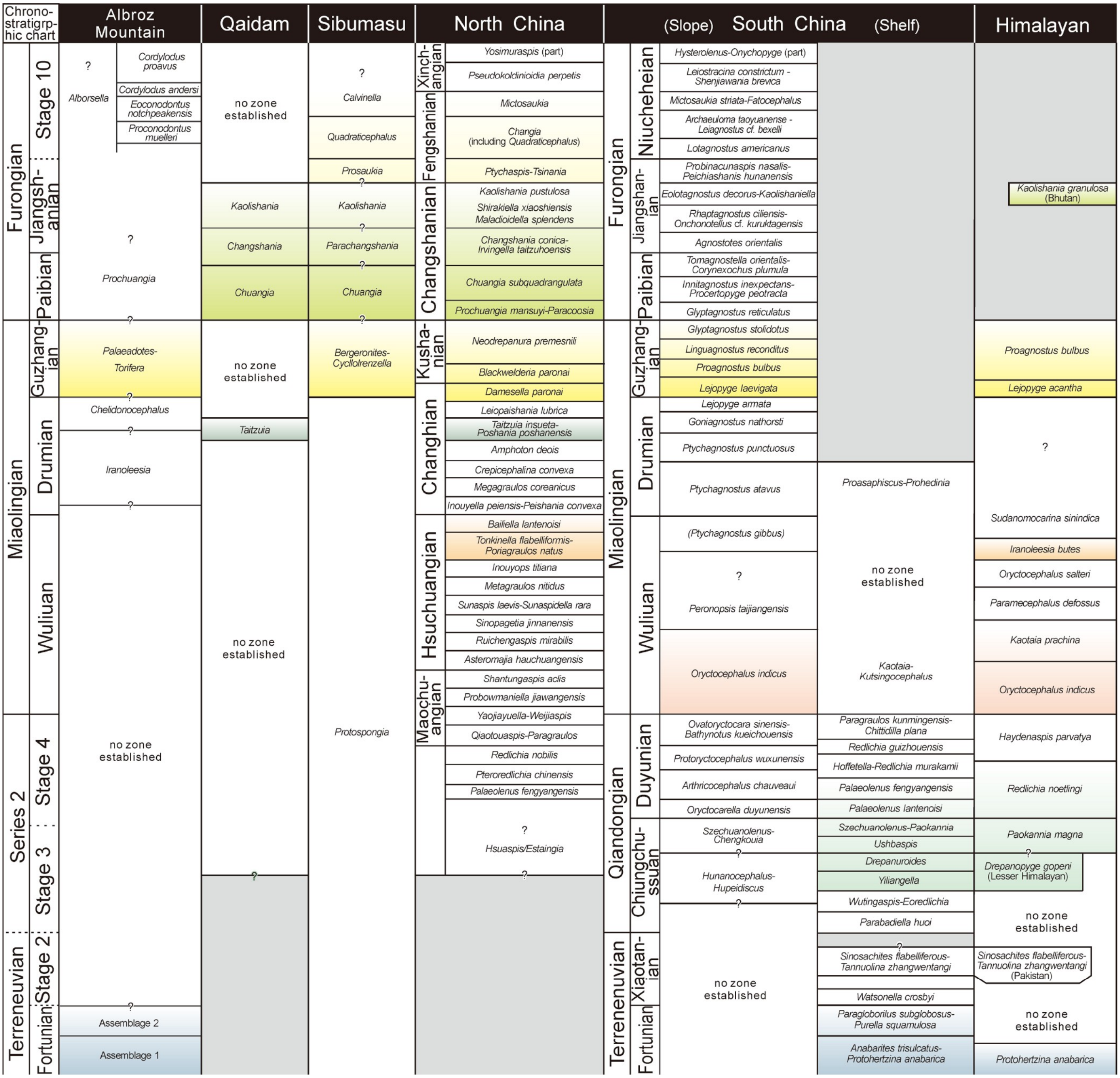

Figure 5 Correlation chart for the Cambrian biostratigraphic unites of major areas in the Qinghai-Tibetan Plateau and its surrounding areas, modified from Luo (1985b), Peng et al. (1999, 2020), Hughes (2016), and Geyer (2019).

Consequently, the biostratigraphic significance of this trilobite for regional correlation remains uncertain.

The Alborz Mountains in northern Iran has been a classic area for Cambrian research, and here the Cambrian biostratigraphic framework is established based on biozones of small shelly fossils, trilobites, and conodonts (Kushan, 1973; Müller, 1973; Wittke, 1984; Peng et al., 1999; Jahangir et al., 2016; Devaere et al., 2021). Among them, the basal Cambrian assemblage biozones of small shelly fossils and the upper Cambrian conodont biozones can be well correlated with the global chronostratigraphic framework (Jahangir et al., 2016; Devaere et al., 2021), but the rest of Cambrian strata cannot be precisely correlated with the global framework since the majority of the trilobites in the Alborz Mountains are endemic taxa. Except for the *Palaeadotes-Torifera* Zone, which can be correlated with the Guzhangian, other trilobite zones can not be directly correlated with the global chronostratigraphic framework. Although the *Prochuangia* Zone was established in the Alborz Mountains, unlike *Prochuangia* Zone from the basal Paibian in North China, *Prochuangia* in the Alborz Mountains co-occurs with *Palaeadotes* of the Guzhangian and *Kaolishania* of the

Jiangshanian (Kushan, 1973). Therefore, additional work is required to confirm whether the two eponymous biozones in Iran and North China are biostratigraphically correlatable or not.

The Cambrian biostratigraphic framework has also been established in the Baoshan of western Yunnan, including 7 trilobite biozones from the Guzhangian to the Cambrian Stage 10 (Luo, 1985a, 1985b; Yunnan Bureau of Geology and Mineral Resources, 1990). Although most of these fossil zones are eponymous with those of North China, their seemingly straightforward correlations need to be cautious since their index fossils are similar mostly at the genus level rather than at the species level. For example, *Parachangshania* in North China occurs below the *Chuangia* Zone (Qian, 1958; Wang et al., 2020), while in western Yunnan, their occurring sequence is reversed (Luo, 1985a, 1985b). Therefore, the biostratigraphic framework in western Yunnan and its correlation with other areas need to be further studied.

In the Qaidam Block, four Cambrian trilobite biozones have been established based on comprehensive data (Lai et al., 1984). These fossil zones exhibit a similar sequence as that of the eponymous zones in the middle and late Cambrian of North China, suggesting a potential direct correlation between the two areas. However, many of the index fossils are only taxonomically identified to the genera level, and there is a lack of formal systematic descriptions of these fossils. Therefore, establishing a coherent biostratigraphic correlation framework between these two areas awaits support from additional data.

Besides above areas, Cambrian fossils with certain biostratigraphic significance have also been recorded in the Qilian Mountains, the Songpan-Ganzi-Sanjiang Belt, Tianshuihai Block, Shan Plateau of Myanmar, Tarutao Island of Thailand, Afghanistan, Central Iran and Oman (see the Chapter 2). Most of these areas only contain Cambrian fossils from a single stratigraphic horizon, and it does not necessitate establishing a regional biostratigraphic framework. Although abundant trilobite fossils have been recovered from the Cambrian of the Qilian Mountains, due to the tectonic complexity of the Cambrian rocks in the area, the fossil horizons in different sections are difficult to be accurately correlated, and the biostratigraphic framework remains elusive.

In summary, the study of the Cambrian biostratigraphy and chronostratigraphy in the Qinghai-Tibetan Plateau and its surrounding areas is still in its early stage. While relatively basic biostratigraphic and chronostratigraphic frameworks of the Cambrian are established in a few areas, identifying major chronostratigraphic boundaries of the Cambrian remains challenging in most blocks of the realm. Therefore, more detailed biostratigraphic work needs to be enhanced for refining our understanding of the Cambrian chronostratigraphy in the area.

4. Cambrian paleobiogeography of the Qinghai-Tibetan Plateau and its surrounding areas

During the Cambrian Period, the Qinghai-Tibetan Plateau and its surrounding blocks belonged to the same paleobiogeographical realm, i.e. the Oriental Province or the Weste Pacific Province (Lu et al., 1974; Zhang, 1989), and generally there was no significant difference in the appearance of their biological assemblages. Among them, Central Iran, Afghanistan, Lhasa, Qiangtang, Sibumasu and other blocks, together with India and Arabia, are all part of the Gondwana (Torsvik and Cocks, 2017; Wu et al., 2020) (Figure 6). The Cambrian biological assemblages found in these areas are remarkably similar to those of the shallow-water platform biotas in South China, North China, Australia and even Antarctica (Zhang, 2003; Álvaro et al., 2013). A bit paleogeographically different from the above areas, the Qilian-Qaidam region in the northeastern Qinghai-Tibetan Plateau was geographically isolated from Gondwana by the Proto-Tethys Ocean during the Cambrian. Although the Qaidam region still exhibits the shallow-water biota that is similar with that of North China, the deep-water biota similar to that in the slope zone of South China occurs in the Qilian Mountains (Zhou et al., 1996; Lin et al., 1995).

4.1 Continental margin of the Gondwana

There are only a few early Cambrian fossil records in the marginal area of the Gondwana, e.g. trilobite fossils being recovered in Kerman of Central Iran Block (Wolfart, 1974b; Ameri, 2015; Ameri and Zamani, 2016), the Salt Range of Pakistan, and the Himalaya of northwest India (Jell and Hughes, 1997; Hughes et al., 2005; Hughes, 2016; Peng et al., 2009). Trilobite assemblages in these areas show remarkable similarities with coeval trilobites from the Yangtze shelf. For example, the Himalayan genera *Chittidilla*, *Drepanopyge*, *Malungia*, *Protolenella*, *Kaotaia*, *Kunmingaspis*, *Yuehsienszeella* and Kerman's *Kermanella* only occur in the above-mentioned areas and the Yangtze shelf. Moreover, *Xela* and *Gunnia* from the Himalaya also exhibit typical characteristics of Australia.

In addition to trilobites, early Cambrian small shelly fossils have been recovered in northern India, Kashmir, the Lesser Himalaya of northern Pakistan, and the Alborz and Soltanieh Mountains of northern Iran (Fuchs and Mostler, 1972; Mostler, 1980; Bhatt et al., 1985; Brasier and Singh, 1987; Hamdi et al., 1989; Hughes, 2016; Devaere et al., 2021; Pan et al., 2023; Ahmed et al., 2023). Among them, India, northern Pakistan, and Kashmir share more common elements with the small shelly fossil assemblage Zone I of the Yangtze shelf, including such as *Anabarites trisulcatus*, *Protohertzina anabarica*, *Olivooides multisulcatus*, *Barbitositheca ansata*, *Hexangulaconularia formosa*, *Punctatus*

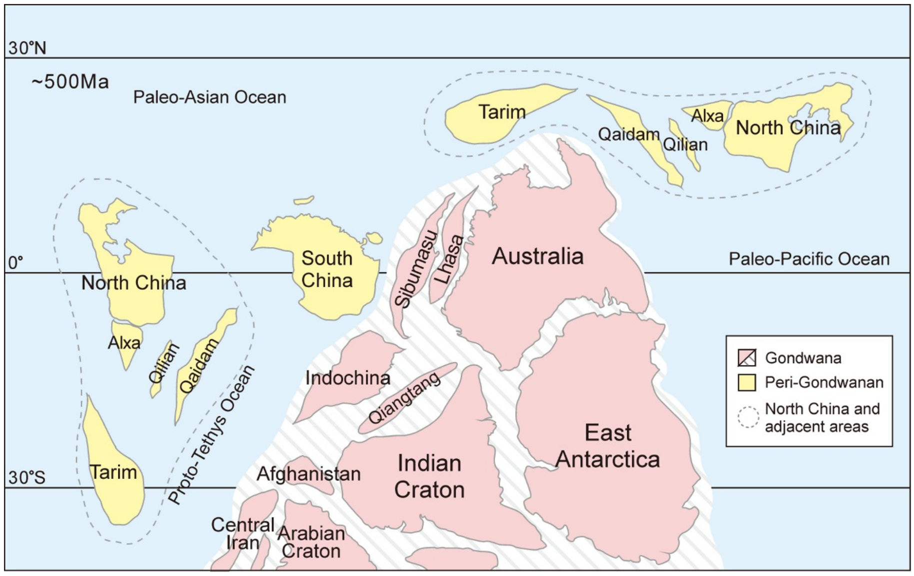

Figure 6 Paleogeographical map of northern Gondwana showing the distribution of tectonic units within the Qinghai-Tibetan Plateau and its surrounding areas during the middle Cambrian (500 Ma), modified from Torsvik and Cocks (2017) and Dong et al. (2021). Note that the possible location of North China and surrounding blocks remains controversial (Mark with dashed lines).

emeiensis, *Maikhanella pristinis* and *Spirellus columnaris* (Ahmed et al., 2023). Northern Iran also shares some elements with the Terreneuvian small shelly fossil assemblages in South China (Zone I and II), e.g., *Protohertzina anabarica*, *Anabarites trisulcatus*, *Maikhanella multa*, *Purella squamulosa*, *Oelandiella korobkovi* and *Aetholicopalla adnata* (Devaere et al., 2021). Recently, Pan et al. (2023) discovered *Tannuolina zhangwentangi*, the index fossil of the small shelly fossil assemblage Zone IV in the Yangtze shelf, from the Hazira Formation in the Abbottabad area, northern Pakistan. It is the first time that this species was recovered outside of the Yangtze shelf. This further supports that there existed distinct faunal similarity between Lesser Himalaya and South China during the Terreneuvian and both had a close biogeographic connection. In general, these small shelly fossil assemblages are similar to those in the contemporaneous strata of the Yangtze shelf in South China.

During the Miaolingian, trilobites were abundant in the Gondwana marginal shelfs, with the highest diversity recorded in the Tethys Himalaya in northwest India. The composition and paleogeographical implication of trilobite assemblages in these areas have been well analyzed, supporting that the Tethys Himalaya is in close proximity to South China and North China, particularly the former (Jell and Hughes, 1997; Peng et al., 2009; Hughes, 2016). In the southwestern Qinghai-Tibetan Plateau, Miaolingian fossils have also been found in Oman, Alborz Mountains of Iran, Kerman, and Bamiyan of Afghanistan. Despite the relatively lower diversity of the Miaolingian trilobites in these areas and some species being endemic, the occurrence of *Paracoosia*, *Torifera* and damesellids in these areas (Wolfart, 1974a; Kushan, 1973; Fortey, 1994; Peng et al., 1999) provides evidence that they shared connection with eastern Gondwana. In addition to the above areas, the mid-Cambrian strata with Gondwanan affinity also occur in Baoshan, Yunnan in the southeastern of the Qinghai-Tibetan Plateau. Most of the trilobites from this area are new genera and species with poor preservation. Nevertheless, the existence of *Palaeadotes*, *Blackwelderia* and *Fenghuangella* suggests its paleogeographical connection with South China (Luo, 1982).

The fossil records of the late Cambrian (Furongian) along the Gondwana margin are significantly fewer mainly due to the widespread influence of the Kurgiakh Orogeny (or other peripheral Gondwana-forming orogenies). Furongian fossils have been occasionally reported in Oman, Alborz Mountains of Iran, Bhutan, Baoshan of Yunnan, Shan Plateau of Myanmar, and southern Thailand. However, except for Baoshan in Yunnan, fossils in these areas generally exhibit low biodiversity. Despite that, some representative trilobite genera from these areas, such as *Prochuangia*, *Kaolishania*, *Pagodia*, *Prosaukia*, *Yokusenia* and *Maladioidella* (Luo, 1985a, 1985b; Shergold et al., 1988; Fortey, 1994; Peng et al., 1999), demonstrate that these areas had a close paleogeographical relationship with North China and South China, as well Australia (Zhang, 2003).

The above mentioned paleobiogeographical recognitions have also got support from other paleogeographical studies in recent years. For example, analyses of the late Neoproterozoic to early Cambrian magmatic activities and detrital zircon data suggest that Iran located in proximity of the Arabian Block along the northwestern margin of the Gondwana during the time interval (Hassanzadeh et al., 2008; Zoleikhaei et al., 2021), while the Lhasa Block was possibly at the northeastern margin of the Gondwana near Australia (Zhu et al., 2011). Furthermore, based on detrital zircon data, Yang et al. (2020) proposed that South China came into contact with the northwest margin of the Indian Craton in the Cambrian. This inference can be further supported by remarkable similarities of the Cambrian paleontological records between the two areas. However, it is important to acknowledge that not all evidence is consistent with the proposed paleobiogeographical reconstructions. For instance, recent studies on detrital zircons suggested that the Tarim Block was located closer to India or Arabia along the Gondwana margin during the Cambrian Period, rather than in direct proximity to South China (Li et al., 2008, 2023; Zhao et al., 2018; Wang et al., 2021, 2022). However, there is a relatively low similarity in trilobite assemblages between Tarim and these areas. Apparently, to solve this contradiction, it needs more paleogeographical data from different research fields.

4.2 Qilian-Qaidam region

Unlike above areas on the Gondwana margin, the Qilian-Qaidam region in the northeastern Qinghai-Tibetan Plateau was geographically separated from the adjacent Gondwana by the Proto-Tethys Ocean during the Cambrian Period. Its distinct biological assemblages are different from those of shelf environments on the Gondwana margin. Since the initial discovery of the Cambrian fossils in this region, researchers have presumed that the Qaidam and North China blocks belonged to the same paleobiogeographical realm during the Cambrian (Lu, 1962), while the Qilian Mountain area had a fossil assemblage similar to the slope-facies assemblage of South China. Subsequent studies on the middle and late Cambrian trilobites from the Qaidam Block provided additional evidence supporting the close affinity of Qaidam with North China. For instance, some trilobite genera unique to North China, e.g., *Taitzuia*, *Keipingella* and *Changshania*, have also been found in the Qaidam Block (Zhu, 1960a; Zhu et al., 1979), but no diagnostic trilobites of South China have been recovered so far from the Qaidam Block.

The Qilian Mountain area has long been considered as a part of the North China Block in terms of paleogeography (see Zhu et al., 2021 and literature therein). However, the increasing researches on Cambrian trilobites from this area (Zhu et al., 1979; Zhou et al., 1996), and particularly, recent systematic studies of trilobite assemblages in Laji Mountain (Lin et al., 2013, 2015) and Daliang in Menyuan County (Zhu et al., 2021) have shown that the trilobite assemblages of this area are closely related to the slope-facies fauna of South China, implying that Qilian Mountain was geographically not in a close proximity to North China during the Cambrian Period. However, in consideration of the strong resemblance between trilobites from the shallow water facies of Qaidam and North China, and the low geographic diversity of the global slope-facies biota in the Qilian Mountains during the mid-late Cambrian (Zhou and Zhen, 2008; Álvaro et al., 2013), the proposed similarity of the slope-facies biotas between the Qilian Mountains and South China cannot alone be taken as the definite evidence for evaluating their paleogeographical relationship.

In addition, recent detrital zircon data suggest that the Qilian Mountain might be relatively close to the Indian Craton at the earliest Cambrian, and subsequently drifted away from Gondwana towards Alxa and North China blocks, and eventually collided with Alxa Block during the early Paleozoic (Song et al., 2013; Yu et al., 2021; Dong et al., 2021). The Qaidam Block may be in close proximity to the Qilian Mountain (Song et al., 2014). However, there are different models in the global paleogeographical reconstructions for the relative position of North China with Gondwana during the Cambrian Period (Hu et al., 2013; McKenzie et al., 2011; He et al., 2017; Wan et al., 2019; Zhao et al., 2021), therefore, it remains challenging to suppose the exact position of the Qilian-Qaidam region and their relations with the Gondwana during Cambrian (Figure 6).

5. Summary and perspective

Over the past century, the understanding of the Cambrian stratigraphic sequence, biotas and palaeogeographical evolution in the Qinghai-Tibetan Plateau and its surrounding areas has achieved considerable advances. Combining with these works, we summarize the general characteristics of the Cambrian sequences in different tectonic units in the areas. However, the regional tectonic complexity has resulted in significant challenges in determining the definition, age, and spatial distribution of many lithostratigraphic units in these areas. Apparently, it requires further detailed investigation to unravel the complexities and to refine our knowledge of the Cambrian stratigraphy in these areas. The Cambrian biostratigraphical frameworks in these areas are mainly established based on the extensive studies conducted in the Himalaya, Iran, western Yunnan and Qaidam. However, most of the Cambrian strata in the Qinghai-Tibetan Plateau, including the aforementioned areas can not be well correlated with the current international chronostratigraphic standard. This is mainly due to the scattered preservation and endemicity of the Cambrian biotas, as well as the limited systematic paleontological and biostratigraphical studies in these areas.

In general, most of the Qinghai-Tibetan Plateau and its surrounding areas were clustered in the northwestern margin of the Gondwana during the Cambrian Period and their paleogeographical relationship is relatively well understood.

However, there are still significant debates regarding the relative positions of the blocks in Qilian Mountains and its surrounding areas within the Proto-Tethys tectonic belt, thus, further detailed analyses integrated with paleobiogeographical, detrital zircon and other tectonic data are needed to provide a more comprehensive and robust understanding of the tectonic and paleogeographical history of these blocks. Although the Qinghai-Tibetan Plateau and its surrounding areas encompass a vast realm, the research on the Cambrian lithostratigraphy, biostratigraphy, chronostratigraphy, biotas and paleogeography is still in its early stage and requires further improvement in all directions. In view of the complex tectonic history and the importance of paleogeographical changes of different tectonic units, an in-depth study of the Cambrian stratigraphy, biota and paleogeographical evolution of these areas can not only provide new important information for revealing the tectonic evolution history of the Qinghai-Tibetan Plateau, but also provide new evidence for unraveling the evolution of the Cambrian Earth-life system.

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